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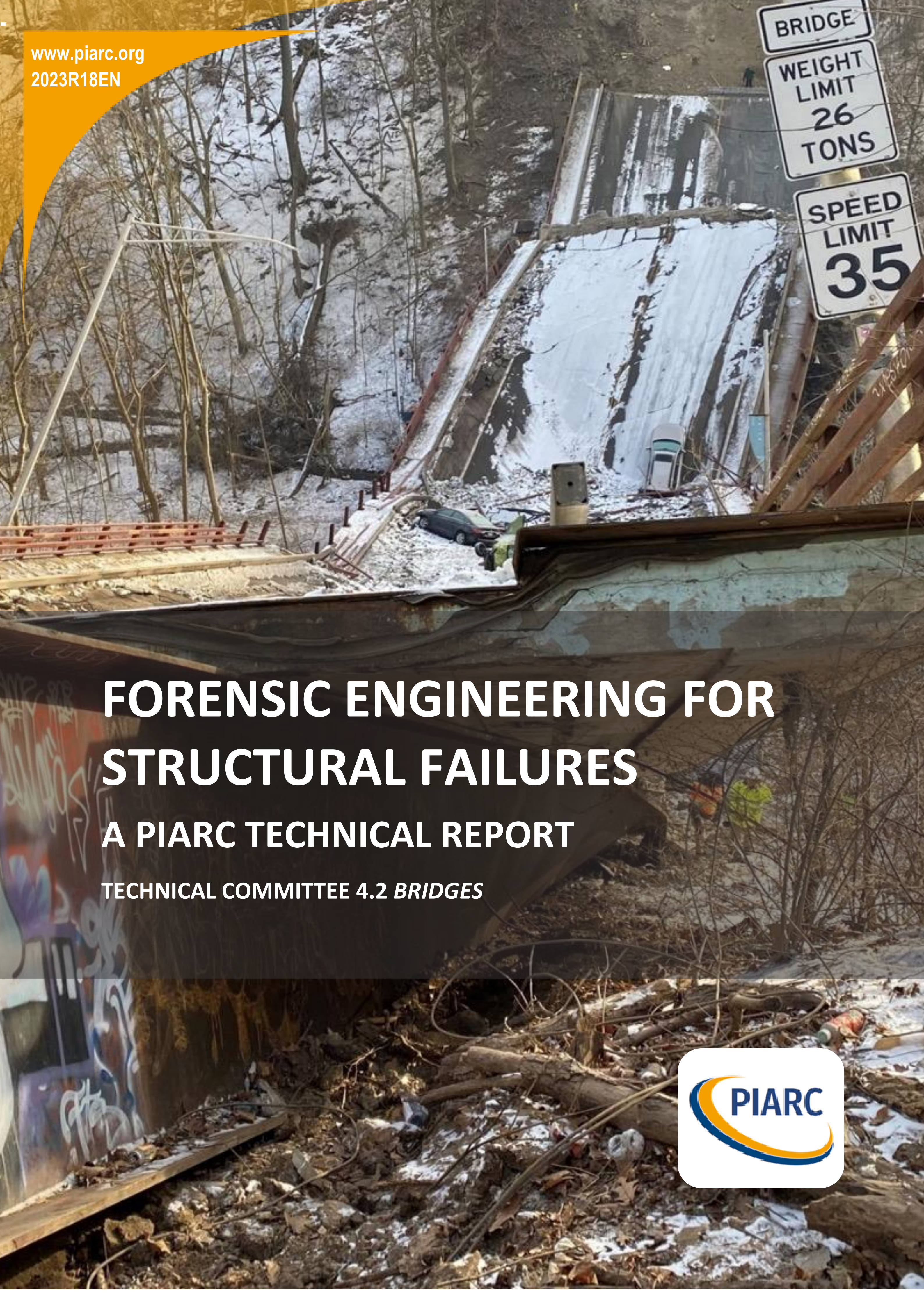

FORENSIC ENGINEERING FOR STRUCTURAL FAILURES

A PIARC TECHNICAL REPORT

TECHNICAL COMMITTEE 4.2 *BRIDGES*

PIARC

STATEMENTS

The World Road Association (PIARC) is a nonprofit organization established in 1909 to improve international co-operation and to foster progress in the field of roads and road transport.

The study that is the subject of this report was defined in the PIARC Strategic Plan 2020–2023 and approved by the Council of the World Road Association, whose members are representatives of the member national governments. The members of the Technical Committee responsible for this report were nominated by the member national governments for their special competences.

Any opinions, findings, conclusions and recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of their parent organizations or agencies.

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EXECUTIVE SUMMARY

2023R18EN

FORENSIC ENGINEERING FOR STRUCTURAL FAILURES

A PIARC TECHNICAL REPORT

When a bridge collapse occurs, engineers investigate the cause of collapse to identify how design, materials, workmanship, and/or overloading affected structural performance. In this meaning, forensic engineering plays an important role in improving the safety of bridges. Engineers learn from the results of forensic engineering investigations and make improvements to the requirements of design, construction, and maintenance in order to prevent these tragedies from reoccurring.

As a result, there is interest in how these tragedies are investigated and how lessons learned are identified and implemented. The engineers investigating these failures generally have two primary objectives, (1) determine the probable cause of the failure with a high level of confidence, and (2) clearly communicate that cause so that it is well understood by both the well-informed and non-technical audiences.

The objectives of this report were to provide guidance to practicing bridge engineers on the elements that make up and the factors that influence a competent forensic investigation, and on how lessons learned from a forensic investigation are identified and communicated. It is TC 4.2's expectation that this report will be used to as a reference for experienced engineers, and as an introduction to forensic engineering for a bridge engineer who has yet to participate or conduct a failure investigation.

One overarching conclusion from the information collected was that bridge failure is rare, and the circumstances associated with bridge failures are too diverse to make possible the establishment of a detailed formal process. Some specific conclusions resulting from a thorough review of the information collected are:

- Forensic investigations are conducted to determine the probable cause of a failure, and to disseminate the knowledge developed so that a similar failure does not occur elsewhere.
- In most countries, the primary responsibility to investigate a bridge failure resided with the bridge owner or operator. However, if the failure was catastrophic or resulted in fatalities or serious injuries, in some countries an independent governmental authority or the judiciary could be charged with conducting or managing the investigation.
- Only one country reported having a formalized process for a forensic investigation which consisted of a schematic high-level procedure on the initial investigative steps.
- No countries had guidelines on how to construct a forensic investigation team. However, all that responded indicated that these teams were generally made up of engineers with the expertise needed from either the bridge owner, a hired consultancy, an appointed expert, or a combination.
- All failure investigations started with the collection of existing records and information on the design, construction, inspection, maintenance and rehabilitation or repairs, if any, of the bridge.

Recommendations were drawn from the findings and conclusions of the report. Bridge owners are recommended to maintain a comprehensive file of information on each bridge (bridge file) in their inventory, establish and maintain a centralized database of those bridge files, and to regularly archive and communicate the results of forensic engineering investigations. Understanding the broader value of the information collected, it was recommended to PIARC to continue to collect and share case studies of failure investigations.

CONTENTS

1. INTRODUCTION

Recent high-profile bridge collapses in Italy, Taiwan, France, the United States, and Norway have reinforced the need for engineers to continue to learn from failure in order to improve future practice. As a result, there is interest in how these tragedies are investigated and how lessons learned are identified and implemented. The engineers investigating these failures generally have two primary objectives, (1) determine the probable cause of the failure with a high level of confidence, and (2) clearly communicate that cause so that it is well understood by both the well-informed and non-technical audiences. This study was an effort to provide guidance to practicing bridge engineers on the elements of and the factors that influence a competent investigation, and how to best communicate investigation results.

Figure 1: Wreckage of the I-35W Saint Anthony Falls Bridge which collapsed into the Mississippi River in Minneapolis, Minnesota, USA, on August 1, 2007.

By the very nature of their work, engineers play a very distinct and trusted role in the lives of the public as they are primarily responsible for the bridges and tunnels used by many every day. Due to the diligence and dedication of public officials and bridge owners in most countries to routinely inspect bridges and to regularly assess in-service bridge damage and deterioration by qualified engineers, bridge failures are extremely rare. While in service, bridges experience a variety of damage or deterioration stressors that can result in the partial or total failure of a bridge. If left unchecked, damage or deterioration can accumulate over time due to environmental impacts, repetitive or increasing live loads (increasing cycles of application and increasing load limits), use of deicing salt or chemicals, poor detailing, deficient construction, or insufficient maintenance that can result in failure. Failure can also be incident based when caused by natural or manmade extreme events including overloads, earthquakes, flooding, fires, impact of vehicles or vessels or similar severe loadings. Although extremely rare, when failures do occur, it is a significant responsibility of the investigating organization to competently determine the probable cause of failure, and to communicate that probable cause widely within the technical community at an appropriate level of detail to ensure that a similar failure does not occur again in the future.

Despite modern management methods and approaches, there are still bridge collapse disasters due to insufficient inspection, deteriorated materials or systems, construction defects, overloads, and poor design. Recent examples include the collapse of the I-35W Bridge over the Mississippi River in the United States, the Genova Bridge in Italy, and the Trenten Bridge in Norway.

When a bridge collapse occurs, engineers investigate the cause of collapse to identify how design, materials, workmanship, and/or overloading affected structural performance. In this meaning, forensic engineering plays an important role in improving the safety of bridges. Engineers learn from the results of forensic engineering investigations and make improvements to the requirements of design, construction, and maintenance in order to prevent these tragedies from reoccurring.

Laboratory experimental techniques and computer simulations have become highly developed to analyze material and system failures. Strategically placed cameras and data recording systems can often capture failures as they occur, greatly reducing the uncertainty of conflicting eyewitness reports. An understanding of how to best capture all of this data and documentation to produce actionable information would be of value to the bridge engineering community and lead to the improved safety of bridges. Therefore, it is required to study the current approaches to forensic engineering in order to improve the safety of bridges and to include the findings in a report.

This work by the Road Bridges Technical Committee (TC) 4.2 builds on efforts from the previous two PIARC work cycles. Guidance on how to regularly assess in-service bridges for their load carrying capacity considering their current conditions is the subject of the publication ESTIMATION OF LOAD CARRYING CAPACITY OF BRIDGES BASED ON DAMAGE AND DEFICIENCY (PIARC publication 2016R02EN) which was produced by the PIARC Technical Committee on Road Bridges during the 2012-2015 work cycle. Perspectives on damage and deterioration assessment techniques and a decision-making process that can be used as a guide during any assessment are the subjects of the publication DAMAGE AND DETERIORATION ASSESSMENT DECISION-MAKING FOR HIGHWAY BRIDGE SAFETY (PIARC publication 2019R28EN) which was produced by the same committee during the 2016-2019 work cycle.

1.1. Objectives

The objectives of this report are to provide guidance to practicing bridge engineers:

- On the elements that make up and the factors that influence a competent forensic investigation, and
- On how lessons learned from a forensic investigation are identified and communicated.

It is TC 4.2's expectation that this report will be used to as a reference for experienced engineers, and as an introduction to forensic engineering for a bridge engineer who has yet to participate or conduct a failure investigation.

1.2. Methodology

The Road Bridges Technical Committee (TC) 4.2 determined a general questionnaire would produce a diverse collection of worldwide case studies that could be used to fulfill the objectives of this study. Based on the collective knowledge of the workgroup, a questionnaire was developed that included questions on the major elements of a forensic engineering investigation. This questionnaire was then circulated to the membership of TC 4.2 and eighteen (18) responses were received.

The information in the responses was analyzed and synthesized by topic from which summaries were developed. In addition to the information included in the questionnaire responses, the members of TC 4.2 developed additional information through selected references and by documenting the professional experiences of those on the workgroup.

1.3. Discussion of Failure

For the purposes of this study, failure is defined as an unexpected loss of structural capacity due to unknown or unapparent circumstances that has reduced the level of service provided by a bridge. The workgroup was primarily interested in failures while a bridge was in-service, and failures during construction or rehabilitation that were the result of a deficiency in a permanent structural element. Typical causes of failure include design error, improper use of a material, inferior material or a material defect, fabrication flaw, construction error, unintended or unforeseen load during service, and intentional overload (knowing or unknowing).

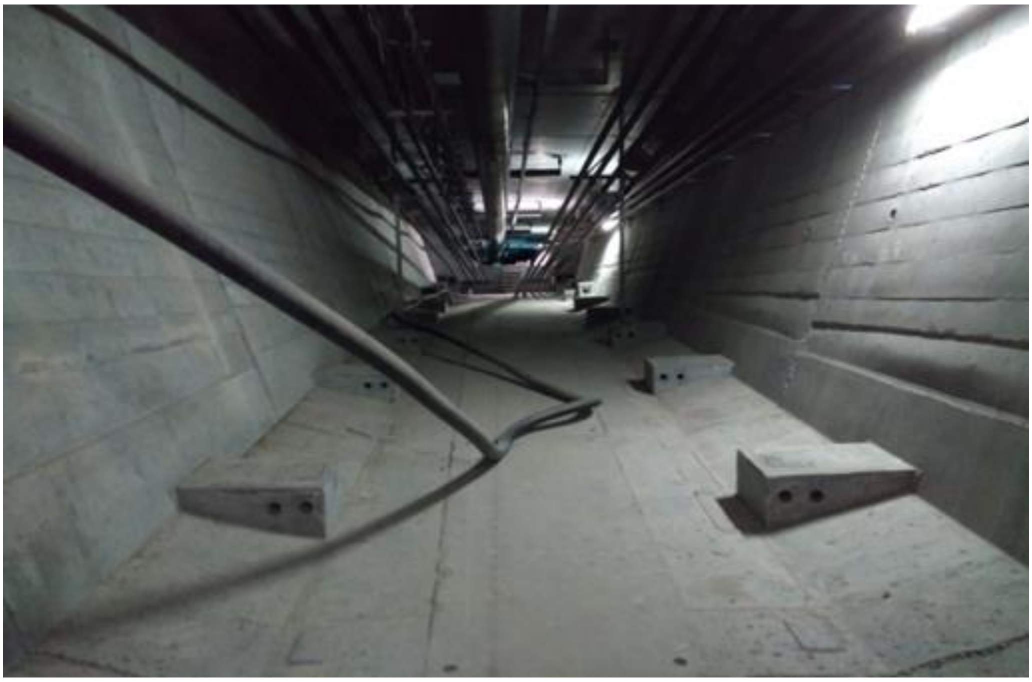


Figure 2: Photo of a failed post-tensioning tendon inside the Ré Island Bridge outside La Rochelle, France, on September 13, 2018.

Failures where the cause is known (impact, excessive deterioration, fire, earthquake, etc.) and performance met expectations, or failures that are the result of the means and methods employed during construction were not within the scope of this study.

1.4. Discussion of Forensic Engineering for Structural Failures

Forensic engineering for this study is defined as the methods, processes and procedures used to identify the probable cause of failure. Typically, these are investigations of the design, materials, products, structures, or components that failed or did not behave or function as intended. Forensic engineering is not an established discipline of engineering, rather it is generally recognized as the application of one or more engineering disciplines using accepted, rigorous, or accredited scientific and engineering principles. While the outcomes of these investigations are important to inform or educate practicing bridge engineers, the focus of this study is on the investigative process that produces the outcomes.

For additional clarity in responding to the questionnaire, it was also deemed important to distinguish between inspection and investigation. Consistent with other established PIARC definitions and interpretations, an inspection is defined as the diagnostic evaluation of a bridge for the purpose of documenting current conditions or changes in behavior. This evaluation is primarily conducted via visual methods but may also employ mechanical methods or advanced technologies when engineering judgment or experience deem them necessary.

An investigation is defined as the additional engineering, study, or research, including the physical testing, experimentation, or analytical efforts necessary to determine the cause of changes in conditions or behavior of a bridge. In general, investigations are conducted in reaction to the results of some type of inspection or observation unless full or partial collapse of the bridge has occurred when the first step of the investigation is generally to inspect and document the failure.

1.5. BRIDGE FAILURE STATISTICS

Collecting statistics on bridge failure can be a challenge due to the metadata associated with each data set. For example, the Federal Highway Administration (FHWA) in the USA, has collected specific data on bridge collapses since July of 2020. However, that data set is limited to bridges that meet the FHWA definition of a highway bridge, and are allocated into two subgroups; (1) total bridge collapse, and (2) partial bridge collapse. Total bridge collapse is defined as the complete loss of one or more spans of a bridge. Partial bridge collapse is somewhat more subjective. Considering a multibeam bridge as an example, partial collapse includes, among others, the collapse of one end of a beam, the loss of support for one or more beams, the complete loss of one or more beams, or the loss of the deck between two or more beams. In general, a partial collapse leaves a part of the bridge operational to some level of traffic loading.

With that metadata as background, between July 2020 and December 2022, out of an inventory of more than 620,000, 27 bridges experienced a total collapse in the USA [Figure 3]. Of those, more than half (59%) were due to scour or flooding of which nearly half (44%) where due to flooding or surge associated with storms or other extreme weather events and the remaining (15%) where due to flooding or scour not associated with an extreme weather event. Of the remaining, 11% each were due to impact from a live load (truck or cargo) or a fire, and 7% were due to overload. The last 11% collapsed from causes that were not readily identifiable. Of the other categories tracked in the USA, no bridges collapsed from an earthquake or degradation (deterioration) during the same time period.

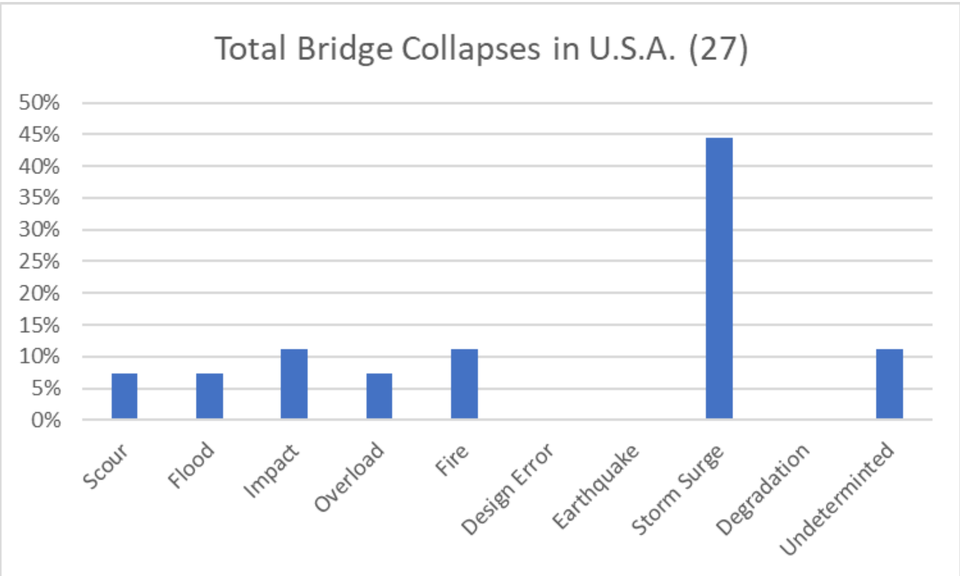


Figure 3: Highway Bridge Collapses in the U.S.A.

Also, from July 2020 through December 2022, an additional 60 bridges suffered a partial collapse in the USA [Figure 4]. Although degradation (deterioration) resulted in no bridges suffering a total collapse, 40% (24) partial collapses were due to degradation during the same 30 months. This was followed by scour or flooding due to storm surge or an extreme weather event (18%), flooding not associated with an extreme weather event (13%), impact (10%), scour not associated with an extreme weather event (7%), overload (5%), fire (2%), with an additional 5% partially collapsing from causes not readily identifiable.

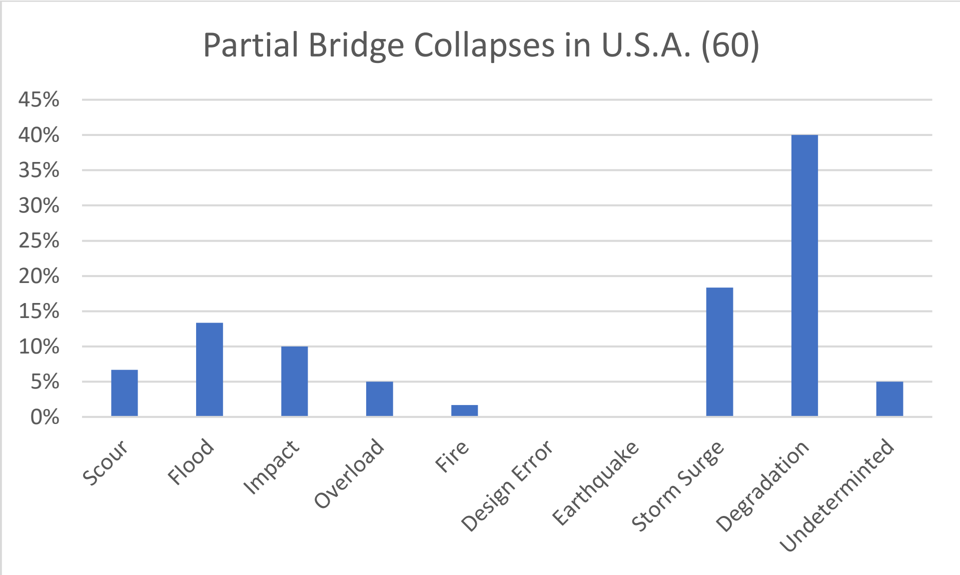


Figure 4: Highway Bridge Partial Collapses in the U.S.A.

In his 2010 book, ***Failed Bridges: Case Studies, Causes and Consequences***, Joachim Scheer reports bridge failure data for more than 400 bridges in Switzerland and Germany [Figure 5]. Most of these collapses (44%) were due to any source of flooding or scour, or storm surge. Of the remaining, 19% were due to impact, 14% were due to overload, 5% were due to degradation, 4% were due to fire, and 3% each were due to either a design error or earthquake. The last 8% were due to causes not readily identifiable.

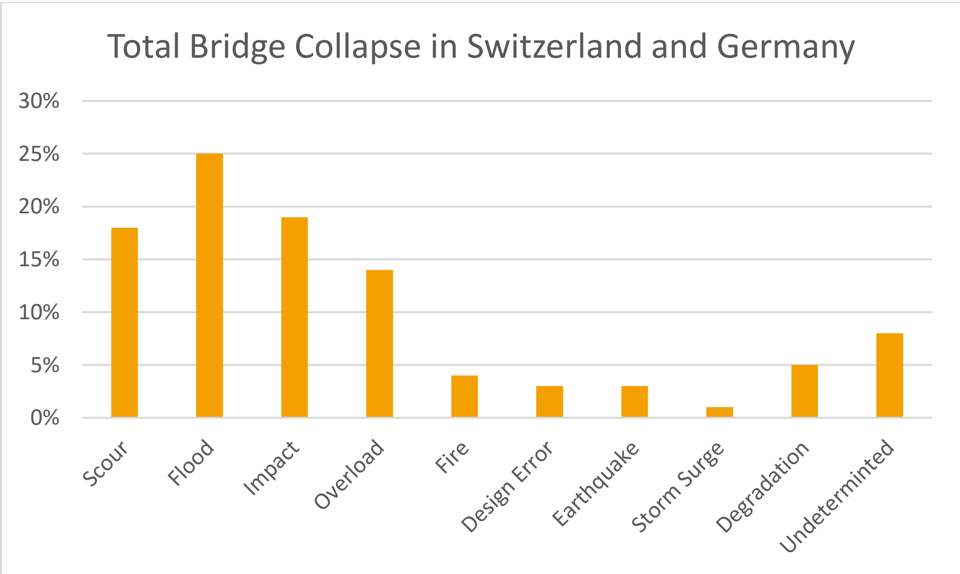


Figure 5: Highway Bridge Collapses in Switzerland and Germany

Comparing the statistics from the USA with those from Switzerland and Germany, if the causes for collapse due to scour, flooding or storm surge are aggregated together regardless of definition, then the distribution of the cause of collapse between the two datasets are very similar [Figure 6].

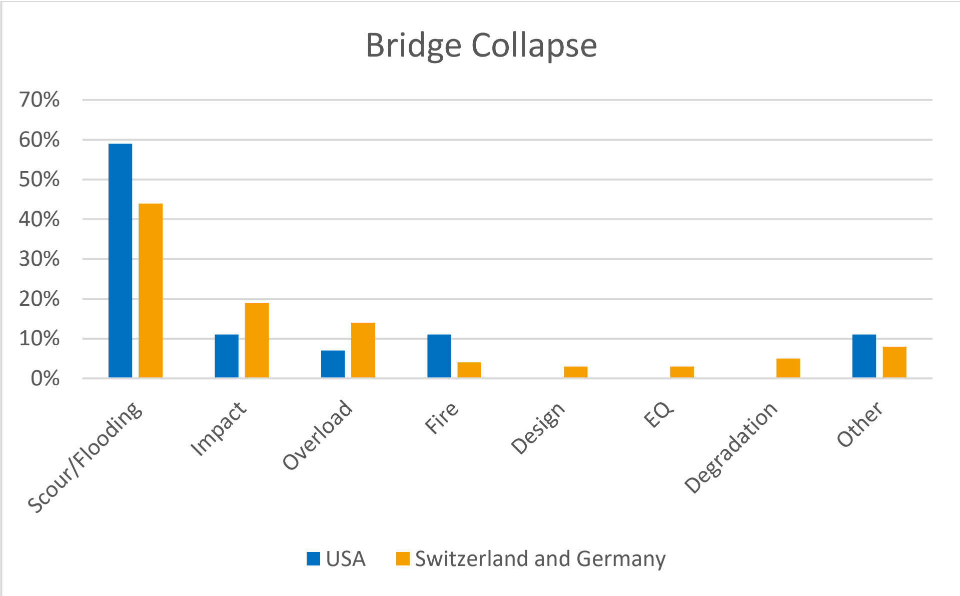


Figure 6: A comparison of the cause of bridge collapse between the U.S.A and Switzerland and Germany.

2. CASE STUDY QUESTIONNAIRE

2.1. DESCRIPTION

Using the collective experiences of the workgroup, the questionnaire was built by systematically identifying the components and elements of known investigations. Once the workgroup was satisfied with the extent of what seemed an exhaustive list of forensic investigation elements, the questionnaire was developed by grouping elements and questions with similar topics into sections.

The resulting questionnaire had fourteen (14) sections, some with a single question and others with multiple questions, that could be answered referencing an example case study. Most of the questions asked could be separated into one of two groups, a characteristic of the investigation (investigating organization, legal constraints, investigative process, organizational structure, investigator qualifications) or a component of the investigation (investigation documentation, testing, experimentation, analyses, files and records, lessons learned).

The questionnaire started with asking for a description of the bridge and the failure from the example case study. From there the focus became what organization conducted the investigation and what legal constraints they were operating under, if any. The next questions also addressed characteristics of the investigation asking if there was a standardized process used, if there was a formal structure of the investigation organization, and what investigator qualifications were required. Then the questions explored the components of the case study investigation, what documentation was produced, whether any standardize testing was conducted, the types of analyses performed, and whether additional experimentation was needed. Finally, there were questions on what data files and records on the bridge were available to investigators, what lessons learned were identified and a catchall question on other impacts that might have affected how the investigation was conducted.

2.2. RESULTS AND DISCUSSION

Each section from all eighteen (18) questionnaire responses were evaluated by a member of the workgroup. When a response motivated an additional question/s by the evaluator, those questions were sent back to the TC 4.2 member who submitted the response for follow-up. Using the whole of the information developed through the questionnaire and follow-up, the evaluator then provided a summary for inclusion in this chapter of the report.

2.2.1. Investigation Organization

The different case studies provided in response to the questionnaire showed that there are several possible organizations to investigate bridges failures. Sometimes a country has no independent authority capable of investigating, sometimes, it exists. It seemed that in most cases, the primary responsibility resided with the bridge owner: a State, a city, a regional or national network, or a concessionary motorway.

In some countries under certain circumstances, investigations are conducted by an independent authority, like in the United States, Canada, Korea, Portugal, or France. These authorities are either leveraged into conducting the investigation depending on the severity of the tragedy or significance of the asset. If there were no fatalities or injuries, a failure will usually be handled by a centralized bridge office of the bridge owner or at the head of the administration of the country that provides oversight to bridge safety. If the failure results in a death or severe injury, in general, the investigation will initially be the responsibility of law enforcement. In some countries, law enforcement will usually hire independent assistants such as a technical body of the administration or university professors to conduct the technical part of the investigation, if needed, and will publish a summary of their findings along with recommendations in a report to the government.

These authorities can create a group of experts whose role is to determine the probable cause or causes of the failure, issue safety recommendations, study transportation safety issues, and evaluate the safety effectiveness of government agencies involved in transportation.

2.2.2. Legal Constraints

During the development of the questionnaire, it was postulated that legal authorities and any associated constraints might affect who conducts an investigation and how the information developed is shared. As a result, a question was included to try to identify these requirements within each responding country to provide any necessary context to the remaining survey responses. Of the eighteen (18) responses to the questionnaire, nine (9) contained unique answers for the question on legal constraints.

In Belgium, in general there are no specific legal constraints on how a bridge failure is investigated or the information produced is disseminated. However, if the failure resulted in injuries or fatalities, then law enforcement conducts the official investigation.

In Canada, if the actions or neglect of an individual is identified as responsible for the failure by a public commission, then prosecutors can elect to lay charges. If that is the case, then the investigation is transferred to the judiciary. This legal or law enforcement investigation is precluded from relying on the testimonies developed by the commission, but it can use the findings of the commission's technical expertise.

In the Czech Republic, when there are injuries or fatalities or in the case of a significant or catastrophic bridge failure, law enforcement conducts the investigation. In these cases, the information produced by the investigation is strictly non-public. So, information is not officially available to the profession or public during the investigation, and even afterwards it can be difficult to get complete information due to legal restrictions.

In France, there is no legislation that regulates the investigation of a bridge failure. However, the legal authorities do typically intervene at several levels:

A criminal court (in French a "tribunal penal") typically conducts the investigation when there are injuries or fatalities. Recognized expertise is used to conduct the investigation whose findings are then forwarded to the investigating judge.

A district or high court (in French a "tribunal d'instance ou de grande instance") is used when contradictory findings or conclusions are developed by the expertise investigating a failure.

An administrative tribunal within the framework of public tenders is used to settle contractual disputes. Similarly, a commercial tribunal is used to settle disputes between private companies.

When the different courts intervene, they appoint experts accredited to the respective courts who conduct the investigation process; these investigations are then carried out within the framework of the confidentiality of the judicial process unless the outcome is obvious.

In the event of a major failure of a bridge managed by the French State, the Ministry of Transport typically conducts the investigation by setting up technical committees that bring together representatives of the manager of the structure and experts from a government institution (CEREMA) and the University Gustave Eiffel (ex-IFSTTAR). These committees are chaired by a General Engineer. This investigating organization is desirable when there is a major failure and is typically used by other bridge managers such as private motorway companies or local authorities.

In Germany, like other countries, if a bridge failure results in injuries or fatalities the public prosecutor conducts the investigation through the judiciary system. The prosecutors appoint experts to examine the failure, and their findings become the basis for any further investigation.

In Spain, while there are no legal constraints on a bridge failure investigation, a law on transparency and access to information and good governance does require that the government provide access to information about public activities. This law can be used as the basis for information requests on failure investigations by the profession and general public.

In Switzerland, an investigation by the legal authorities is required when injuries or fatalities result from a bridge failure. In these cases, the findings or conclusions are not accessible by the public until the authority has completed the investigation and reached a decision. If an investigation is conducted outside of the legal system, it is the responsibility of the public or private owner who ordered the investigation to regulate the accessibility of the investigation results. Public owners are obliged by law to disclose the findings and conclusions of an investigation no later than at its completion unless this would involve unreasonable effort.

In the USA, the Federal government and each State government have freedom of information or transparency laws that typically make all information developed during an investigation available to the general public after the deliberative process is completed and findings have been made. For investigations conducted by the National Transportation Safety Board (NTSB), the digital files of all data and information developed are available in a single docket through their website. Investigations lead by others have disseminated this information in a variety of ways, generally upon request, but sometimes also through publishing on a dedicated website.

Also, in the USA, by statute the NTSB has the authority to determine all facts for investigations that they lead.

2.2.3. Investigative Process

Only one of the countries responding to the questionnaire indicated that they had a formal, structured investigative process for failures, South Korea. However, the process reported was qualified as a schematic procedure that is contained in the operations manual for an Accident Investigation Committee (AIC). The schematic requires the AIC to initially conduct a site investigation to preserve the site and plan field and laboratory testing, if needed. After that, the AIC is required to establish detailed investigation procedures to be used to carry out the site investigation in collecting information.

In general, the case studies indicated that if a failure was catastrophic including a partial or full collapse of the bridge, or involved fatalities or injuries, law enforcement and first responders maintain and investigate the site first as a rescue scene, and then as a recovery scene, if necessary. Once these first responders are satisfied, the site was generally turned over to the owner or agency having jurisdiction for the investigation. Once first responders are no longer involved, the procedures or process used to conduct the investigation was then left to the experience of the investigators and the counselors or advisors they collaborate with.

Figure 7:First responders investigating the site of the De la Concorde overpass collapse outside of Montreal, Quebec, Canada on September 30, 2006.

The lack of a formal process for the countries that responded is primarily recognition that the failure of bridges is very rare. It is also recognition that the circumstances associated with these infrequent failures are generally diverse enough that it might be unreasonable to expect a standardized process be created. However, the case studies also indicate that there is a reasonable order of events that make up the process of the investigation.

This order of events typically starts with a detailed visual inspection and documentation of the failure. If a partial or full collapse, this can take weeks to accomplish competently. Investigators are looking for indications of where and how the failure started and for evidence of any mechanisms that developed or "witness marks" that might indicate the sequence of failure. This step also typically includes the identification of elements or components of the bridge that may need additional investigation through either laboratory examination or testing. Once the documentation is completed, any elements or components needing additional study are recovered and shipped to the appropriate facilities.

Usually in parallel with the inspection and documentation of the failure, any existing documentation on the design, construction, inspection, and management of the structure are gathered and reviewed. If the onsite investigation has identified an area or areas of the bridge that may have initiated or failed early in a collapse sequence, the design calculations for those elements are generally studied for indications of errors or incompetence.

Once the investigation onsite is completed, the testing or examination of the elements or components recovered from the bridge begins. The testing done during this phase of the investigation is generally standardized and relies on accredited personnel to be conducted. Any detailed examination using nondestructive testing technologies or laboratory microscopes, or equipment also requires the necessary expertise. These individuals are typically experienced and skilled in creating the type of report needed to support an investigation.

If after the onsite investigation, a review of the related and relevant documentation, and any testing or examination of elements or components of the bridge there is still uncertainty to the probable cause of failure, the next steps in a general process typically involved analytical modeling and/or experimentation.

2.2.4. Organizational Structure

Considering all the case study responses, forensic analysis is often treated like the reaction to a critical inspection finding and the organizational structure is about the same as for that process. Generally, these reactions are led by the bridge owner with some internal or external bridge design experts hired by the bridge owner. Depending on the case, the makeup of the team may be more or less important. Furthermore, the team may sometimes be only composed by external bridge experts. Even if this step is identified in the Bridge Management System of the organization, generally there are no guidelines on how the team should be comprised. It should be noted that Germany has some guidelines: « Guidelines for the Uniform Documentation, Assessment, Recording and Evaluation of the Findings of Structural Inspections in Accordance with DIN 1076 ». However, those guidelines were developed for use in responding to inspections findings and not specifically for a forensic analysis.

In USA, there is a National Transportation Safety Board that has the authority (but not the obligation) to investigate bridge failures. If mandated, NTSB will lead a group with **all** interested parties including parties that may or are likely culpable. All parties share information and can submit an analysis for the consideration of the NTSB. With the permission of the NTSB, the owner of the bridge may conduct an independent parallel investigation as long as all data and information developed are shared with the NTSB and the parallel investigation does not make any conclusions until after the NTSB determines probable cause. Otherwise, the bridge owner is also free to conduct an independent investigation once the site and evidence are released by NTSB. If the independent investigation produces significantly different results, there is a formal process to petition the NTSB for reconsideration of the determination of probable cause considering the new information developed.

In Canada-Québec, the Government may decide to create a public enquiry commission which will generally use design experts to conduct an investigation. In this case, the experts decide what expertise is needed for the investigation which was the case for investigating Concorde overpass collapse. In this case, the bridge owner decided to conduct a parallel investigation using independent experts.

2.2.5. Investigator Qualifications

In the case studies submitted, no specific qualifications nor licenses for the role of a forensic engineer were mentioned. For the case where a failure is of limited impact to the whole structure – without sudden full or partial collapse of the structure, without injuries or casualties, or when the failed element can be quite easily repaired or replaced – professionals working for or hired by the bridge owner/managing body are usually in charge of investigating the failure. Their qualifications are normally those which they need for their usual scope of work – a degree in Civil/Bridge engineering with some years of relevant professional experience. Some jurisdictions require these engineers to be Chartered (licensed by public administration or by an independent professional body qualified to do so) which usually represents a proof of skills and a minimum of 5 to 10 years of relevant experience required by the certification committee. In some countries, such as Germany, Czech Republic and the United States, the oversight authorities require specific types of training and certification for bridge inspectors, who are eligible to perform compulsory periodic bridge inspections. These inspectors are often the first to discover a failure on site. Sometimes the investigation requires an invitation of professionals with some specific proficiency, such as welding engineers (with IWE certificate), or knowledge in other fields of civil engineering (geotechnical or hydraulic experts, etc.).

In cases of a large-scale structural failure (loss of structural stability or collapse) with or without serious consequences, usually the bridge owner/managing body or a superior authority will not be satisfied with a routine investigation of the incident by their own engineers or by usual staff, but rather appoint a committee of well recognized senior experts, professors, researchers, or others.

Figure 8: A group of engineers and scientists investigating the failure of a post-tensioning tendon.

If the failure becomes a law enforcement investigation (cases with injuries, casualties, or high costs), the judiciary typically takes over the control of the process. Usually, they ask relevant experts for their opinion or testimony. In some countries, such as Czech Republic, there are court-certified experts (with specified fields of expertise), who are entitled to issue an Expert evidence report, which is then relevant in the ongoing police investigation or trial. Unfortunately, it was reported that due to the lack of court-certified experts with thorough experience particularly in bridges, this system does not always guarantee sufficient proficiency in pursuit of finding the probable cause of failure.

2.2.6. Documentation

There were two questions about this topic in the case study questionnaire:

a) Describe how the failure was documented on-site?
b) How was physical evidence collected, documented, and controlled?

From the case study responses, it became obvious that no general rules existed to be applied for this task. The methods and details of documenting the failures described depended highly on the type and severity of the structural defect and its consequences.

Generally, photo and video documentation is indicated as being the most obvious and simple tool for recording the failed state of the structure. Many of the respondents also identified one or more Non-Destructive Testing (NDT) methods which were used to document the failed elements.

In addition, some kind of physical measurements (e.g. laser scanning, monitoring of settlements, surveying, section loss detecting, etc.) of the failed structure or structural element were also cited by many respondents as a frequently used method of documentation.

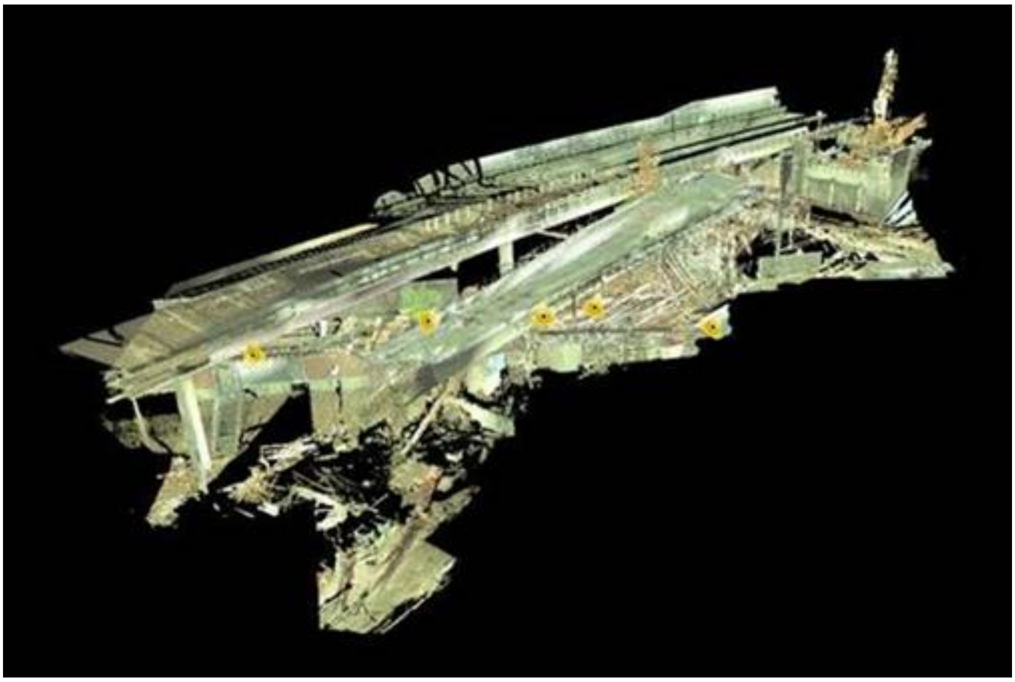


Figure 9: LIDAR point cloud documenting the position of the F3 Murbruecke Frohnleiten Bridge wreckage which collapsed in Austria on February 21, 2015.

In cases of serious structural damage with casualties the structural investigation might sometimes be delayed by the official investigation authorities (police, disaster management bodies, court). In these cases, it can be stated that the elimination of a condition that may cause a subsequent accident or emergency and the stabilization of elements that are considered unstable is one of the most important measures taken to preserve the integrity of the failed structure and the safety of investigators. These actions are usually made in parallel with the photo and video documentation process.

Some of the respondents stated that a survey plan and/or an inspection report is prepared for the damaged condition, which, for example, details the location of cracks or similar damage and deterioration.

In those cases where the structure did not suffer significant enough damage as a result of the defects identified to result in a loss of load-bearing capacity (i.e., the structure did not have to be rebuilt, dismantled or replaced and it was determined sufficient to treat the defects), a separate methodology was defined for the examination of the defects, after their documentation and stabilization.

In many cases, physical sampling was performed on the structure or structural element that was the source of the failure (e.g., corroded tension cables, anchor rods, etc.), which were then subjected to laboratory tests.

2.2.7. Testing, Experimentation and Analyses

All of the questionnaire responses submitted identified either testing, experimentation or analytical modeling as used in support of the forensic investigation in the case study. Some of the details of the methods used and the results produced are described in this section of the report. However, it is important to keep in mind that the methods and approaches discussed are not intended to be all-inclusive of those that might be justifiably used during a forensic investigation.

2.2.7.1. Testing

Typical material tests were conducted in almost all case studies to evaluate the following:

- Material quality, e.g., the conformity to regulations, design standards, and the detailed specifications for the structure investigated.

- Mechanical and chemical properties for fatigue and delayed fracture of steel, prestressed concrete strands, anchors, high-tension bolts, etc.
- Material properties for inputs in further analyses and experiments, e.g., stiffness, strength, shrinkage, creep, and so on.
- Soil investigations, e.g., the site characteristics and subsoil structures, for evaluating the stability of the foundation and surrounding soils.
- In the cases involving the breakage of cables or tendons, further laboratory and field observations were conducted as follows:
- Fractographic examination: Electron microscopy scanning is often used to observe the fractured surface and seek the similarity to the crack growth marks of fatigue, stress corrosion, hydrogen embrittlement and so on.
- Examination for corrosive factors inside cables: cable covers, sockets, and anchorages are opened to observe the cables and wires inside visually, in order to identify the existence of corrosion and corrosive materials such as water and chlorides. The permeability of cable cover materials is also tested at times.
- Examination for corrosive factors in concrete and grout: Specimens are sampled from the site, such that the existence of water paths and chloride contents can be sought.
- Field observations are also documented in many of the case studies. The documentation reported included:
- Damage and crack maps.
- 3D measurements, laser scanning, and imaging.
- Reaction force measurements at temporary supports.
- The distribution of the observed manifestations of distress could be a vital indicator to understand both the deformation of the whole bridge and the local stress effects on the damaged components. These observations are often used to evaluate the reliability of any structural analysis conducted in a later process of the forensic investigation. Some examples of the types of failure and the related field observations or measurements from the case studies surveyed included:
- Ruptures of hidden/embedded tension members, such as cables, prestressed concrete tendons, and anchors,
- Vibration frequencies measured to check the integrity of the cables and estimate the tensile force,
- Cracks in steel members,
- Damage and crack maps made in terms of defects at welding and misalignments,
- Magnetic particle tests and ultrasound tests are conducted to seek hidden cracks,
- Stress ranges and vibration frequencies are measured,
- For box cross-sections, endoscopy investigations are conducted to check the weld quality and plate arrangements inside a closed cross-section,
- Failure of concrete members,
- Crack distributions and locations are recorded with photos, 3D scanning, and sketches,
- Failed portions are sometimes sawed to observe the crack distributions and reinforcement arrangement inside as well as the deterioration of reinforcement and concrete,
- Non-Destructive Evaluation (NDE) such as the stress (impact elastic) wave tests are conducted to check the existence of hidden distress inside the concrete,
- Monitoring is conducted for the gradual change in displacement and inclination of structural members if needed,
- Scour and others, and

- Underwater topography and erosion depths are measured surrounding the foundation.

Figure 10: Concrete Elastic Modulus and Poison's Ratio testing to support a rigorous structural analysis.

In terms of NDE technologies, some of the case studies reported that NDE did not always work as expected, including NDE for measuring the remaining cross-sectional areas at anchors embedded in concrete, cables inside sheathing, and wires inside the cable inlet. In those case studies, a calibration process on site or by using model specimens was included in the forensic engineering investigation to check the reliability of the NDE employed.

Work safety must be secured for field investigations. For example, in the case of Ré Island Bridge in France, where the rupture of an external prestressing tendon occurred in a post-tension concrete box-girder bridge, a framework was installed to keep other tendons from whipping out if they suddenly broke endangering investigators or construction workers. Another example can be seen in the case of a continuous post-tension box-girder bridge over the Reuss River in Switzerland, where severe flooding washed out the surrounding soil from piers and foundations, resulting in the movement of those structures and severe cracking in the girder deck and web. In the failed state, the bridge was at imminent and severe risk of further movement that could lead to a complete collapse. To mitigate the risk to investigators, gravel and rock were put in front of the critical piers immediately after the incident and before the investigation. Also, possible flooding and avalanches that could reach the bridge were monitored during the investigation and the recovery work.

2.2.7.2. Experimentation

In the case studies submitted, laboratory and on-site loading experiments were conducted for the following reasons:

- Hydraulic experiments are conducted to examine the possible evolution of scour because it can be difficult to simulate numerically.
    - In the case of a bridge over the Reuss River in Switzerland, hydraulic laboratory experiments were conducted to understand the development process of the scour that resulted in the failure, and the feasibility and effectiveness of different types of flood protection measures.

- Loading experiments using model specimens are employed to verify the assumptions of failure mechanisms or to check the feasibility of NDE.
    - In the case of De la Concorde bridge in Canada, load tests with full-sized models were conducted to study the influence of misplaced reinforcement on the bridge failure.
    - In a case from France, a failure caused by the instability of corbelled precast sidewalk slabs attached to overpasses, the failure mechanism was examined using laboratory experiments, focusing on the failure of the embedded anchors in the concrete. After the experiment, the models were sawed and dismantled to observe the damaged cross-sections.

Figure 11: Scaled component experiments used to support the Cofiroute investigation a failed precast corbel sidewalk to deck slab connection at the Elancourt Structural Engineering Laboratory in Paris, France.

Sometimes a forensic investigation is required for an older structure, and there is little information on the structural details and materials used in the construction of the particular bridge. In the case of De la Concorde Bridge in Canada, other bridges believed to have similar structural details were identified and studied in terms of the signs of distress and the maintenance histories, such that the information obtained could be referred to when contemplating the scope and methods of the forensic investigation.

2.2.7.3. Analyses

In almost all case studies, finite element analyses were conducted to support an investigation. They were also employed to evaluate the safety of the post-failure structure for investigations at the site, possible traffic resumption, or remedial work.

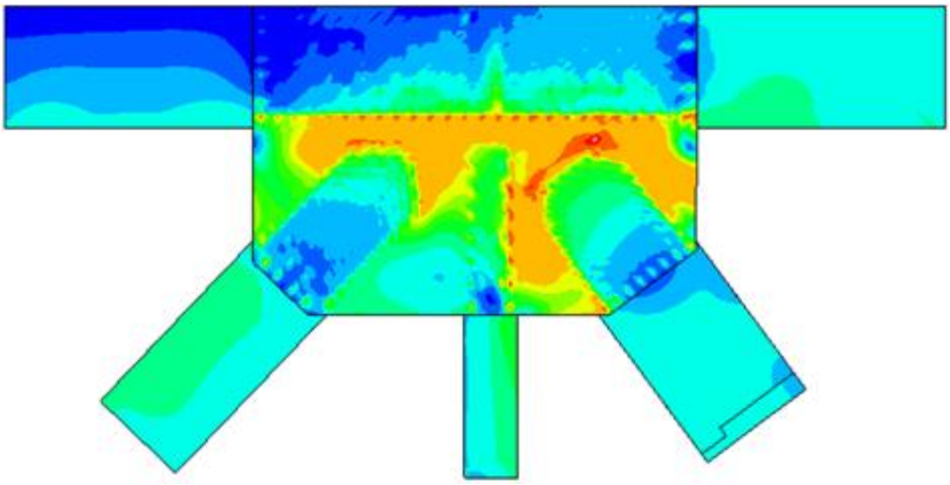


Figure 12: Finite Element Analysis of a gusset plate connection on a steel truss bridge.

The purposes for the analyses in the case studies reported can be classified into the following two categories:

Evaluating the relationship between overall bridge behavior and local stress effects.

Understanding the failure mechanism and remaining strength for the damaged component.

Before starting a numerical study, a thorough investigation of the bridge geometry and the type and extent of distress should be completed to support the modeling and evaluation of the bridge and ensure the accuracy of the numerical results. In the case of the failure in a continuous post-tension box-girder bridge in a valley in Switzerland, severe flooding washed out the surrounding soil from the piers and foundations, resulting in movement of a pier. The girder had settled and deformed torsionally with serious cracking in the deck and the web close to the integral part of the pier and girder. A comprehensive investigation for crack distributions and the change in bridge geometry including the movement of expansion joints and bearings was first conducted. It determined that there was an urgent need to secure the safety and stability of the bridge before any additional work could be done. Accordingly, it was decided to restore the superstructure back to the original geometry. During the lifting operation to restore the superstructure, the jack forces and the bridge behavior were monitored to prevent overstressing in the girder based on the numerical results with a variety of assumptions on stress distribution.

Various load effects can be attributed to the causes of distress, not only live loads or extreme events. In some case studies, temperature variation was a possible cause of the failure for both steel and concrete bridges. Creep and shrinkage were also found to have a profound effect on bridge behavior. For example, in the case of Hohenwarthe Elbe bridge in Germany, the structure was modeled with a comprehensive three-dimensional model using exact cross-sections and dimensions based on physical measurements. The analysis found that live load effects and weld quality played a major role in the cause of the fatigue cracking observed. However, the analysis also determined that the constraint stress due to shrinkage and prestressing in the concrete deck significantly contributed to the extent of the fatigue damage. Another example is from Portugal where a shear failure developed in the reinforced concrete piers at one end of a very long continuous concrete slab bridge. All piers supporting the bridge were connected monolithically to the slab, but the damaged end-piers were shorter than the others. Finite element analyses found that the end-piers could not accommodate the deformations/displacements due to the long-term effects of concrete shrinkage and creep, and sustained temperature changes because they were shorter than the others.

To examine the failure mechanism and remaining strength of a particular failed bridge component, detailed and sophisticated three-dimensional finite element models are often employed. In the case of a report from France where embedded anchor bars that connected prefabricated corbelled sidewalks to a bridge were broken, numerical calculations were used to estimate the decrease in structural capacity based on the reduction in the cross-sectional areas of the corroded anchor bars. In the case study from the USA, errors were found in both the original design calculations and the original analytical modeling. Additional modeling and computation were conducted to verify and identify the influence of those errors. Another example from Canada used finite element analyses to validate the load test results with full-sized models having similar misplaced reinforcement arrangements to the actual structure and reinforcement arrangements as intended by the design engineer.

2.2.8. Files and Records

In the case study responses, it was indicated that all available documentation from the service life of the bridge was used to support the forensic investigations. This starts with the original design calculation and the original plans, if they are still available, and ends up with the more recent reports on all inspection, maintenance, and rehabilitation activities.

In the case of older bridges, the documents (restructuring, war losses) are sometimes missing, resulting in a reliance on more recent data. Depending on the complexity of the case to be examined, the following documents were used as a basis for all case studies:

- Original design calculation and documentation
- Original construction plans
- Inspection reports

If prior evaluations or investigations have been conducted, the results were included with the bridge data. Examples for this are material certifications and test results, structure logs, site logs, recalculations, load testing protocols and monitoring protocols.

In addition, it should be noted that, depending on the operator model of the bridge, documents such as licensing and approval certificates, communication records between a contractor and supervisors, financial documents, construction site diaries, and project status reports were used for the investigation.

It is important to note that all parties to the investigation had access to the information developed, but that did not mean that the information was available to the public. Rather, all experts collaborating on the investigation were granted access to the information.

2.2.9. Outcomes

A successful outcome of a forensic engineering investigation is the determination of the probable cause of failure. Although determining probable cause is often the primary purpose, investigators are frequently charged with identifying other bridges that have similar design details, used a related method of construction, or have a comparable inspection and maintenance history that could be likewise affected. While not always the situation, the case studies provided many examples of the outcome of an investigation having an influence on either bridge engineering or existing bridge inventories.

2.2.9.1. Influence on Bridge Engineering

In the example from Canada, the lessons learned identified a need for improved quality control and documentation of as-built details during construction, and a need for shear reinforcement in certain bridge components. These lessons were presented to the organization that maintains the Canadian Highway Bridge Design Code which resulted in a change in design requirements.

The case study from France that considered the reinforcement details of a cantilevered sidewalk found that the details of the design were vulnerable to deterioration over time and can result in failure. In reaction, the design detail that failed was replaced with a detail that is less risky considering the effects of deterioration.

From the USA case study, the lessons learned included support for more rigorous evaluation of analytical results and a need for a truly independent evaluation of design calculations. In response, additional emphasis was incorporated into the national level design standards, and a training course on analytical methods was recommended. The changes and training were promoted through regular meetings and conferences nationally.

The investigation in the case study from Switzerland identified an underestimation of the forces exerted by extreme weather events as the cause of failure. As a result, nationwide hazard maps were produced to better inform engineers of the loads that need to be addressed in design.

2.2.9.2. Influence on Bridge Inventories

The Belgian case study identified that management of a bridge by more than one organization can result in insufficient communication and coordination. As a result, the practice of shared management of a bridge was abolished within the Belgian Road Administration.

In the case study from France on the cantilevered sidewalks, similar bridges were identified and retrofitted with additional stringers eliminating the risk of sidewalk failure. This action essentially eliminated the design detail of concern paralleling the influence that this case study had on bridge engineering in France.

The French case study on cracking in a box girder bridge unsurprisingly identified fatigue as the cause. The bridge was designed and constructed before fatigue provisions were added to the design requirements in 1994. As a result, the Ministry of Transport required fatigue calculations be conducted for all pre-1994 steel bridges to identify other structures that may develop similar cracking.

3. EXISTING PROCESSES

It must be recognized that the results of a forensic investigation will be disseminated widely to prevent similar failures and events from happening again. Accordingly, the purpose of forensic engineering investigations is not to solely identify the physical causes of the failure, nor the probable cause of the failure. Forensic engineering investigations should be conducted to determine all the facts and symptoms related directly or indirectly to the failure, from the design, construction, inspection, and maintenance of the bridge. The idea is to understand how or if the failure could have been avoided by a change during operation and management of the bridge.

In the case studies, two countries reported that they had an existing process to be followed to perform a forensic engineering investigation of a structural failure. The process from Chile was proposed for use, while the process from Germany had been formally adopted but was primarily developed for use in responding to inspection findings and not specifically for a forensic analysis.

3.1. CHILE

3.1.1. Process

While no formal process for conducting a forensic engineering investigation was submitted through the case studies, a proposed process was supplied that is being implemented and refined in Chile. In this section, the proposed process or guide from Chile for the forensic analysis once a failure has already occurred is explained. The process relies on obtaining relevant information associated with the failure that covers the design, construction, inspection and maintenance histories of the bridge through an incident checklist, which is complemented using a Risk Management (in Spanish “**G**estión de **R**iesgo de **D**esastre **R**egional”or GRDR) forensic sheet . With this information, the root cause of the failure can then be investigated in depth.

3.1.2. Incident Checklist

To start the investigation process, an incident checklist (Figure 1) must be completed, which focuses on the occurrence of the event and determination of the impact. When a failure occurs, it is typically identified and reported by one of two different sources: a road user, or a maintenance (including inspection) program. In general, there are two types of alerts:

Early warning: this type of alert is generated when damage, defect or deterioration is found on a bridge that, if left unaddressed, could lead to failure. For this case, the GRDR forensic sheet (Figure 3) should be used.

Emergency: this type of alert corresponds to the report of a partial or total collapse.

For an emergency, the investigation should proceed to look for information that will help to define the scope and focus of the forensic analysis. For this, it is important to investigate whether there is only damage to the structure, in which case the investigation may be driven by an administrative, political, or economic approach, among others. If users are impacted (injuries or fatalities), an investigation lead by the judiciary is generally necessary.

Regardless, both types of investigation start with gathering evidence. Collect any background information on the failure, which is likely to be available from multiple sources. For this step, it is necessary to collect evidence of two types:

- Volatile evidence. Volatile evidence is information or data that can be easily changed, intentionally or unintentionally, or can change or its availability can change over time. This type of evidence includes documentation and information gathered at the site of the failure. For example, photographs or inspection results of the failed component or element in-situ post-incident. It could also include witness interviews or video, or images captured in the vicinity of the failure.

- Non-volatile evidence. This type of evidence includes newspaper articles, media interviews, weather or traffic conditions, or other information that is documented in a way that it is not altered easily or can change with time. It also includes inventory and inspection data and information about the bridge. Inventory data and information rarely, if ever, change such as the as-built drawings or design specifications used. Inspection data and information change periodically like the current conditions of a bridge or preservation technologies used.

The next step often includes a field visit to collect background information and conduct interviews with people involved or affected by the incident.

After that, the failure should be categorized according to the type of loading experienced and life-cycle stage of the bridge. For the latter, the investigation will proceed by differentiating the type of information required to support the development of an expert opinion, using the following cases:

- Design: In this case, project data such as design manuals, design drawings and codes will be needed.
- Construction: In this case, it will be necessary to have everything related to the project execution stage, considering technical specifications, as-built drawings and construction reports, such as a statement of means and methods, workbooks, material tests, among others.
- Operation: In the event of a failure in the operation stage, information will be collected from inspection reports, material tests, extracting and contrasting samples, annual average daily traffic (ADT), overweigh loads, among other sources.
- External event: Case in which threats must be analyzed, which can be man-made or natural. For the man-made case, the actions that took place just before and after the event must be analyzed, such as the illegal removal of material or elements required for the safe operation of the bridge, impacts to the structure generated by collisions, among others. In the case of natural hazards, it should be investigated whether there was an earthquake, tsunami, or debris current, among others, near the location of the structure.

Incident Checklist Data: __/__/____				
Bridge Name:				
Region / Location:				
Time of Failure: ___:___ hrs.			Date of failure __/__/___	
Time of Inspection: ___:___ hrs.			Date of Inspection __/__/___	
Name of Inspector in charge:				
Technical Visit (Check with X).				
Who detected the warning?	User		Maintenance program	
Type of warning:	Early warning		Emergency warning	
Type of Damage:	Material		Injuries/Fatalities	
Was bridge closure needed?			Yes: ______	No: ______
Date of bridge closure: __/__/___			Time of bridge closure ___:___ hrs.	
Gathered evidence (attach as annexes).				
Volatile evidence (check with an X)			Yes	No
1.- Photographs of the failure area				
2.- Interviews of those involved				
Other volatile evidence				
1.-				
2.-				
3.-				
Non-volatile evidence (check with an X)			Yes	No
1.- News documents prior to the failure				
2.- Inspection sheet				
3.- Sampling				
4.- Gathering of project drawings				
5.- Gathering of As-built drawings				
6.- Gathering of Technical spec.				
7.- Gathering construction reports				
Other non-volatile evidence				
1.-				
2.-				
3.-				
Classification of damage according to type of failure.				
Failure			Comments	
Partial Collapse				

Total Collapse		
Damage classification according to engineering stage.		
Design		Comments
Construction		
Operation		
Extreme Event		
Information collected according to the engineering stage associated with the failure.		
1.-		
2.-		
3.-		
Sequence of failure / collapse		
1.- 2.- 3.-		
___________________________ Signature and stamp of reception		___________________________ Inspector signature

Figure 13: Incident Checklist (Felipe Kramm & Matias Valenzuela).

Once the vulnerabilities are known, an analysis can be carried out with the GRDR forensic sheet.

3.1.3. GRDR Forensic Sheet

The GRDR forensic sheet gathers useful data to identify the distress (cause and effect) observed on the failed element of the structure. Then, the impact that the distress generates on the structure is weighted according to a severity index. Finally, this sheet is used to generate the lessons learned from the failure and collect information for a database.

To generate the GRDR sheet it is necessary to have basic data regarding the failure, including:

- Element: Element or structural part that failed.
- Distress: Any damage that affected the element prior to the failure.
- Material index (α): Measure of the severity of the impact of the distress on the material of the structural element, scaled from 1 to 5, where 1 is less severe and 5 is more severe.
- Location index (β): Severity measure of the impact of the location of the distress on the structural element, scaled from 1 to 5, where 1 is less severe and 5 is more severe.

Note: While a 1 to 5 scale is suggested here, the measure and threshold for the indices should match the methodology or approach used by the country/state administration where the investigation is conducted.

Example:

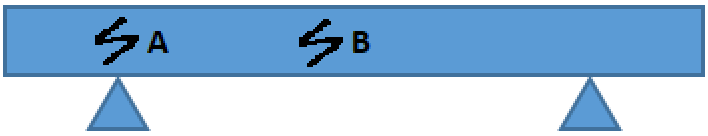


Figure 14: Bending moment failure of a beam (Felipe Kramm & Matias Valenzuela).

For the case of a beam that presents bending cracks, location B would be the most unfavorable as it is in the zone of maximum moment, so the location index would be assessed with severity 5. In the case of location A, when it is near one of the supports, it is evaluated with severity 1.

Given the previous analysis, the following sheet was developed:

GRDR Forensic Sheet Date: __/__/_____				
Bridge: Classification (by engineering stage): Classification (by type of failure): Cause: location of damage:				
Element	Distress	material index (α)	structure index (β)	ϒ element
______________________________ Signature and stamp of reception.			______________________________ Inspector signature	

Figure 15: GRDR Forensic Sheet (Felipe Kramm & Matias Valenzuela).

For cases where more than one element fails, a redundancy analysis (capacity of the structure to redistribute load in a process of progressive collapse) is carried out. Therefore, what must be analyzed in the forensic study is the progression of damage.

Since the GRDR forensic sheet needs element, location, and damage data, this sheet is used to document a base or minimum condition at the time of failure or structural collapse in bridges.

3.1.4. Determination of the Cause

Once the Incident Checklist and GRDR forensic sheet have been completed, the cause of the failure can be determined, where reverse engineering is carried out to explain the failure mode from the evidence already collected and to support or refute any failure hypotheses developed with the same information.

The cause of the failure is determined by discarding analysis techniques, in the following order.

FEM Model. A FEM model is built considering the conditions of the bridge. A global model can be used to analyze the full bridge and/or a detailed model can be used to study a specific element or fault zone. In case that the model does not provide the cause of the failure, the investigation then proceeds to Step 2.

As-Built Details. In this step, a comparison of the requirements of the design codes and structural details provided on the bridge is carried out. If this comparison does not result in identifying the cause of the failure, the investigation then proceeds to Step 3.

Testing. For this step, two types of tests must be carried out.

On-site tests: basic engineering procedures, surveys of installed elements (quality control) and topographic survey to detect distortions with respect to what was designed in the project.

Laboratory tests: Analysis of undisturbed or altered samples. The types of testing performed should include tests of the material used, either mechanical tests or structural tests, depending on the focus of the investigation. If after all the testing and analysis are conducted and it is still not possible to have a supported damage hypothesis, the investigation then proceeds to Step 4.

Operation and maintenance analysis: in this step a critical analysis of the inspection maintenance records is conducted to identify if inspection errors could have prevented the risk of failure from being detected early.

3.2. GERMANY

3.2.1. Process

In Germany, the results of a forensic investigation are also disseminated broadly to prevent similar failures and events from happening again. The investigations generally involve attempting to identify faults in the bridge structure (design, construction, and material), and assessments of the approval and administrative processes used to ensure quality.

Although it was not possible to derive a comprehensive process covering all eventualities from the case studies, various countries do have structured sub-processes. This section shows how an investigation is implemented in Germany, starting with the reporting channels. From this basis, a further course of action is then outlined.

3.2.2. Reporting and Determining the Further Course of Action

In Germany, local governmental bodies must inform the Ministry for Digital and Transport (Ministry) immediately of significant events in their area of responsibility. There are formal standing orders for this, including a structured reporting form. Significant events are defined as follows:

- Serious accidents during construction (e.g. collapsing structures, fatalities);
- Damage to structures, especially bridges and tunnels, that threatens their structural stability;
- Sudden extensive damage to roadways, such as landslides on embankments or cuttings;
- Fires, disasters, flooding and similar that cause prolonged restrictions to the roadway and right-of-way.

These reports on structures, and bridges in particular, must be sent to the Civil Engineering Division in the Ministry. That means that all information in Germany on a given event is collated by a single organization. In order for that process to be effective, a structured reporting form must be used.

Based on the report, a further course of action is determined in coordination with the local governmental body. The reporting form is structured as follows:

Question	Answer
1. Name of the person entering the report	
2. Date and time	
3. WHO is reporting? (authority, name of the person reporting, official position, telephone number)	
4. WHAT happened? (incident, course of events, ongoing threat, personal injuries or property damage)	
5. WHERE did it happen?	
6. WHEN did it happen? (date, time)	
7. Initial appraisal by the person reporting (traffic obstructions, emergency, disaster, special situation?)	
8. What measures have been taken?	
9. Which measures will be required and who will initiate them?	
10. Which bodies are already aware?	
11. Who is in charge at the site of the event?	
12. Who can be contacted with inquiries? (agency, telephone number)	
13. Other information	
14. Report forwarded	By To Date Time

Figure 16: Germany Federal Ministry Significant Event Reporting Form.

3.2.3. Investigations and Reports

If the incident did not involve injuries or fatalities, the further course of action including conducting an investigation and the experts to be commissioned for that investigation is defined with the involvement of the Federal Ministry.

The person with primary responsibility at the site, and the person with the lead responsibility among the experts are also identified. These individuals are generally identified through on-site meetings which are necessary to gain an understanding of the situation.

All investigations are based on the structure log containing information on the bridge as outlined in the « Guidelines on the uniform detection, evaluation, recording and analysis of bridge inspection results according to DIN 1076».

The investigation process is overseen by the responsible local governmental body. Meetings on the investigation procedures are held with the Ministry, so that initial findings can be derived for the general public, where applicable, or more in-depth investigations can be started. There is no structured, uniform process for this, as the damage analysis can vary in type, scope, and depth. However, decisions based on the « Guidelines for Object-related Damage Analysis (OSA) ». See *Figure 17* for the uniform nationwide structure for expert reports in Germany.

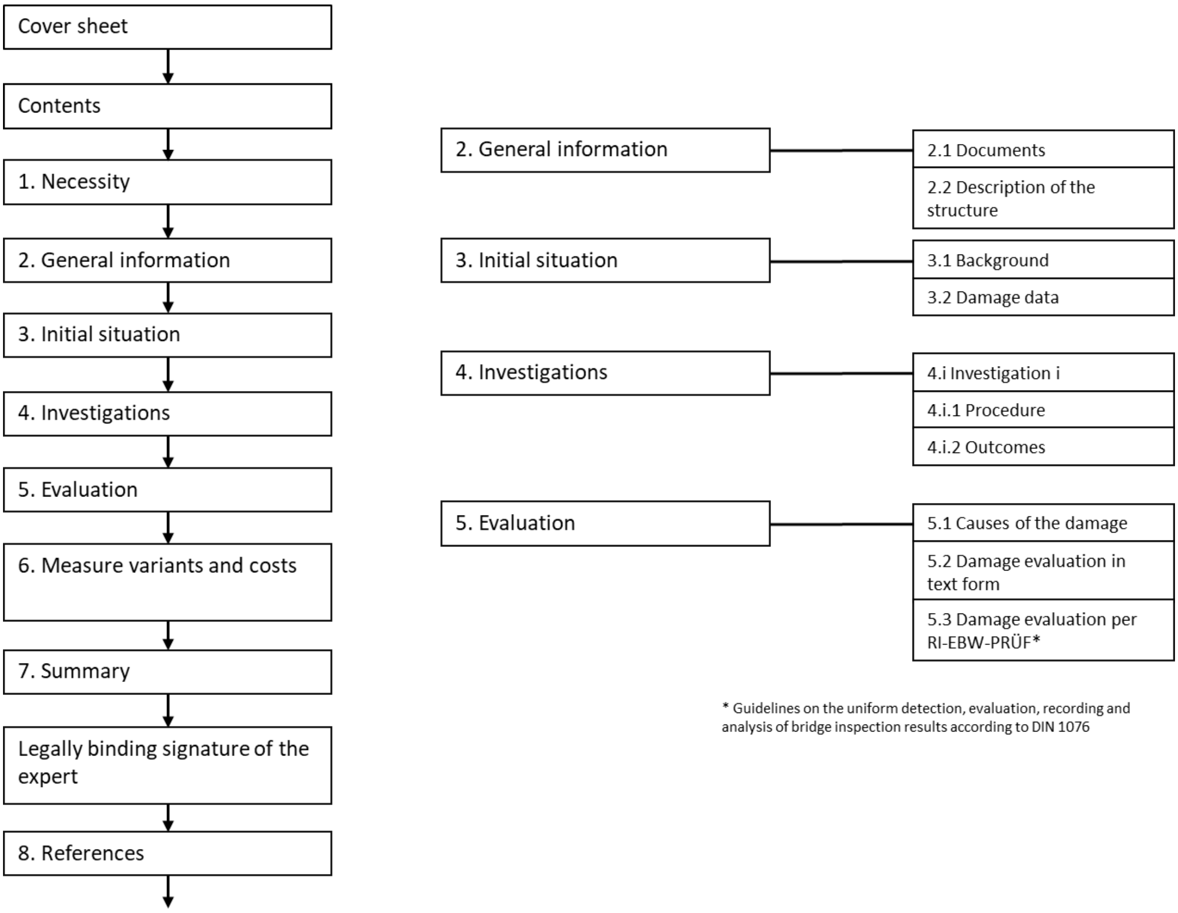


Figure 17: Structure of an Expert Report for Object-Related Damage Analysis used in Germany.

3.2.4. Outcomes and Follow-Up Actions

Findings made during or after an investigation are evaluated together and, when necessary, follow-up actions are formulated.

In that formulation, the following criteria are considered:

- Individual case
- Relevant for administration

- Relevant for multiple bridges

An individual case is defined as a bridge with a specific fault that is not transferable to other bridges. For example, if a failure resulted from using a defective material that was not previously detected during external or in-house controls, it is not likely the same defective material was used elsewhere, and the investigation process would likely end with this one bridge. However, the findings of the investigation are likely to inform potential repairs to the structure (see the expert report) if possible, depending on the extent of the damage to the bridge and their practicality.

Investigation findings are considered to have administrative relevance when they are primarily related to workflows. For example, there was a case in Germany in which a noise barrier anchored to a retaining wall fell onto the carriageway, causing a fatality. The forensic investigation determined that the barrier elements were held in place by a detail that used tie-back anchoring into a rail in the retaining wall. However, due to construction tolerances, the barrier was not able to be anchored at every anchor point along the rail, and in some cases post-installed brackets were used. As a result, these brackets were not fully inspected during construction. While a structural analysis was conducted for the change using the brackets, it was never submitted for final review and acceptance by the appropriate authority. In addition, those that supervised the construction of the barrier did not consistently follow up on the issue after construction was completed. Furthermore, the company lost interest in the project after receiving a final payment coupled with a restructuring within the administration resulted in the issue being forgotten. After the forensic investigation of the incident, which occurred roughly 10 years after the walls were installed, the procedures for the administration of structures during construction were re-evaluated and the process of acceptance and consistent documented follow-up was improved.

An investigation is relevant for all bridges when the findings identify a need for general improvements in the regulations which can then be passed on by the Ministry to all governmental bodies with bridge authorities within their area of responsibility. Should the findings also be significant for other transport modes, such as railways or federal waterways, the appropriate governmental bodies are also informed so that they can disseminate the information in a properly targeted manner. Depending on the urgency or criticality of the findings, changes in standardization may be relevant. As the Civil Engineering Division of the Ministry also chairs the DIN Bridge Coordination Committee, the findings can directly inform the standardization process, or guidance on standards can be coordinated and posted on the DIN website for dissemination if the relevant standards themselves cannot be updated directly.

4. RECOMMENDED PRACTICES

In this section the workgroup has used the case studies, the existing processes, and their own experiences to identify best practices and share advice. It is not the intention to suggest that these practices will be best in all situations and, of course, it remains the responsibility of the lead investigating organization or individual to make decisions on whether to implement these recommendations or not. However, based on the information collected for this study, the success of forensic engineering efforts considered seem to have some common elements that are discussed further in this section of the report.

It is also necessary in this section to distinguish between recommendations for forensic investigations of structural failures without fatalities and those that included fatalities. In some countries, when a bridge failure causes fatalities or serious injuries only the judiciary has the authority to investigate and determine the probable cause.

4.1. FORENSIC PROCESS WITHOUT FATALITIES OR SERIOUS INJURIES

When a bridge failure occurs without causing fatalities or serious injuries the framework of the investigation process is generally very straightforward. The process used generally includes the following elements:

1. Establish a team, a decision-making process, and a communication procedure.
2. Initial investigation efforts to be pursued simultaneously:
    a. Collect evidence/documentation (photos, videos, etc.),
    b. Analyze existing bridge documents (drawings, design calculations, inspection reports), and
    c. Identify, organize, and conduct any needed testing and sampling.
3. Analyze step 2 results
4. If necessary, conduct additional analysis, testing and sampling
5. If necessary, repeat steps 3 and 4
6. Complete the forensic analysis and write the report

4.1.1. Investigation Team

Capable leadership seems a hallmark of successful forensic engineering investigations. A leader with competency in the subject matter and a willingness and curiosity to investigate objectively is preferred. However, when the subject matter expertise is not available within the investigating organization, a leader with sound judgment and an engineering background can be successful. This leader will need the confidence to appropriately question the experts and have the ability to comprehend their answers. Also, this leader must be an independent and experienced bridge engineer who is capable of coordinating a group of experts and lead the forensic engineering process with an open mind. In general, the leader will have the final responsibility of the forensic report established with the support of all the experts that contributed to the investigation.

The group of experts should include those who are familiar with current and past methods and practices of bridge design, construction, and maintenance. These are not typically engineers that are only knowledgeable in design, construction, and/or inspection, but also have some structural experimentation background most likely associated with an advanced academic degree or through related professional experiences. Depending on the nature and extent of the failure, the investigation team may also need expertise in related disciplines such as geotechnical engineering, hydraulic engineering, or material science. These engineers and scientists are likely to need further support from licensed or certified technicians.

For failures that involve the total collapse of a bridge, the tendency is to assign the most experience bridge engineers in an organization to the investigation. Often in these cases there is also a competing need to get a new bridge built to restore mobility. One recommended best practice is to be sure that capable engineers are also left to address the design and construction of the replacement bridge which will likely occur under an accelerated timeline and with significant media, political or public oversight or pressure.

4.1.2. Data Collection and Documentation

Existing information

For large-scale or bridge-scale investigations, the data and documentation collected on the design, materials, fabrication, construction, inspection, maintenance and rehabilitation or repair of a structure can be significant and challenging to collect and manage. Although needed for the forensic structural engineering process, this information is not always available in a database and may need researching or a search of records in multiple locations in order to accumulate it.

It is important to highlight that, when available, the codes and standards corresponding to the design and construction period of the bridge should be considered in addition to modern standards. Also, it should be recognized that for a variety of reasons, including the date of original construction, that standards and similar documentation may not be available.

Forensic data

Forensic data is needed to understand the sequence and cause of the collapse. For that reason, it includes information and establish facts.

The forensic data needed generally falls into two categories, volatile evidence, and non-volatile evidence. Volatile evidence is information or data that can be easily changed, intentionally or unintentionally, or can change or the availability of which can change over time. Volatile evidence could include all the witness interviews and any video or images captured in the area of the collapse. It is important to collect this information soon after a failure while recollections are clear and sources available.

Non-volatile evidence generally includes conditions and information documented by other sources, such as newspaper articles or media interviews, recorded weather or traffic information. It could also include information collected to reconstitute any missing inventory data.

Careful thought on how the information will be referenced during and after the investigation can inform the structure of a filing system or directory used to store the data and documentation. The usefulness of these directories is generally enhanced by establishing a strict nomenclature for the types of information contained and how that information is related to the physical structure.

As digitally based tools that can adeptly combine data like images, drawings, videos, and calculations have advanced, an approach sometimes referred to as Forensic Information Modeling (FIM) has been employed to provide an intuitive reference for the data and documentation developed during a failure investigation. FIM models generally assign tags to the members of a bridge in a series of two-dimensional images (plan views, elevation views and detail views), or an interactive three-dimension model. Each tag is then linked to a database of information associated with the member or a specific location on a member of the physical structure. Accessing the tag displays all of the types of information available for the location of interest which can be used to inform an understanding of the behavior of the member as it failed or as it reacted to a failure occurring elsewhere in the structure.

4.1.3. Trigger (Collapse Initiator)

When considering the possible causes of failure, it is important to separate causes that are primary to the failure from those that contributed to the failure, or which created the possibility of the failure. Sheer (2010) defines primary causes as those that enable a failure, secondary causes as those that trigger or initiate the failure, and tertiary or derivative causes as those that resulted from the management of the bridge.

As an example, consider a significantly deteriorated bridge that has collapsed under a heavy but legal load. If primary or enabling cause of the collapse was the deterioration, the secondary or triggering cause of the collapse would be the legal load. Finally, the tertiary cause of the collapse could be either a failed inspection program that permitted the bridge to stay open despite its poor condition or a failed maintenance program that was intended to repair the deterioration before it could progress to failure.

When starting the investigation of a collapse, it is usual to first try to identify the trigger that caused the initial step of the collapse. In some cases, it may not be possible to immediately identify a single trigger until more is known about the nature of the collapse. However, once identified, a trigger is considered a fact or verified circumstance of the failure. Although not always, triggers are usually external causes and examples include unintentional overload, scour or settlement of a pier, impact, fire, earthquake, and similar.

For each potential trigger it is necessary to establish a hypothesis to explain the presence of the trigger and how it initiated the collapse. If more than one potential trigger is investigated, this process will produce a tree of understanding. Each trigger and hypothesis on that tree should then be investigated until it can be eliminated from further consideration. It is likely that this rigorous evaluation process will result in identifying the trigger and supporting hypothesis that is the most probable to have caused the failure. However, if more than one trigger is considered to have similar probability, a consensus of the informed judgment of the investigators may be needed to identify the most probable cause.

4.1.4. Hypotheses

Following the collection and consideration of the data and documentation, it is necessary to establish reasonable hypotheses related to the primary, secondary, and tertiary causes for the collapse. Initially, it is likely that more than one hypothesis will need to be consider. As such, it is important to keep an open mind when developing and assessing hypotheses.

Developing hypotheses using a brainstorming (expert elicitation or informed speculation) process, a process to suggest solutions to a problem or generate ideas to address an issue, that includes all members of the investigation team often results in the generation of a number of reasonable hypotheses to be investigated. It is usually possible to categorize these hypotheses into the following groups:

- Design issue hypotheses
- Construction issue hypotheses
- Service Life issue hypotheses
- Deterioration process
- Extreme event
- Man-made action

It is possible that the failure was the result of a combination of different hypotheses. For example, the investigation of the 2007 collapse of the I-35W Bridge in Minneapolis, Minnesota (USA), considered the design and current condition of the bridge, but also the construction operations being conducted on the bridge at the time of collapse. The investigation determined that although a design error existed in the bridge, it would not have collapsed without the large construction load placed on the bridge deck very near the resulting vulnerability. In this case, the probable or primary cause of failure is the design error; the secondary cause of failure or trigger is the construction load.

4.1.5. Testing and Experimentation

Documentation and evidence collection in addition to field observations provide the baseline facts in a forensic engineering investigation when considering the hypotheses proposed. If additional information is needed to evaluate or assess a hypothesis, it is usually possible to define a program of testing, experimentation, or specific analyses to develop the additional facts or information needed to confirm or refute a theory.

It is sometimes necessary to quickly remove the debris of a bridge collapse in order to restore traffic to a roadway below the bridge or install a temporary structure in order to maintain emergency services or access considered vital for the safety of the public or the movement of freight or services. This urgency sometimes results in an inadequate time for investigators to fully document or understand the wreckage of the bridge before it is removed. In those cases, a program of testing and experimentation can be essential to the proper consideration of all reasonable hypotheses.

When needed, testing is typically used to produce or confirm the following information:

- Current bridge geometry (if absence of a total collapse)
- Conformity of material quality and quantity to regulations and particular requirements for the structure investigated
- Pathology detection e.g., mechanical and chemical properties of the steel, concrete, timber, etc. used in construction
- Basic engineering investigations of inputs for further analyses and experiments, e.g., geotechnical properties, hydraulic characteristics, etc.

A thorough field observation is typically conducted to establish the bridge geometry as well as the location, type, and extent of distress. These facts will be used to understand the behavior of the structure, find hidden and unidentified locations of similar distress, and compare with any numerical results developed. Typical field observation actions include:

- Visual inspections
- 3D measurements, laser scanning, and imaging
- Testing and Non-Destructive Evaluation (NDE)

It is worth noting that NDE do not always work as expected. A calibration process is sometimes necessary at each particular use-case to determine if the technology applied is appropriate, understand the variation in results that can be associated with a change in operators or technicians, and if the accuracy of the results will be suitable for use in the forensic engineering investigation. For example, when detecting the corrosion in reinforcement bars inside concrete, the requirement levels of need can range from accurately evaluating the amount of cross-section loss to simply detecting the existence of a complete breakage or not. It is also worth mentioning that investigator and technician safety has to be secured during a field investigation. The integrity of all structural elements should be checked to keep further secondary distress from occurring.

Laboratory and on-site loading experiments are sometimes conducted to verify the assumptions of a failure mechanism, for example, load tests of concrete structural member specimens having specific structural details. In addition, when numerical simulations have difficulty in reproducing the characteristics of a failure, laboratory experiments can be very useful for identifying behaviors or constraints that should be considered during an analysis. For example, hydraulic experiments can be used to study the evolution of scour around a foundation and wind tunnel experiments can be used to identify the properties or features contributing to cable vibration.

Figure 18: On-site sustained load testing of post-installed adhesive anchors.

Experiments can also be helpful in producing:

- Damage maps
- Inputs to apply in a sensitive analysis of the structural model of the bridge (global or local)
- An understanding of the collapse sequence

In general, the difference between testing and experimentation is that most testing uses standardized methods that are reliable and repeatable. Experiments leverage accepted scientific principles, require documentation of the associated metadata and assumptions, and qualification of the results so that findings and conclusions are considered appropriately.

4.1.6. Forensic Structural Analysis

Finite element analyses are also a powerful tool to understand the bridge behavior and the failure process. They can be especially useful in understanding the relationship between overall bridge behavior and local stress effects. Finite element analyses can also be used to evaluate the remaining structural safety for the on-site investigation, possible traffic resumption, and remedial works.

Different types and complexities of finite element models, ranging from frame-type to shell-type elements, are selected based on the need of the investigation. However, when examining the failure mechanism and remaining strength for a specific structural element or connection, detailed and sophisticated three-dimensional finite element analyses are often conducted.

At times, numerical simulations should incorporate not only dead and live loads but also construction loads, time-dependent sustained loads such as those from creep or shrinkage, and daily thermal variation effects into the evaluation of the local stress distributions. The evolution of the damage observed is sometimes caused by a single transient source of stressors, but it can also be caused by a combination and accumulation of different stressors over time. As such, some numerical modeling investigations will need to include the effects of the construction and maintenance histories of the bridge, and any previous repair works because the accumulation of the stress to the present state may be attributed in some part to the factors that caused damage to the structure.

Typically, when considering all the information and results of the investigation including the results of any testing, experimentation, and structural analyses, it is possible to determine the probable cause of the failure or collapse. However, if uncertainties remain after the scrutiny of all of this data and information, the forensic process must continue with potentially a new hypothesis which may generate additional needs for data collection, testing, experimentation, and structural analyses.

Although not generally the case when investigations are conducted by experienced bridge engineers and scientists, forensic engineering of structural failures can be an iterative process. However, when the uncertainties are clear or negligible, a final report documenting the failure and the findings and recommendations of the investigation can be produced and easily defended.

4.1.7. Report

A forensic report can include not only information relevant and appropriate to the failure and the investigation, but other information required by the investigating authority, the bridge owner/operator, or governmental institution with oversight responsibilities for highway bridge safety. However, a typical table of contents of a forensic report includes:

- Scope of the investigation
- Description of the collapse
- Summary of the data collection
- Tree of understanding
- Triggers
- Hypotheses
- Findings per each trigger and hypotheses (Summary)
- Testing report
- Experimentation
- Structural analysis
- Probable cause and hypotheses that explain the collapse
- Cite evidence of the investigation that supports probable cause
- Recommendations
- Regarding the rehabilitation of this bridge (if it is possible)
- Prevention of this type of bridge
- General recommendation - learned lessons

ANNEX

- Data collection
- Testing, experimentation, and structural analysis reports

Depending on the needs or preference of the investigating authority, sometime a separate document is produced that leverages the findings of the forensic report to identify and communicate the determination of probable cause and any associated recommendations developed. Finally, whether one document or two, abstracts are generally needed that clearly communicate determination of probable cause and recommendations to the structural engineer community and to a non-technical general public.

4.2. FORENSIC PROCESS WITH FATALITIES

In some countries when a bridge failure or collapse results in fatalities or serious injuries, only judicial system or law enforcement have the authority to conduct an investigation. In other countries (i.e., USA) a legal investigation may be conducted in parallel to a technical investigation. In either case the forensic process may be similar to the investigation of a failure or collapse without fatalities, except for certain aspects, primarily data collection and documentation.

If the failure involved injuries or fatalities, it is likely that law enforcement or a judicial organization will be part of or monitoring the forensic investigation. In these cases, coordinating early in the investigation with those other institutions on how data or evidence collected onsite needs to be documented and controlled is imperative to success. Often law enforcement agencies require very detailed documentation that includes the names of those involved in collecting each piece of data/evidence and those that witnessed the collection. In addition, the transportation, storage, and access to that evidence is sometimes strictly regulated. Maintaining this chain of custody is required by most legal systems for evidence to be used in a trial or court proceeding.

5. IMPLEMENTATION OF RESULTS

A forensic investigation generally results in the determination of the probable cause of a failure, as well as a series of recommendations aimed at improving the state of the practice or addressing a specific flaw. Once a probable cause is determined, it is just as important that the cause and any underlying contributors are communicated adequately to the profession in order to prevent a similar failure from occurring. As a probable cause of failure is generally associated with a breakdown within the design, construction or management processes of the bridge, a sensitivity often exists when reporting on the cause as the process breakdown is always associated with action or inaction of an institution or company with responsibilities or authorities for the safe operation of the bridge.

This reality can sometimes place the communication of the results of a failure investigation in competition with an alternate interpretation of the information developed that best serves the interest of the potentially responsible party. This argument can be understood as the difference between probable cause and possible cause.

Probable cause is an engineering determination that is based on the most straightforward interpretation of truths informed by the facts developed during the investigation. The higher the confidence in the truths/facts, the higher the probability that the cause identified was responsible for the failure. A probable cause can be determined by a direct path of investigation that tests a specific hypothesis, or indirectly by disproving or refuting a number of hypotheses, possible causes, leaving only one. As these investigations generally involve very technical issues and an advanced understanding of material and structural behavior and interaction, appropriately communicating a probable cause requires an informed audience that is unbiased by its relationship to the failure.

The championing of a possible cause can be used by a potentially responsible party to create doubt within the less informed as to the confidence in the probable cause. While it may be appropriate to maintain a possible cause when constructing a defense during a judicial proceeding, it is incumbent on the affected community of practice to reject hypotheses refuted during the investigation in order for any lessons learned to be effectively communicated and, if necessary, support a change in practice.

In the United States, the investigation of a bridge failure by the National Transportation Safety Board (NTSB) not only results in a determination of probable cause, but also in formal recommendations made to any institutions, agencies, organizations, companies, or individuals associated with the probable cause of failure. The implementation of those recommendations is formally tracked by the NTSB and reported to the legislative branch of the Federal government. Occasionally, the recommendations or a lack of progress on their implementation can motivate the legislature to enact a statutory authority, a law, requiring action. For example, after the 2007 partial collapse of the ceiling in the I-90 portal tunnel in Boston, Massachusetts, the USA Congress reacted to a recommendation by the NTSB and passed a law requiring the Federal Highway Administration to establish inspection standards that applied to all highway tunnels in the country.

5.1. INVENTORY MANAGEMENT

Once an investigation is completed and the results communicated, it is always incumbent on other bridge owners to identify if the probable cause of failure has the potential to affect other bridges within their inventories. If other structures that can be similarly impacted are identified, it is often necessary to develop a strategy to ensure bridge safety that includes the following actions:

- Identify the type of structures or elements that will or might be affected by the results of an investigation.
- Develop a methodology that prioritizes the bridges identified for any required inspection, monitoring or remedial actions.

- Construct a timeline to implement the results that includes an appropriate level of urgency for the bridges identified

Once any potential impact to safety is mitigated from a bridge inventory, the need to make broader changes in the design or construction of a bridge should be considered and, if necessary, acted upon.

5.2. DESIGN AND CONSTRUCTION

Regardless of what authority conducts a failure investigation, any recommendation generated that requires a change in the specifications that normalize practice, is most effectively implemented through the organizations that issue and maintain the governing specifications for design and construction. Sometimes a change in specification is not needed, but emphasis is needed within the commentary that complements the specification. In fact, commentary can be crucial to maintaining the understanding behind requirements in the specification and effective implementation of those requirements.

When a change in specification is not needed, the implementation of a recommendation can be less straightforward and is generally left to the discretion of the investigating organization or highway bridge owners/operators. However, it is typical to present the findings through the issue of articles or papers in publications of professional practice or scholarly articles, presentations at conferences or seminars, or discussion during the meeting of committees that have a purview including the topic being addressed. In all cases, it is important to present a consistent context and message so that the understanding of engineers and related professionals are appropriately aligned with the results of the investigation.

6. CONCLUSIONS

Although not common, despite the best efforts of bridge engineers, inspectors and managers around the world, bridge failures do occur. The engineers and scientists investigating these failures generally have two primary objectives; (1) determine the probable cause of the failure with a high level of confidence, and (2) clearly communicate that cause so that it is well understood by both the well-informed and non-technical audiences. As such, the objectives of this report were to provide guidance to practicing bridge engineers on the elements that make up and the factors that influence a competent forensic investigation, and on how lessons learned from a forensic investigation are identified and communicated.

The information collected through the case studies submitted was substantial (18 cases studies). One overarching conclusion from that information is that bridge failure is rare, and the circumstances associated with bridge failures are too diverse to make possible the establishment of a detailed formal process. Some specific conclusions resulting from a thorough review of the information collected are:

Forensic investigations are conducted to determine the probable cause of a failure, and to disseminate the knowledge developed so that a similar failure does not occur elsewhere.

In most countries, the primary responsibility to investigate a bridge failure resided with the bridge owner or operator. However, if the failure was catastrophic or resulted in fatalities or serious injuries, in some countries an independent governmental authority or the judiciary could be charged with conducting or managing the investigation.

Only one country reported having a formalized process for a forensic investigation which consisted of a schematic high-level procedure on the initial investigative steps.

No countries had guidelines on how to construct a forensic investigation team. However, all that responded indicated that these teams were generally made up of engineers with the expertise needed from either the bridge owner, a hired consultancy, an appointed expert, or a combination.

All failure investigations started with the collection of existing records and information on the design, construction, inspection, maintenance and rehabilitation or repairs, if any, of the bridge.

7. RECOMMENDATIONS

7.1. RECOMMENDATIONS FOR DECISION MAKERS

When a bridge collapse occurs, engineers investigate the cause of collapse to identify how design, materials, workmanship, and/or overloading affected structural performance. Engineers learn from the results of forensic engineering investigations and make improvements to the requirements of design, construction, and maintenance in order to prevent these challenges or tragedies from reoccurring. To facilitate these investigations, the following recommendations are made:

7.1.1. Maintain a Bridge File

Forensic engineering for structural failures can be complex and require specific expertise. However, as demonstrated in the cases studies, each investigation starts with the collection and review of pre-failure data and information that contain details on the design, construction, and performance of the bridge. As such, it is recommended that bridge owners keep a detailed file of data and information on each bridge in their inventory. Although a digital file is preferred, if that is financially challenging for LMICs, a well-developed and indexed physical file of documents will also meet the need.

7.1.2. Establish and maintain a Centralized Database

It is also recommended that all bridge files or a copy of each bridge file be maintained in a centralized repository or database. The first challenge is to establish this database. The second one is to guarantee a centralized repository of data. Often bridge inspection, maintenance, rehabilitation, or preservation activities can be the responsibility of separate departments or offices within a bridge owning organization. The sometimes associated stovepipes created by those independently acting groups can be a barrier to information sharing or collection. As such, it is also recommended that the central repository be maintained by a level within the organization with authority over all of the departments or offices (including non-State nor Federal governmental departments, for example municipalities, concessionaries, public private partnership, etc.) that have responsibilities for a bridge.

7.1.3. Archive and communicate Forensic Engineering Investigation Results

Lastly, it is recommended that the upon the completion of a forensic investigation and the dissemination of results, all of the data, metadata and documents generated during the investigation be archived in a way that they will be accessible by engineers and bridge managers for reference in the future. While a successful investigation will determine the probable cause of failure and share that cause with practicing engineers and managers so a similar failure can be avoided in the future or in another country, once the next generation of engineers and managers is in place, they sometimes have to redevelop this institutional knowledge. This next generation will benefit from an archive of data and information on prior failures to support that development and inform engineers of the reasons behind specific provisions within a design or construction code when it comes time for those codes to be updated, improved, or rewritten.

7.2. RECOMMENDATIONS FOR PIARC

7.2.1. Continue Collecting Case Studies

While the case studies collected in support of this report provide substantial information on the bridge failures they document, they represent a relatively small data sample from primarily HICs. As such, it is recommended that PIARC continue to collect case studies that document failure investigations. Over time, this additional information may support a revision of this report or an addendum that specifically addresses the experiences and needs of LMIC.

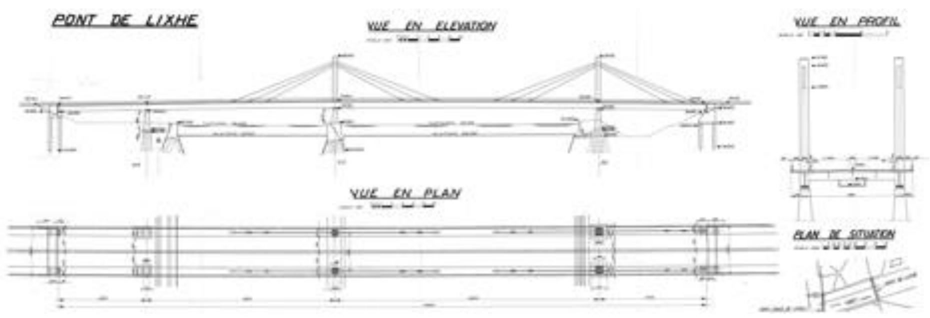
Also, it would be very valuable for PIARC to organize a way to give the opportunity to bridge engineers to submit new case studies and to analyze all the case studies already submitted. The idea is to create worldwide database on bridge failure that can be referenced by practicing engineers, universities, and other interested parties for the purpose of learning and application.

7.2.2. Continue Sharing Case Studies

Engineers, in particular, enjoy careers of continuous learning. As such, it is also recommended that PIARC continue to disseminate information on bridge failures so that those unfamiliar with the details of a collapse can still take advantage of the lessons learned or benefit from the successes of the subsequent investigation. As failures and, in particular, collapses are rare, collecting and sharing this information from across the membership of PIARC will accelerate the learning of engineers at all levels within a bridge owning organization. The previously mentioned worldwide database will be instrumental in achieving this goal.

8. APPENDICES – CASE STUDIES

8.1. CASE STUDY 1: BELGIUM ANCHOR BAR FAILURE

Case : *Lixhe Bridge*	
1) Brief description of the bridge (type, material, year of construction, …	Provide a short description of the bridge including bridge type, material (steel, reinforced concrete, prestressed concrete, timber, masonry, …), year of construction, span lengths, …
Answer	The Lixhe Bridge is a 309 m long cable-stayed bridge with composite beams, 4 spans (42 m, 90 m, 126 m, 51 m) and 2x2 pylons. This structure, constructed in 1985, allows a 2x2 lane roadway to cross the Albert Canal. The upper roadway does not carry much traffic. On the other hand, the lower waterway is part of the European network and allows the passage of class VIb pushed convoys (up to 12,000 tonnes and 198 m long).
Picture of the bridge	
2) Description of the failure.	Provide a detailed description of the failure. Include sufficient relevant context to support the failure being unanticipated or producing unexpected performance.
Answer	One of the 2 abutments is characterised by the presence of negative reactions varying from 1400 kN (under dead load) to 2300 kN (under full load) for each of the 2 supports of this abutment. These connecting rod bearings are connected to the foundation by 6 post-tensioned Dywidag bars (36 mm). In the early morning of February 8, 2018 (before 6:15 am), the anchors of one of the two abutment supports broke, causing the deck to partially lift. The height of the uplift in a stabilised situation was approximately 65 cm. It is likely that in the dynamic phase of the uplift, a height of approximately 80 cm was reached, given the traces left on the concrete.

Picture of the failure	 *Picture of the support before failure*  *Picture of the support after failure* 

Case : *Lixhe Bridge*	
	
3) Investigating organization.	If one or more specific agency or institution has the responsibility to investigate bridge failures in your country, please name them and describe their authorities.
Answer	At the time of the incident, the bridge was managed by two departments of the administration: the road manager for the superstructure including the supports and the waterway manager for the infrastructure. These two departments were supported by a bridge investigation department. All those departments are parts of the same public road administration. The responsibility to investigate bridge failure is not officially assigned. But usually the bridge investigation department do it.
4) Legal constraints.	If there are legal constraints on the transparency or process of a bridge failure investigation in your country, please describe those.
Answer	In Belgium, there are no legal specific constraints about bridge failure investigation. Only if someone is injured or killed, then the judiciary initiates an official investigation. It was not the case here. The investigation was only done internally by the road administration.
5) Investigative process.	Please describe how the investigation was conducted. If a standardized and documented process or procedure was used to guide or inform the investigation, please also describe it here and include a copy with your response.
Answer	There is no process or procedure that guide the investigation. The investigation was conducted by a more or less informal committee conducted by the bridge investigation department.

Case : *Lixhe Bridge*	
6) Organizational structure.	Describe the organizational structure used by the investigators.
Answer	No structure
7) Investigator qualifications.	Describe the qualifications of those involved in the investigation. Education, licensing, training, experience, etc.
Answer	Engineers with many years of experience in bridges (design, investigation, management).
8) Investigation documentation.	a. Describe how the failure was documented on-site?
Answer	There were 3 main parts: - Examination of the broken support (including removing the dywidag bar by hydrodemolition of the concrete below the bearing) - Measurement of the forces in the stay cables - General inspection of the bridge
	b. How was physical evidence collected, documented and controlled?
Answer	By measurement and inspection
9) Testing.	a. What type of physical testing was conducted to support the investigation?
Answer	Microscope observation of the broken dywidag bars Measurement of the forces in the stay cables by frequency method
	b. If standardized test methods were not used, why not?
Answer	No standard test methods exist. But the test methods used are well knowed.
	c. How was test data stored and documented?
Answer	In our bridge data base
10) Experimentation.	If experimental testing was conducted, please summarize the need, describe the experiments, and outline how the results were used.
Answer	No experimental testing
11) Bridge files and records.	a. What records (design, fabrication, construction, inspection, etc.) of bridge were collected to support the investigation, and how where they reviewed?
Answer	The original design calculation report, the drawings and the previous inspections reports were analysed by some engineers in parallel while others were on site for the first investigations.
12) Analyses.	What type of analysis or modeling tools (engineering calculation, structural analysis, finite element modeling, others) were used to support the investigation and describe their use?
Answer	None
13) Lessons learned.	a. With regard to the cause of failure, what were the findings of the investigation?

	Case : *Lixhe Bridge*
Answer	Corrosion of the dywidag bars 
	b. What lessons learned were derived from the findings?
Answer	If possible, avoid the use of dywidag bars because it is impossible to know if there is any corrosion.
	c. How were the lessons learned communicated to the bridge engineering, construction and inspection communities?
Answer	The information was given at conferences and at meetings of bridge managers. It is also included in bridge design guide of PIARC.
	d. Describe any changes to the state of practice resulting from the lessons learned.
Answer	The management of a structure by two managing departments is not an optimal solution. In this case, the collaboration was very good, but it should nevertheless be noted that the two services were not informed at the same time, which means that the road and canal were closed to traffic in different ways. This type of shared management is now abolished within the road administration. But it still remains between road administration and rail company.
	e. Identify any challenges the resulted from the process or procedure used to conduct the investigation, and any recommended changes to the approach or methodology used to address those challenges or otherwise result in improvements.
Answer	We still need to improve the access to our information channel. We have a traffic management centre open all the time. But the driver who observed the problem or even the police did not use this information channel to contact the road administration. They try to contact people they know. And this took some time.
14) Other impacts on the investigation.	a. If there was a need for a timely repair to address a long detour or simply the restoration of service, please describe how that need impacted the decisions made or process used for the investigation.
Answer	None
	b. Please describe how financial considerations (potential cost of the investigation, cost to the traveling public, cost of the repair, etc.) impacted the decisions made or process used for the investigation.
Answer	No impact because the cost of the investigation and the cost of the repair were low.

Case : *Lixhe Bridge*	
	c. Please describe any additional considerations or risks that impacted how the investigation was conducted and what those impacts were.
Answer	None

8.3. Case Study 2: Canada Bridge Collapse

Case : De la Concorde Overpass	
1) Brief description of the bridge (type, material, year of construction, …	Provide a short description of the bridge including bridge type, material (steel, reinforced concrete, prestressed concrete, timber, masonry, …), year of construction, span lengths, …
Answer	De la Concorde overpass was a bridge that was constructed in 1970 over a freeway North of Montreal. It spans one of the important access links between the northern suburbs and the Island of Montreal. The bridge was made up of two reinforced concrete abutments that held with two cantilever arms a central drop in span. Each cantilever had a length of 13 ft (4m). The drop in span was made up of prestressed concrete box girders tied together and had a 90 ft length (27.5 m). Expansion joints were located at each end of the central span, that was supported on bearing pads resting on concrete corbels
Picture of the bridge	
2) Description of the failure.	Provide a detailed description of the failure. Include sufficient relevant context to support the failure being unanticipated or producing unexpected performance.
Answer	On September 30^{th} 2006, the central span of the south lanes (half the bridge width) collapsed on the freeway underneath. Saldly, five people died as a result of the collapse. It was apparent from the debris that the collapse was the result of the failure of one of the cantilever arms of the abutments. 30 min prior to the collapse, concrete debris had been picked up by roadway maintenance personnel, that did not however idendify the urgency of the situation due to lack of knowledge of structures. The debris fell from the side of the structure, exposing a very wide crack. In the years prior to the collpase, diagonal cracking had appeared on the side face of the cantilever but that cracking was not deemed critical since it was fairly thin and it was assumed that it was limited to the exterior zone of the structure (sidewalk area) and rebar were effective in supporting the structure.

Case : De la Concorde Overpass	
Picture of the failure	 General view of the collapsed bridge  Rescue operations on the collapsed center span

Case : De la Concorde Overpass	
	 Collapsed cantilever section of the East abutment. The deck joint profile is still in place and the center span bearing pads are visible at the bottom right of the picture  Collapsed cantilever. The corbel is at the bottom, laying against the abutment wall, hanging from the bottom mat of rebar

Case : De la Concorde Overpass	
3) Investigating organization.	If one or more specific agency or institution has the responsibility to investigate bridge failures in your country, please name them and describe their authorities.
Answer	There is no specific organism that has the responsibility to investigate failures. In Canada, road bridges are under the responsibility of the provinces so failures will be handled by each province according to their own standards. In Quebec: The investigation will be managed depending on the severity of the consequence. If there is no death or injury, a failure will usually be handled by our centralized bridge office at the Ministry. This office employs bridge engineers in different domains of expertise (design, rating, hydraulics, quality assurance, etc.) This is the type of failure that can result for instance in a road closure. The ministry has the authority on all bridges of the province (around 10 000) except those in major cities (around 500) and the ones over the St-Laurence seaway (5). If the failure results in the death of someone or severe injury, the investigation will initially be the responsibility of the police. If there are no criminal aspects such as negligence involved, the investigation is then usually handled by the coroner's office when fatalities are involved. They will usually hire independent assistants such as university professors to conduct the technical part of the investigation if needed and will publish a summary of their findings along with recommendations in a report to the Government. In some high-profile cases, such as the one presented here, the Government can decide to create a public enquiry commission, where a three-member board of directors is formed and is responsible to name experts to conduct the technical investigations, can call witnesses to testify, etc. A report is then produced, containing causes and recommendations. The commission has a near judicial powers as it can assign witnesses to testify, identify individuals or organisms as responsible for the collapse, etc. They can not however press criminal charges.
4) Legal constraints.	If there are legal constraints on the transparency or process of a bridge failure investigation in your country, please describe those.
Answer	If an individual is identified as responsible for the collapse by a public commission, the prosecutors can elect to lay charges. The case is then transferred to the courts. The commission testimonies cannot be used during the prosecutions in these cases, but the technical expertise can.
5) Investigative process.	Please describe how the investigation was conducted. If a standardized and documented process or procedure was used to guide or inform the investigation, please also describe it here and include a copy with your response.

Case : De la Concorde Overpass	
Answer	When the failure occurred, the scene was under the responsibility of the first responders (fire department) up until all injured or all bodies were recovered. Minimal investigating is done during that initial phase. Once the scene is cleared by the first responders, the provincial police (since it was on a highway) took over to investigate regarding criminal intent (usually negligence). In this case, they hired a university professor, specialised in concrete materials, to coordinate the technical investigations. Once the scene falls into the police's responsibility, the investigation is very organised and treated as a crime scene. In this case, since the failure had caused 5 deaths, the Government decided to create a public enquiry commission in the days following the collapse. In this case, the technical investigation was headed by the same professor that had started the investigation and a second one was named for the structural part. The provincial police assisted the public enquiry until it was fully functional but since there was no criminal aspects, it eventually stopped managing the enquiry.
6) Organizational structure.	Describe the organizational structure used by the investigators.
Answer	Technical investigating was directed by two experts, named by the commission. They had the responsibility to conduct field testing, laboratory experiments, etc. and assist the commission's directors in assigning witnesses and conduct the archival research. They also assist the commission's legal counsels to prepare the different testimonies. They can adjoin themselves with other specialists. In this case, other college professors were asked to give their opinion on specific matters regarding the collapse. Since the commission has a near judicial power, the participants can produce their own expertise and have their own lawyers. In this case, the Ministry had hired his own expert to conduct a parallel investigation.
7) Investigator qualifications.	Describe the qualifications of those involved in the investigation. Education, licensing, training, experience, etc.
Answer	The two experts were distinguished professors in their respective field of expertise. One is an expert in concrete deterioration and the other is an expert in reinforced concrete structures. They adjoin themselves skilled engineers in technical characterisation of materials, structural analysis, etc. The ministry's expert was also a distinguished professor specialised in bridge analysis.
8) Investigation documentation.	a. Describe how the failure was documented on-site?

Case : De la Concorde Overpass	
Answer	On site prior to removal, the collapsed part of the structure (abutment) was documented by photos, laser scanning and measurements. The central span girders were rapidly removed because of rescue operations. Minimal documentation with photos was taken during that initial phase. Some measurements were made by the police investigators during that phase.
	b. How was physical evidence collected, documented and controlled?
Answer	All concrete parts of the bridge's central span and the failed abutment's cantilever were stored in a guarded area during the length of the enquiry. Core sampling in the collapsed cantilever was conducted before removing. Core samples were transferred to laboratories for testing. The ministry had the opportunity to have is own samples for parallel testing. Laser 3D mapping of the failed concrete abutment. The failed cantilever section was sawn into movable pieces (roughly 2m by 6m), all sections were identified and stored at the same guarded location
9) Testing.	a. What type of physical testing was conducted to support the investigation?
Answer	Core sampling of different parts of the failed sections for evaluation of the concrete on different aspects. After conflicting testimonies regarding the cause of the observed cracking on the side of the structure prior to the failure, the exterior portion of the failed concrete cantilever was sawed transversely to map the internal cracking pattern.
	b. If standardized test methods were not used, why not?
Answer	
	c. How was test data stored and documented?
Answer	All investigators reported to the two main experts who stored centrally the results of each investigation. All data produced by the Ministry's investigation was made available to the commission All results were eventually published in a report
10) Experimentation.	If experimental testing was conducted, please summarize the need, describe the experiments, and outline how the results were used.
Answer	Two sets of full-sized models of the concrete cantilever section were made and tested in laboratory conditions. The first set of models were done by the commission's experts while the others were done by the Ministry's expert. Since rebar placement was the main issue first identified for the structural failure, for each investigation, one model was cast as designed (shown in plans) and another was cast as built. The models were tested to failure

Case : De la Concorde Overpass	
11) Bridge files and records.	a. What records (design, fabrication, construction, inspection, etc.) of bridge were collected to support the investigation, and how where they reviewed?
Answer	All records of construction were investigated, as well as all the existing plans from the initial construction as well as all repairs done Since there was no central storage unit (each regional office had it's own dossier as well as centralized expertise offices) and the structure had been managed by two different regional offices during it's lifespan, information collection was very long and tedious The plans collected for the original construction were the ones used for public tender, as built plans were never found and were probably never made.
12) Analyses.	What type of analysis or modeling tools (engineering calculation, structural analysis, finite element modeling, others) were used to support the investigation and describe their use?
Answer	Again, two finite element models were done to prepare the full-size samples. The models were then calibrated with the full-size lab test results
13) Lessons learned.	a. With regard to the cause of failure, what were the findings of the investigation?
Answer	Poor concrete quality in a critical part of the bridge, heavily exposed to de-icing salts and very hard to inspect or repair. Poor quality control on site during construction, that resulted in rebar being misplaced. Since no records were made of the as built structure, the engineers inspecting and managing the bridge never had the knowledge of that fact. The concrete cantilever and the faulty rebar placement allowed the cracking to progress inside the full depth concrete slab that eventually failed in shear Poor management of the deterioration process regarding repair or rehabilitation work that was not done in a timely manner. Some repairs (deck joint replacement) may even have contributed in aggravating the cracking at the early stages.
	b. What lessons learned were derived from the findings?
Answer	Numerous lessons were derived from the findings of the investigations - Need for better materials, especially better quality concrete (this was already implemented at the time of failure) - Need for better quality control/assurance during construction - Need better documentation of the changes made during construction - Need to invest more money on repairing our aging infrastructures - Need to have a single centralized record for each structure so the archived information can be made available easily - Avoid the use of concrete corbels and in span deck joints for bridges - Avoid full depth concrete slabs without any shear reinforcement in bridge uses - More documented and responsibility-oriented documentation of the quality control process

Case : De la Concorde Overpass	
	c. How were the lessons learned communicated to the bridge engineering, construction and inspection communities?
Answer	With published report. The English version of the report is joined. Representations made by members of the Ministry at the Canadian bridge design code technical committees in order to adjust some design code requirements Several presentations made at local, national and international conventions.
	d. Describe any changes to the state of practice resulting from the lessons learned.
Answer	Systematic shear reinforcements in full depths slabs designed by the Ministry Systematic use of less permeable concretes (systematic use of silica fume, 1000 Coulombs or less permeability, freeze-thaw cycles testing, etc.) – Already implemented at the time of failure No concrete corbels used in new construction in bridges, replacement of all existing concrete corbels in bridges. Mandatory one-week training course for all quality control personnel present during construction Quality control engineer and designer are both required to stamp as-built drawings encompassing all changes made during construction Creation of a 24/7 hotline where road patrollers and road monitoring personnel can contact a bridge engineer regarding observations made on bridges Significant budget increase for the maintenance and replacement of the province's bridges
	e. Identify any challenges the resulted from the process or procedure used to conduct the investigation, and any recommended changes to the approach or methodology used to address those challenges or otherwise result in improvements.
Answer	
14) Other impacts on the investigation.	a. If there was a need for a timely repair to address a long detour or simply the restoration of service, please describe how that need impacted the decisions made or process used for the investigation.
Answer	The roadway underneath, where the bridge had collapsed, had to be cleared rapidly because it was a major transit route in and out of Montreal. The prefabricated box girders from the central drop in span had already been removed by cranes during the rescue operations. In order to clear the debris within a few days, the collapsed structure was documented by photos, laser scanning and measurements. The cantilever part of the collapsed abutment, which was of greater interest to the investigation, was cut into five or six pieces in order to move them in a yard a few miles away, along with the central span girders.

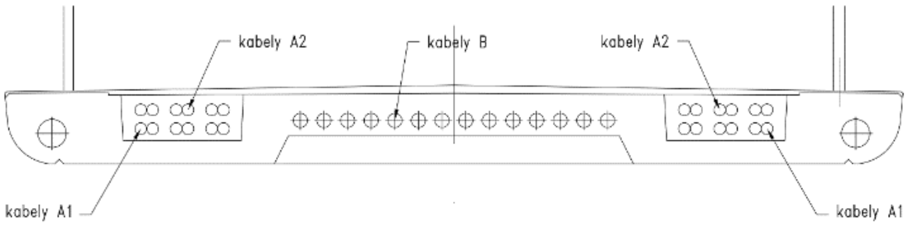
Case : De la Concorde Overpass	
	The rest of the structure, that was deemed of less interest by the experts, was demolished afterwards A similar bridge, that was situated a few hundred meters from the one that had collapsed, was supported by shoring and used for investigating. It was eventually replaced in the months following because it had the same kind of defects (although the cracking was almost non-existent)
	b. Please describe how financial considerations (potential cost of the investigation, cost to the traveling public, cost of the repair, etc.) impacted the decisions made or process used for the investigation.
Answer	Since it was a major collapse and a public enquiry, there was very little consideration for limiting the investigation's and the commission's budget
	c. Please describe any additional considerations or risks that impacted how the investigation was conducted and what those impacts were.
Answer	

8.4. Case Study 3: Czech Republic Bridge Collapse

Case : *Troja stress ribbon footbridge*	
1) Brief description of the bridge (type, material, year of construction, …	Provide a short description of the bridge including bridge type, material (steel, reinforced concrete, prestressed concrete, timber, masonry, …), year of construction, span lengths, …
Answer	The Troja footbridge across the Vltava river in Prague (CZ): Stress-ribbon structure made of prestressed concrete was formed by precast segments in spans and cast-in place saddles rigidly connected to intermediate piers. All segments were suspended on bearing tendons, which were anchored in the massive embedded abutment blocks and tensioned across the river. Continuous internal prestressing was added after completion of the superstructure to gain stiffness and desired compression in the deck. The bridge of 3 spans of 85,5 + 96 + 67,5m was built in 1984.
Picture of the bridge	 

<table>
<tr><th colspan="2">**Case :** *Troja stress ribbon footbridge*</th></tr>
<tr><td></td><td></td></tr>
<tr><td>2) Description of the failure.</td><td>Provide a detailed description of the failure. Include sufficient relevant context to support the failure being unanticipated or producing unexpected performance.</td></tr>
<tr><td>Answer</td><td>In December 2017 unforseen sudden collapse occurred. Actually no live load was present on the bridge during collapse (only 4 people on the bridge, fortunately no casualties).

Immediate cause of the collapse was apparently a sudden fracture of both bearing tendons (A) and prestressing tendons (B).



During years before collapse the bridge had been obligatorily inspected on regular basis, diagnostics were performed after major floods in 2002 and also in 2010, in 2013 the bridge condition was checked by dynamic testing. Also continuos monitoring was installed during last years focusing on behavior of joints between segments and sag measurement in main span. Some rehabilitation works were exectued in 1998 a 2012. Overall, the bridge was quite well monitored, the evaluation of the condition was only recently worsened from grade V. (bad) to grade VI. (very bad) on a scale I. to VII. – where grade VII. represents emergency condition. But no evidence of forthcoming collapse was apparent.</td></tr>
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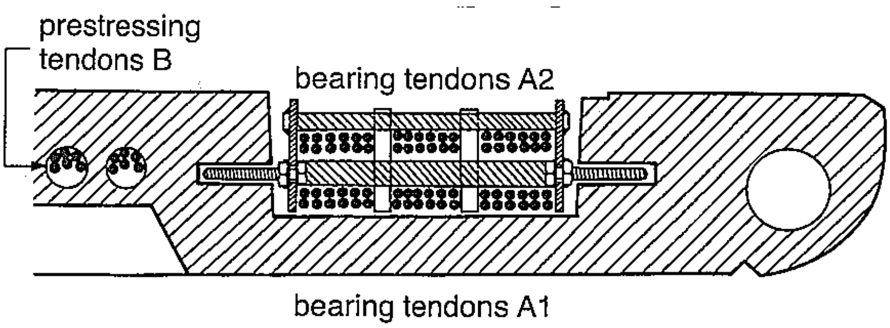
Case : *Troja stress ribbon footbridge*	
	From the first moment it was almost certain that the fracture of the tendons was caused by its deterioration (corrosion). The question was, what was the cause of such serious corrosion and why there were no signals in change of the bridge behaviour prior to collapse.
Picture of the failure	  

Case : *Troja stress ribbon footbridge*	
	 
3) Investigating organization.	If one or more specific agency or institution has the responsibility to investigate bridge failures in your country, please name them and describe their authorities.

Case : *Troja stress ribbon footbridge*	
Answer	There is no such specific body in the Czech Republic, having the responsibility or mandate to conduct bridge failures investigations. There are several professional organizations, generally independent of state or public administration, such as The Chamber of Chartered Engineers and Architects, The Czech Concrete Society and other, but with no legal authority in such cases. Troja footbridge was owned by Prague Municipality, the bridge was under administration of Prague Technical Administration and Maintenance Agency.
4) Legal constraints.	If there are legal constraints on the transparency or process of a bridge failure investigation in your country, please describe those.
Answer	In the case of such spectacular bridge collapse, all the more when there are casualties or injuries, the Police is in charge of such investigation. The information from ongoing investigation is strictly non-public. So no information is officially available during such investigation to professional public and even afterwards it is difficult to get complete information.
5) Investigative process.	Please describe how the investigation was conducted. If a standardized and documented process or procedure was used to guide or inform the investigation, please also describe it here and include a copy with your response.
Answer	The investigation is in the hands of the Police. Professionals having some relation to the particular collapsed structure (its designer, administrator, contractor, inspection and diagnostics specialist, etc.) are being interrogated by police investigators as a source of information with potential to become accused or witness in possible criminal proceedings. Usually some independent court-certified expert is appointed by police to produce an Expert evidence (report), incl. calculations if necessary, where he (she) is expected to present his (her) view on the incident, what was the cause. Unfortunately only rarely an appointed court-certified expert has a real and deep proficiency and experience in bridge engineering.
6) Organizational structure.	Describe the organizational structure used by the investigators.
Answer	No specific organizational structure. Standard police investigation led by appointed criminalist by means of interrogations of relevant professionals and public, collecting data and evidences incl. Expert evidences (reports), incl. laboratory testing on samples from collapsed structure, etc. According to conclusions of the investigation the case goes to trial or the case is closed.
7) Investigator qualifications.	Describe the qualifications of those involved in the investigation. Education, licensing, training, experience, etc.
Answer	There is no specification for such a qualification, with exception when investigators ask for an Expert evidence report. The court-certified expert must have a degree in Civil Engineering and some length of professional experience in order to obtain court approval (certificate). Unfortunately there is no such specialization as “court-certified expert in bridge engineering” and so far also no rule prescribing that an appointed expert must be also Chartered engineer in bridge engineering.
8) Investigation documentation.	a. Describe how the failure was documented on-site?

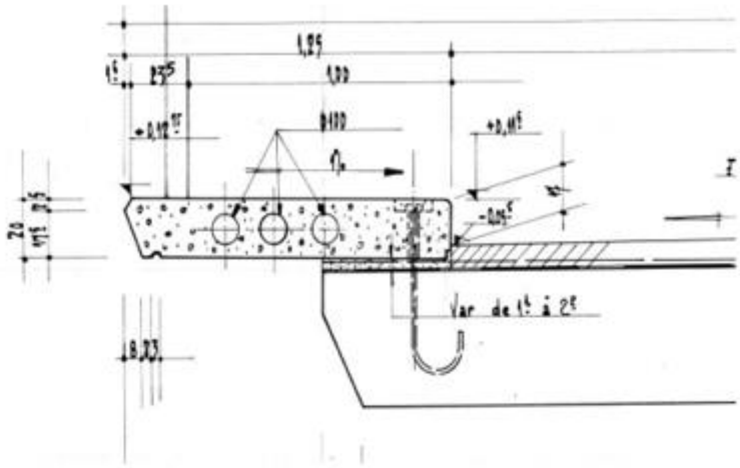
Case : *Troja stress ribbon footbridge*	
Answer	The site of collapse was immediately closed to the public. After rescue operations by Rescue and Medical services ended, investigators, administrator staff and later on an appointed expert were allowed to explore the site and to document collapsed structure by photographs. Even some of other professionals were initially admitted to observe the site.
	b. How was physical evidence collected, documented and controlled?
Answer	Some of segments of collapsed structure, incl. samples of prestressing strands were transported to closed area nearby for further inspection and testing. Access to this samples was limited to investigators and appointed expert. The rest of collapsed structure was demolished, the site was cleared.
9) Testing.	a. What type of physical testing was conducted to support the investigation?
Answer	Non-public information. Definitely the concrete testing was performed (strength, chloride content and penetration), prestressing strand testing (strength, ductility, loss of sectional area due to corrosion).
	b. If standardized test methods were not used, why not?
Answer	Non-public information Probably no need for non-standard test method. *Some doubts were raised if even surface corrosion of presstressing steel (with neglectable effect on loss of sectional area) can influence material grid and thus its behaviour (shortening ductile branch of stress-strain diagram? => the lack of safety margin when reaching yield stress?)*
	c. How was test data stored and documented?
Answer	Non-public information Probably documented in form of test protocols in Expert evidence report.
10) Experimentation.	If experimental testing was conducted, please summarize the need, describe the experiments, and outline how the results were used.
Answer	Non-public information Concrete: - Strength in compression /on drilled samples/ evaluation if concrete grade complied with the design requirements / used in expert's static assessment - Chloride content /on drilled samples/ evaluation if use of de-icing agent (salt) lead to material deterioration and how deep / used in expert's static assessment ; *let's mention, that use of de-icing salt had been prohibited in the design documentation of Troja footbridge (this rule was not followed in practice)* Prestressing strands: - Strength in tension, stress-strain diagram /on cut samples/ evaluation if prestressing steel complied with the design requirements and if the stress-strain diagram differed from standard / used in expert's static assessment - Loss of sectional area due to corrosion /on cut samples/ evaluation the corrosion effect to prestressing / used in expert's static assessment
11) Bridge files and records.	a. What records (design, fabrication, construction, inspection, etc.) of bridge were collected to support the investigation, and how where they reviewed?
Answer	Non-public information - Original design documentation from 80's - Documentation of bridge repairs 1998, 2012 - Protocols from diagnostics 2010

Case : *Troja stress ribbon footbridge*	
	- Protocols from set of bridge inspections - Load testing protocols (dynamic testing 2013) - Protocols for continuous monitoring - Tests of the structural materials after collapse - Testimony of bridge designer, administrator staff, contractor workers, inspection and diagnostics specialists - Expert Evidence (report) incl. static assessment *Some data were complete, some in-complete, some missing*. Data were collected by investigators and handed over to court-certified expert, who incorporated them in his Expert Evidence (report).
12) Analyses.	What type of analysis or modeling tools (engineering calculation, structural analysis, finite element modeling, others) were used to support the investigation and describe their use?
Answer	Non-public information Structural analysis was performed by court-certified expert, using all data collected. Details of this analysis are unknown (non-public)
13) Lessons learned.	a. With regard to the cause of failure, what were the findings of the investigation?
Answer	Non-public information (trial is currently on the way) The sudden fracture of bearing tendons was caused by unpredicted scale of corrosion of these tendons. This corrosion was provoked by intrusion of water (containing de-icing salt) through the weared insulation layer inside the trough, where the bearing tendons were placed (filled by cast-in-placed concrete following the tensioning the second half of these tendons (A2), the concrete was of poor quality and not evenly and fully filled out the through), and also through the joints between segments.  Because the worst corrosion of the A1 strands had been developing only locally inside random holes, full of water, hidden in the bottom of the trough, subsequent local overstressing of strands was limited to short sections, thus it did not result in change of overall structural behaviour (no significant development of the joint openings, no sag increment). Also this mechanism of the strand damage was not necessarily accompanied by an increase of water penetration through the joints, as the local defect could be off the joint. So the progress of the strand damage could remain undetectable. Once the local overstress inside the weakened strands exceeds the strand actual limit, the first wire/strand cracked, the force was redistributed to remaining strands and due to domino effect the structure collapsed. *Note: above are not official conclusions, but only possible explanation*
	b. What lessons learned were derived from the findings?
Answer	No official conclusions are available yet.

Case : *Troja stress ribbon footbridge*	
	The example of Troja bridge failure reminds us that sudden collapse without any prior notice is still possible. The need of thorough regular inspection of prestressed bridges (espec. built using segment technology) became obvious.
	c. How were the lessons learned communicated to the bridge engineering, construction and inspection communities?
Answer	No official outcome yet. But the discussion aimed in several directions (technical, organizational, legal) is already on the way.
	d. Describe any changes to the state of practice resulting from the lessons learned.
Answer	The programme of increased inspection of prestressed bridges, incl. necessary diagnostics has been already launched on bridges under administration of Ministry of Transport of Czech Rep.
	e. Identify any challenges the resulted from the process or procedure used to conduct the investigation, and any recommended changes to the approach or methodology used to address those challenges or otherwise result in improvements.
Answer	Legally: - The lack of independent solely professional body with legally guaranteed access to all the data of the collapse is obvious. This body should act as trusted and expert partner to state governed processes (police investigation). - Also the legal liability of the original bridge designer when collapse occurs for different reasons after decades of service should be in question. Technically: - The Troja bridge collapse should accelerate an effort to improve or develop diagnostics methods and techniques (non-destructive or with limited destructive impact), which enable to identify hidden damages, which do not manifest themselves externally. - Also the possible issue of the behaviour of the prestressing strands with only surface corrosion should be addressed as a matter of discussion among professionals.
14) Other impacts on the investigation.	a. If there was a need for a timely repair to address a long detour or simply the restoration of service, please describe how that need impacted the decisions made or process used for the investigation.
Answer	Not applied, collapsed bridge was totally unusable. New footbridge has been already built and opened to service
	b. Please describe how financial considerations (potential cost of the investigation, cost to the traveling public, cost of the repair, etc.) impacted the decisions made or process used for the investigation.
Answer	Not applied.
	c. Please describe any additional considerations or risks that impacted how the investigation was conducted and what those impacts were.
Answer	The lack of expert proficiency on the investigators side and restricted access to data for independent experts during investigation could lead to legal conclusions without comprehensive and correct technical evaluation about causes of the structural failure.

8.5. Case Study 4: France Cantilever Sidewalk Failure

Case : *Precast Bridge Sidewalk*	
1) Brief description of the bridge (type, material, year of construction, …	Provide a short description of the bridge including bridge type, material (steel, reinforced concrete, prestressed concrete, timber, masonry, …), year of construction, span lengths, …
Answer	About 75 overpasses (reinforced concrete PS) built in the 1970s are equipped with prefabricated corbelled sidewalks. The sidewalk elements are attached to the deck with metal anchor rods: 3 rods per slab. Characteristics common to the sidewalk slabs of all the structures involved in the study : • length of the precast element = 2.00 m, • thickness = 0.20 m, • number of fixings per element: 3 units, • guardrail type S8 sealed at 0.25 m from the outer edge of the sidewalk. There are 3 types of slabs (according to their width). Their characteristics are specific to each sidewalk configuration (A, B or C) : Total width of the sidewalk slab = (A: 1.00 m) (B: 1.25 m) (C: 1.75 m) Width of slab support on deck = 0.50m or 0.75m or 1.00m Width of the overhang = 0.75 to 1.00 m.
Picture of the bridge	
2) Description of the failure.	Provide a detailed description of the failure. Include sufficient relevant context to support the failure being unanticipated or producing unexpected performance.

Case : *Precast Bridge Sidewalk*	
Answer	 Each slab is secured with 3 anchors. Over time, these anchors have corroded between the sidewalk slab and the structure slab itself, which raised a problem for the stability of the sidewalk slabs.
Picture of the failure	 We can see that on C1, C5, C6 and C7, there is a significant loss of section. This loss of section occurs between the sidewalk slab and the concrete of the bridge slab at the location of the paving screed.
3) Investigating organization.	If one or more specific agency or institution has the responsibility to investigate bridge failures in your country, please name them and describe their authorities.
Answer	The Project Owner (MOA) has surrounded itself with a Project Manager (MOE), a Project Management Assistant (AMO) and a laboratory.

Case : *Precast Bridge Sidewalk*	
4) Legal constraints.	If there are legal constraints on the transparency or process of a bridge failure investigation in your country, please describe those.
Answer	
5) Investigative process.	Please describe how the investigation was conducted. If a standardized and documented process or procedure was used to guide or inform the investigation, please also describe it here and include a copy with your response.
Answer	There is no standard procedure to detect this type of failure. At the initiative of the project owner, we proceeded to a numerical modeling coupled with a scale 1 modeling to test different types of non-destructive methods. After a bibliographic analysis and tests with electrical methods, it turns out that no method can detect this type of corrosion. We tried to innovate with methods based on heat diffusion (a temperature variation is applied at the top of the slab on the fastener, the goal being to see the temperature rise at the deck level depending on the state of the rod which is supposed to transmit the heat). Calculations have shown that this transfer will be small and not detectable by thermal cameras. We developed the mechanical model and analyzed the different failure modes. We then turned to scale 1 tests on structures to test if they could meet the regulatory load, with obviously a safety margin, which coupled with corrosion kinetics, can estimate the residual life of the structure. Risk management and strategy for case by case decision making by the Project Owner: • The most sensitive structures were subject to heavy repairs of slab replacement, including all structures with small diameter anchor rods. • The structures most exposed to corrosion were also replaced. • The other structures are subject to special monitoring, a resumption of waterproofing to limit the risks of corrosion and are also controlled by a specific test protocol described in the document.
6) Organizational structure.	Describe the organizational structure used by the investigators.
Answer	A project management team An NDT expert (Non Destructive Testing) A specialized calculation team A laboratory team And a field team
7) Investigator qualifications.	Describe the qualifications of those involved in the investigation. Education, licensing, training, experience, etc.

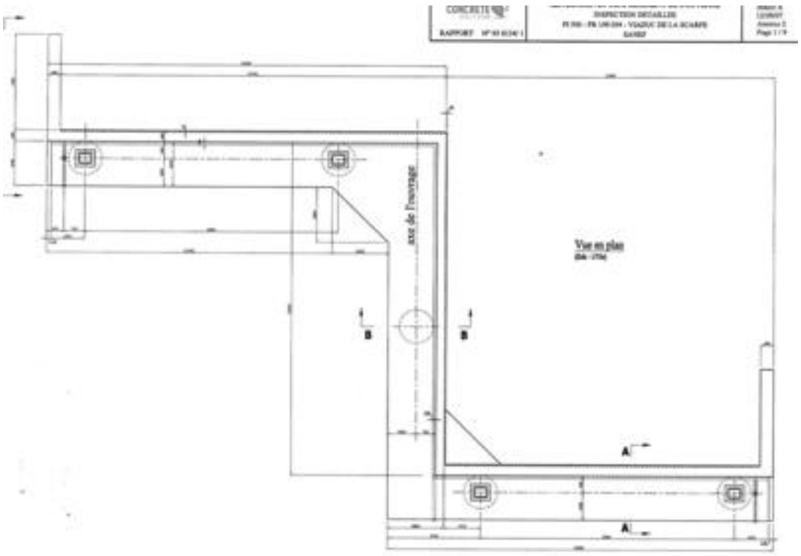
Case : *Precast Bridge Sidewalk*	
Answer	A Doctor in Civil Engineering An expert in finite element calculation An expert in non-destructive methods A team of technicians for the assembly of scale models An expert in metallic calculation Two experts in instrumentation
8) Investigation documentation.	a. Describe how the failure was documented on-site?
Answer	All the structures have been inventoried. A safety program for the structures most exposed to risk has been set up. During the repair of certain structures, the anchors were removed and set aside for examination and experimentation.
	b. How was physical evidence collected, documented and controlled?
Answer	The origin of each anchor was traced. Direct measurements of section loss were made.
9) Testing.	a. What type of physical testing was conducted to support the investigation?
Answer	Tensile tests on the anchors Tests of several non-destructive methods: radar, acoustic... On-site loading tests.
	b. If standardized test methods were not used, why not?
Answer	Laboratory and field loading tests are not standardized because they require special frames.
	c. How was test data stored and documented?
Answer	A full report was prepared for each trial. A final report was produced.
10) Experimentation.	If experimental testing was conducted, please summarize the need, describe the experiments, and outline how the results were used.
Answer	Scale 1 tests were performed on models as well as on site tests. The tests on models allowed to validate the limit sections of the steels as well as the failure modes.

Case : *Precast Bridge Sidewalk*	
	 We were able to follow the loading test in real time, check the impact on the anchors, reproduce a failure of some anchors to understand the impact on the overall failure.  The on-site tests could thus be carried out in complete safety.
11) Bridge files and records.	a. What records (design, fabrication, construction, inspection, etc.) of bridge were collected to support the investigation, and how where they reviewed?
Answer	The files of executed works, which compile the memory of the design and the realization, were used as a basis for the studies.
12) Analyses.	What type of analysis or modeling tools (engineering calculation, structural analysis, finite element modeling, others) were used to support the investigation and describe their use?
Answer	Finite element calculation to determine slab limits and to perform parametric studies on minimum non-corroding steel sections to ensure slab stability.
13) Lessons learned.	a. With regard to the cause of failure, what were the findings of the investigation?

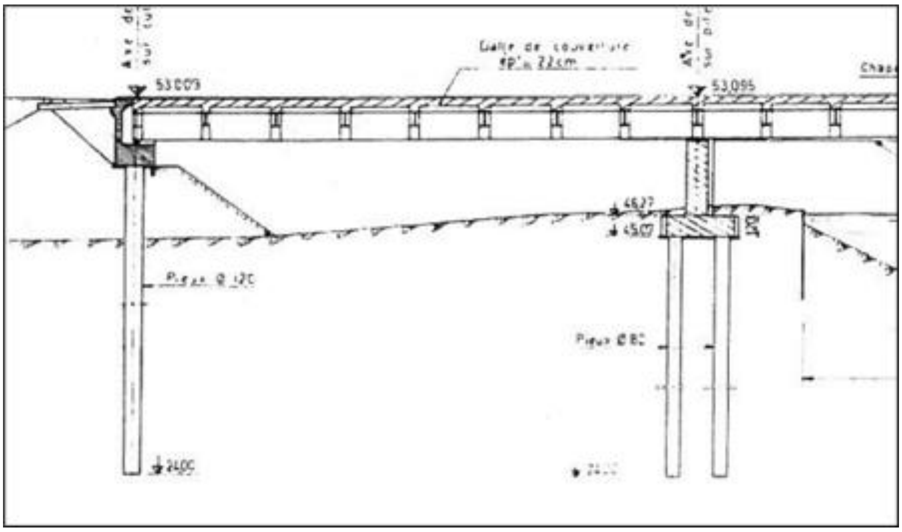
Case : *Precast Bridge Sidewalk*	
Answer	Poor quality of the waterproofing screed between the sidewalk and the deck, and between sidewalk elements. The waterproofing did not rise to the level of the sidewalks. Use of de-icing salt.
	b. What lessons learned were derived from the findings?
Answer	This design does not take into account the risks of aging materials with a failure that can be a brittle failure without prior sign and without the possibility of visual inspection and non-destructive auscultation.
	c. How were the lessons learned communicated to the bridge engineering, construction and inspection communities?
Answer	This design did not last. Quite quickly, this system of corbelled slabs was replaced by slabs anchored by anchor sill.
	d. Describe any changes to the state of practice resulting from the lessons learned.
Answer	Installation of anchoring stringers, eliminating the risk of slab tipping in case of failure.
	e. Identify any challenges the resulted from the process or procedure used to conduct the investigation, and any recommended changes to the approach or methodology used to address those challenges or otherwise result in improvements.
Answer	The challenge was first and foremost to understand the problem but also to understand what would be the best strategy to put in place to demonstrate the stability or not of certain structures. From a practical point of view, we discovered that loading a 15-ton slab safely is not an easy task.
14) Other impacts on the investigation.	a. If there was a need for a timely repair to address a long detour or simply the restoration of service, please describe how that need impacted the decisions made or process used for the investigation.
Answer	As the overall repair cost was not negligible, all affected structures had to be tested (no sampling).
	b. Please describe how financial considerations (potential cost of the investigation, cost to the traveling public, cost of the repair, etc.) impacted the decisions made or process used for the investigation.
Answer	Since a global repair is very costly and has a great impact on the availability of the infrastructure (several structures involved), a method had to be found to guarantee these structures over time.
	c. Please describe any additional considerations or risks that impacted how the investigation was conducted and what those impacts were.
Answer	The most important risk is a slab failure which will have a considerable impact on users. This risk is not acceptable to the project owner.

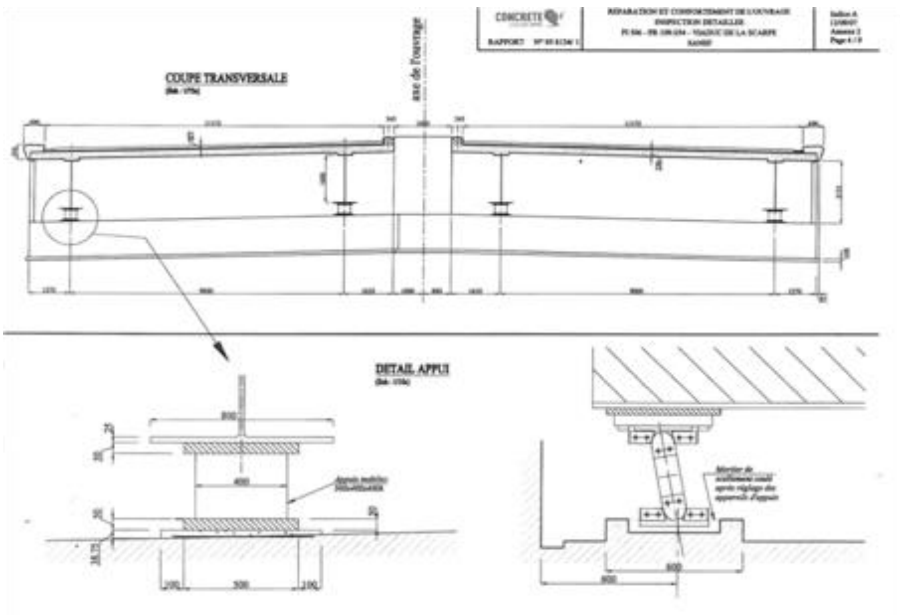
Case : *Precast Bridge Sidewalk*	
	During the tests, we cut off the direction of traffic on the motorway during the loading.

8.6. Case Study 5: France Abutment Backwall Failure

Case : *Failure of Abutment Backwall*	
1) Brief description of the bridge (type, material, year of construction, …	Provide a short description of the bridge including bridge type, material (steel, reinforced concrete, prestressed concrete, timber, masonry, …), year of construction, span lengths, …
Answer	The viaduct design is a double steel beams structure with a reinforced concrete deck, built between 1980 and 1981, opened in 1983. There are 3 spans of 31m, 50m and 31m. The bearings are connecting rods The deep foundations are molded posts going through a peat layer and made of a single line of posts for the abutments. There is a continuity of the backwalls in between the two decks. 

<table>
<tr><th colspan="2">Case : Failure of Abutment Backwall</th></tr>
<tr><td>Picture of the bridge</td><td>





</td></tr>
</table>

Case : *Failure of Abutment Backwall*	
2) Description of the failure.	Provide a detailed description of the failure. Include sufficient relevant context to support the failure being unanticipated or producing unexpected performance.
Answer	From 1983, there is an important settlement of the backfill and a closure of the expansion joints. Corrective measure : Destruction of the transition slabs and corrective measure on expansion joints under warranty in 1988 by jackhammering of back walls to restaure the joints opening. New settlement and closure of the expansion joint which are taken out from the bridge in 2006. The analysis shows that the bridge deck is in compression as per its contact with the abutments. The inclination of the connecting rods is over passing the admissible limit. In 2007, one of the connecting rods is failing and provisional security action is set in place The long term creep coefficient of modern alluvium (peats) under the load of the backfill has generated a tilting of the moulded posts by horizontal stresses. The works operated in 1988 to restaure the joint opening have increased the phenomenon.

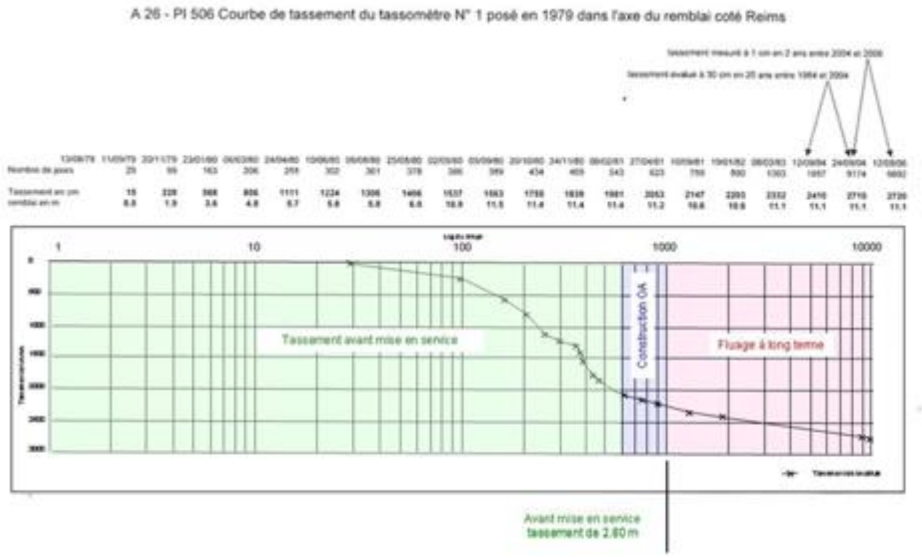
<table>
<tr><th colspan="2">Case : Failure of Abutment Backwall</th></tr>
<tr><td>Picture of the failure</td><td>


Status of the compression of the deck on the backwall after hydrojetting of the backwall :
</td></tr>
<tr><td>3) Investigating organization.</td><td>If one or more specific agency or institution has the responsibility to investigate bridge failures in your country, please name them and describe their authorities.</td></tr>
</table>

<table>
<tr><th colspan="2">Case : Failure of Abutment Backwall</th></tr>
<tr><td>Answer</td><td>
Detailed inspection following the ITSEOA (French recommendations) process. At Sanef, this inspection was performed every 5 years. The local operation center is doing an inspection on yearly basis.

GCA, supervisory authority of France. Cerema expert (former CETE) and the LCPC (now UGE)

The monitoring of the structure was performed by the CETE from 1986 to 2007 with inclinometers :



</td></tr>
<tr><td>4) Legal constraints.</td><td>If there are legal constraints on the transparency or process of a bridge failure investigation in your country, please describe those.</td></tr>
<tr><td>Answer</td><td>
In case of failures in the ten year warranty, and if the structure is not performing as the initial design requirements, the general contractor has to design corrective measures to restore the functionality of the bridge.

After 10 years, if the failure is a hidden defect, the vice fraud process can be engaged in a 5 year period after discovering the failure.
</td></tr>
<tr><td>5) Investigative process.</td><td>Please describe how the investigation was conducted. If a standardized and documented process or procedure was used to guide or inform the investigation, please also describe it here and include a copy with your response.</td></tr>
</table>

Case : *Failure of Abutment Backwall*	
Answer	A complementary geotechnical study has been carried out with 4 pressure meter survey, 2 coring samples and 3 oedometric survey. The main objectives were : • To identify the floor characteristics and to estimate residual settlements. • To delete the origins of failures by bearing the backfill with rigid inclusions and by looking for a smooth transition with the current section with a relevant mesh wider and wider.
6) Organizational structure.	Describe the organizational structure used by the investigators.
Answer	Head of Civil Engineering Infrastructure Management at Sanef to define the investigation and works program. Geotechnical study and Retrofitting design by a specialized engineering firm : Sixense.
7) Investigator qualifications.	Describe the qualifications of those involved in the investigation. Education, licensing, training, experience, etc.
Answer	Sanef : 25 years experienced engineer from ESTP Cachan with several references of non conventional infrastructure construction in general contractor companies. Sixense : Geotechnical expert with past references in the french administration departments Cete (Cerema) : Expert from French Administration.
8) Investigation documentation.	a. Describe how the failure was documented on-site?
Answer	By investigation in our archives including on the reinforcement of the backfill of a metal culvert located at the PR 109.4 ? Monitoring of the settlements ; Observation of the closure of expansion joint up to compression failure of a backwall by corrosion. Observation of connecting rods inclination out of acceptable limit.
	b. How was physical evidence collected, documented and controlled?
Answer	Archives and follow-up By increasing the monitoring process from 2006.
9) Testing.	a. What type of physical testing was conducted to support the investigation?

Case : *Failure of Abutment Backwall*	
Answer	Geotechnical trials (see answer to question 5) Suitability test of rigid inclusions (Bulb creation inside the backfill and inside the bearing substratum)
	b. If standardized test methods were not used, why not?
Answer	Initial design not suited to the geotechnical characteristics of the site.
	c. How was test data stored and documented?
Answer	Infrastructure Archives
10) Experimentation.	If experimental testing was conducted, please summarize the need, describe the experiments, and outline how the results were used.
Answer	Non Relevant
11) Bridge files and records.	a. What records (design, fabrication, construction, inspection, etc.) of bridge were collected to support the investigation, and how where they reviewed?
Answer	Drawings, geotechnical fil, detailed inspections, settlement monitoring, jobsite archives.
12) Analyses.	What type of analysis or modeling tools (engineering calculation, structural analysis, finite element modeling, others) were used to support the investigation and describe their use?
Answer	Design of the rigid inclusion regarding the residual settlement of the backfill.
13) Lessons learned.	a. With regard to the cause of failure, what were the findings of the investigation?
Answer	It is a design issue more than an execution one. The backfill settlement risk was identified from the design stages but this risk was underestimated. The bridge abutments were tilting due to the pressure of the backfill on a compressible area. The failure was fixed by nailing of the backfill with rigid inclusions.
	b. What lessons learned were derived from the findings?
Answer	Fixing (and removing) the origin of the failure before any repair action. To perform an analysis as soon as a failure is identified. The decision to proceed to works in order to re-open the expansion joints in 1988 without investigating on origin of the failure, (with an additional effect on the tilting process) is not acceptable.
	c. How were the lessons learned communicated to the bridge engineering, construction and inspection communities?

Case : *Failure of Abutment Backwall*	
Answer	Internal training session Presentation during technical events
	d. Describe any changes to the state of practice resulting from the lessons learned.
Answer	Getting an expert analysis on any construction program (both external and internal)
	e. Identify any challenges the resulted from the process or procedure used to conduct the investigation, and any recommended changes to the approach or methodology used to address those challenges or otherwise result in improvements.
Answer	Identifying the origin of failure. To take it in consideration and if possible to fix it before any repair remediation.
14) Other impacts on the investigation.	a. If there was a need for a timely repair to address a long detour or simply the restoration of service, please describe how that need impacted the decisions made or process used for the investigation.
Answer	Job site planning was defined with a tilting of highways tracks which was possible on this specific case.
	b. Please describe how financial considerations (potential cost of the investigation, cost to the traveling public, cost of the repair, etc.) impacted the decisions made or process used for the investigation.
Answer	Important cost for the asset's owner who has given priority to those works. It had no impact on highway users.
	c. Please describe any additional considerations or risks that impacted how the investigation was conducted and what those impacts were.
Answer	Non relevant

8.7. Case Study 6: France External Post-Tensioned Tendon Failure

Case : *External Prestressing Tendon Failure*	
1) Brief description of the bridge (type, material, year of construction, …	Provide a short description of the bridge including bridge type, material (steel, reinforced concrete, prestressed concrete, timber, masonry, …), year of construction, span lengths, …
Answer	The bridge, built between 1986 and 1988, consists of two decks with open prestressed voussoirs. Each deck supports a direction of the highway with an overall width of 10.75 m. It is of total length 1266 m distributed over 21 spans (55m + 19 x 60.6m + 59.8m).
Picture of the bridge	   
2) Description of the failure.	Provide a detailed description of the failure. Include sufficient relevant context to support the failure being unanticipated or producing unexpected performance.
Answer	Following a maintenance visit on the highway network, a failure external prestressing cable was discovered on 02 November 2015. Following an examination of the fracture point, it was identified that the failure was due to corrosion of the steel cables due to a leakage defect of the HDPE ducts that was not visible during the visual inspections.

Case : *External Prestressing Tendon Failure*	
Picture of the failure	   
3) Investigating organization.	If one or more specific agency or institution has the responsibility to investigate bridge failures in your country, please name them and describe their authorities.
Answer	The bridge is located on the conceded motorway network, under the management of a private owner. Nevertheless, as it is a major failure and the repair is delicate, the concessionaire company carried out the investigations and repairs with regular exchanges and validation with the State and the Ministry in charge of Transport, the conceding authority.
4) Legal constraints.	If there are legal constraints on the transparency or process of a bridge failure investigation in your country, please describe those.
Answer	The concessionaire company wishes to keep anonymous the bridge that presented the failure described.
5) Investigative process.	Please describe how the investigation was conducted. If a standardized and documented process or procedure was used to guide or inform the investigation, please also describe it here and include a copy with your response.
Answer	A SETRA note, published in December 2007 concerning existing structures with external prestressing protected by grout in contact with reinforcements, focused the attention of bridge's owners to the risks associated with these cables, but also recommended the establishment of an investigation procedure and safety procedures. Several families of investigations were conducted in 2015 in relation to this note:

Case : *External Prestressing Tendon Failure*	
	• Structural recalculations with criticality study on cable and X deck (collateral damage due to cable breakage) • HDPE Duct visual inspection to identify sensitive areas (on current section of cables and at sleeves and vents) • Diagnostics of HDPE ducts to verify their condition and function (mechanical and physico-chemical characterization of HDPE samples) • Steel cable diagnostics (mechanical and physico-chemical characterization) • Cement grout diagnostics (mechanical and physico-chemical characterization) • Water permeability test of broken cable • Non-destructive diagnosis of prestressing cables by on-site analysis to the electromagnetic coil (passage of a coil on all cables except anchorages and deflectors) This note was updated by CEREMA in November 2018, taking into account the evolution of testing techniques and recent feedback.
6) Organizational structure.	Describe the organizational structure used by the investigators.
Answer	The organization is classic for such investigations: Bridge owner (concessionary company), Project Manager, Project Management Assistance and Agent Company. The specificity is the validation by the representative of the Ministry in charge of Transport.
7) Investigator qualifications.	Describe the qualifications of those involved in the investigation. Education, licensing, training, experience, etc.
Answer	In order to develop the technique of NDT testing by electromagnetic coils, persons involved in the testing of cable lifts have been integrated into the approach of design of the electromagnetic coil.
8) Investigation documentation.	a. Describe how the failure was documented on-site?
Answer	The HDPE ducts were fully investigated and the observations were transcribed on a plan allowing each subsequent inspection to check the evolution of disorders. The NDT analysis of the cables by electromagnetic coil was traced cable by cable allowing the opening of the ducts when a defect was detected. As a result, a threading finger left in the duct could be detected on a cable and abundant corrosion was detected on another cable requiring its replacement.
	b. How was physical evidence collected, documented and controlled?
Answer	The broken cable was removed and autopsied to understand the source of the failure (poor sealing of a poorly welded sleeve). This cable also made it possible to carry out water permeability tests and material tests. The replaced cable was also cut and retained for future analysis.
9) Testing.	a. What type of physical testing was conducted to support the investigation?

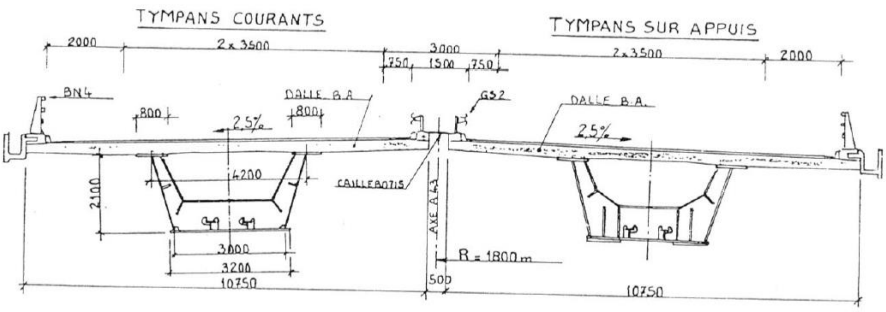
Case : *External Prestressing Tendon Failure*	
Answer	• Mechanical and physico-chemical tests of HDPE, cement grout and steels according to French standards • Water permeability tests for cables injected with cement grout
	b. If standardized test methods were not used, why not?
Answer	• mechanical and physico-chemical testing of standardized materials • Water permeability tests for cables • Interactive booklet Gustave Eiffel University / CEREMA: Sheet B5-6: Detection of section defects in external prestressing cables by magnetic auscultation
	c. How was test data stored and documented?
Answer	The recording of the data is carried out on the network of the concessionnaire compagny. Measurement or test reports shall be delivered to the supervisor and the concessionnaire compagny.
10) Experimentation.	If experimental testing was conducted, please summarize the need, describe the experiments, and outline how the results were used.
Answer	• Electromagnetic coil design with existing magnetized or permanent magnet tests. Dimensional design of the coil to adapt to the different cables and the viaduct. • Design of devices for passing sleeves or vents. • Processing of the acquisition with laboratory tests on prototypes to demonstrate the performance of the coil (detection of a very thin steel wire, detection of streaks or corrosion points on cables, etc.) • On-site data processing with window openings in ducts at each abnormal detection.
11) Bridge files and records.	a. What records (design, fabrication, construction, inspection, etc.) of bridge were collected to support the investigation, and how where they reviewed?
Answer	The bridge file was complete (plans, calculation notes, cables).
12) Analyses.	What type of analysis or modeling tools (engineering calculation, structural analysis, finite element modeling, others) were used to support the investigation and describe their use?
Answer	A 3D model of finite element calculations was conducted to carry out the criticality study of cable and X deck by the Setec design office. This model allowed to appreciate the robustness of the structure.
13) Lessons learned.	a. With regard to the cause of failure, what were the findings of the investigation?
Answer	The corrosion of the external prestressing cables is due to poor sealing of the HDPE ducts (connecting sleeves, non-recapped injection vents mainly), but also to a lack of traceability of the disorders during the execution. “Fanciful” provisions may have been implemented in some cases to ensure continuity of ducts (split sheath element hidden under connecting or injection sleeves) or to compensate for leakage during injections using foam, tissue, etc. . In some cases, the ducts may have torn in the diverter blocks during tensioning, which resulted in the cable being sealed during injection, making it

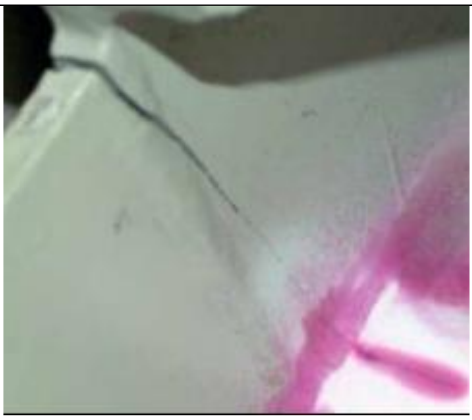
Case : *External Prestressing Tendon Failure*	
	very difficult to change it later. In the event of a leakage failure of the HDPE duct, it was also found that the cement grout did not sufficiently protect the prestressing tendons and allowed the spread of water loaded with aggressive capillary agents.
	b. What lessons learned were derived from the findings?
Answer	The aging of external prestressing cables in HDPE injected with cement grout on open box decks is a serious problem that is starting to see the light in France for more than 5 years. A lack of vigilance and traceability on the sealing of the HDPE ducts was observed during the construction of these structures. The importance of periodic visual detailed inspections on these cables has been demonstrated, but is not sufficient to determine whether or not corrosion is occurring. Non-destructive methods, electromagnetic coil, UScan, allow to control some sections of the cables but not all because they are limited by their environment: not possible to check cables too close to concrete, in the diverter blocks etc… The subject of re-anchorage in the cement grout of broken tendons is a point of vigilance (cable retaining its initial tension) and remains to be quantified empirically to know the limit from which a cable can break. It is absolutely necessary that a rigorous monitoring of the implementation of the cables is carried out by tracing all operations and disorders (non-exhaustive list): • Continuous support of the ducts to avoid the chain effect which will result in their opening and/or buckling, • Quality of HDPE materials and their fittings; use fittings that ensure the same quality as the jacket, pressure 10 bar, • Quality of application of electroweldable sleeves with visible welding indicators, • Loss of one threading finger when installing clear tendon, • Prior sealing before mandatory injection, including pressure-resistance over prescribed time, • Defects in tensioning : breaking or slipping of tendon, which may be revealed by scaling of ducts • Injection, grout or wax quality • Draw up the pressure resistance, • In case of disorder, open a non conformity sheet specifying the actions taken etc External prestressing is a major structural element for the construction and safety of the agents involved. It must be carried out very rigorously by qualified personnel, with traceability of all the phases carried out and disorders encountered. The lack of traceability of disorders jeopardizes security and does not allow the management service to target its monitoring and possible replacement actions.
	c. How were the lessons learned communicated to the bridge engineering, construction and inspection communities?

Case : *External Prestressing Tendon Failure*	
Answer	A request was made by the Ministry of Transports to all the motorway concession companies to identify their structures with external prestressed tendons to carry out a diagnosis of the ducts and monitor their aging. Feedback meetings on the subject are also held in France. The key elements of the feedback are the corrosive environment around the cables and the sealing of the HDPE ducts, which have a strong influence on the aging of the cables. As a result of these defects (and others discovered on other bridges), different actions have been decided or are in progress: • Creation of a feedback group involving different private and public actors on this subject. Launch of a survey to identify potentially relevant bridges, • Cerema and Gustave Eiffel University have published an information note (n°3) to alert bridges owners to the possibility of similar disorders on all external prestressing bridges injected with ciment grout, • Development by Cerema, in partnership with the German company ROTEC and motorway concession companies, of magnetic cable testing equipment. • A project to study the fracture conditions of damaged cables was developed at the initiative of the motorway concession companies and with the assistance of Gustave Eiffel University, Cerema and the ENPC (National School of Bridges and Roads). It is envisaged to study the tensile strength at break under different conditions of damage to individual wires and tendons as well as the conditions of re-anchorage of the cable in its injected duct.
	d. Describe any changes to the state of practice resulting from the lessons learned.
Answer	The sealing of HDPE ducts is the only barrier for prestressing cables injected with ciment grout. Verification of this sealing is essential. In the construction of the structures today, it is recommended to use TGG tendons (coated greased tendons) which benefits from two protections per strand, the grease and the HDPE sheath. These tendons can be assembled in a HDPE collector duct and can even be injected.
	e. Identify any challenges the resulted from the process or procedure used to conduct the investigation, and any recommended changes to the approach or methodology used to address those challenges or otherwise result in improvements.
Answer	• Have additional feedback to communicate with design compagnies, managers on design improvement. • Raise awareness of the risk and fracture mechanism of these cables • Necessary third party design and repair controls. • Anticipate execution control from design by the designer
14) Other impacts on the investigation.	a. If there was a need for a timely repair to address a long detour or simply the restoration of service, please describe how that need impacted the decisions made or process used for the investigation.

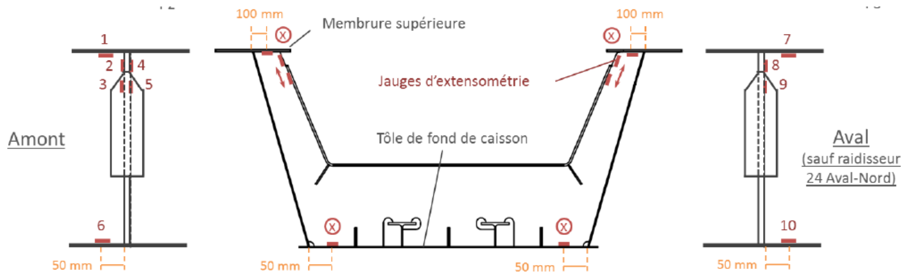
Case : *External Prestressing Tendon Failure*	
Answer	A traffic restriction measure was put in place on the structure until the impact of a cable break by a design compagny was analysed. During the investigations, the circulation could be maintained normally. When the corroded cable identified by the electromagnetic coil was cut, a circulation closure on the structure was carried out with the installation of a deviation.
	b. Please describe how financial considerations (potential cost of the investigation, cost to the traveling public, cost of the repair, etc.) impacted the decisions made or process used for the investigation.
Answer	Replace all cables cannot be used. CND testing of cables required.
	c. Please describe any additional considerations or risks that impacted how the investigation was conducted and what those impacts were.
Answer	The corroded cable once detected, with the abundant corrosion of the exposed steel cables, had to be secured to avoid a sudden failure and risk to the personnel involved. Investigations had to be stopped until the cable was suddenly cut for replacement. In order to prevent the cable from being whipped under sudden breakage, the cable was tied with straps and tires to enable a damping system to be achieved.  

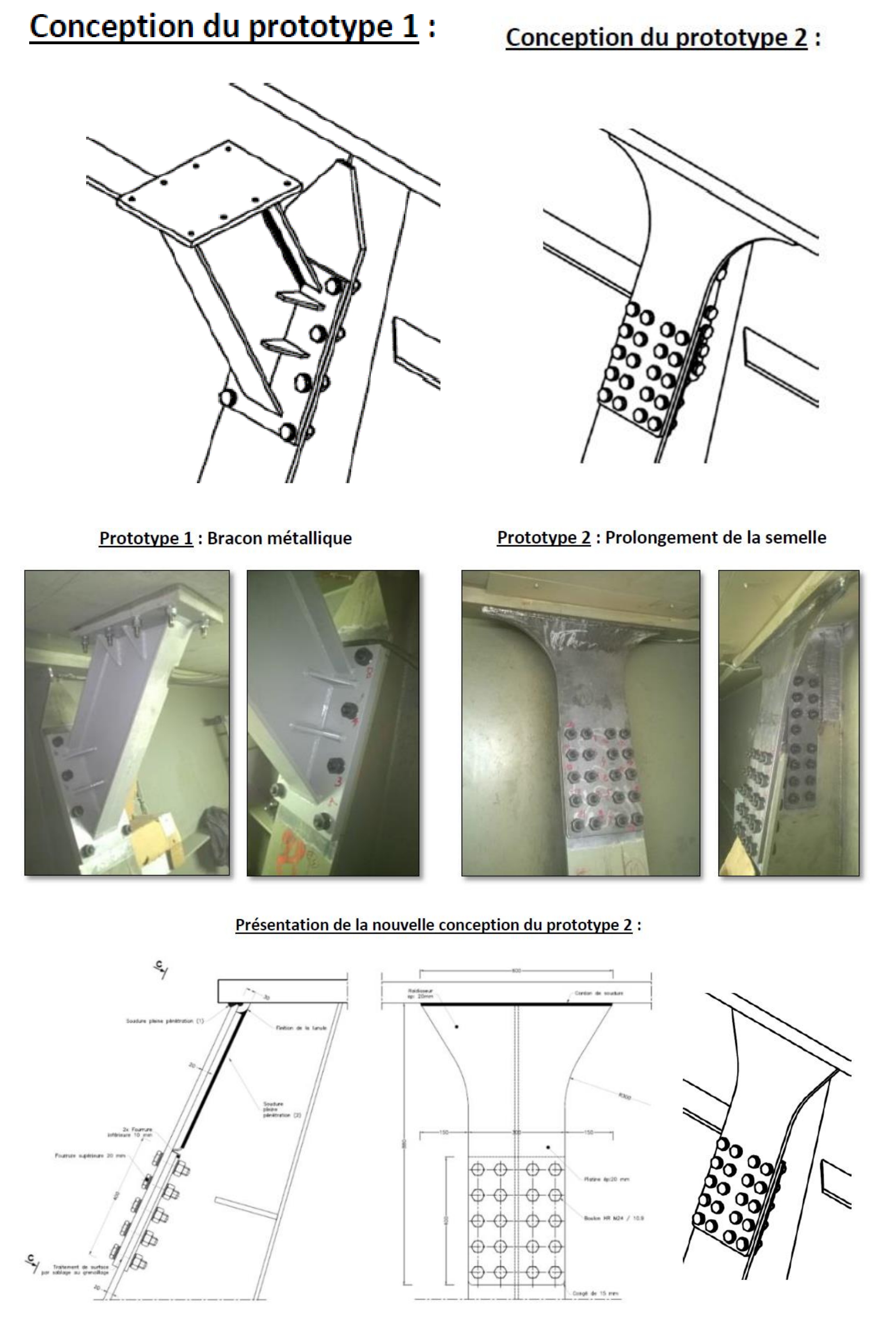
8.8. Case Study 7: France Box Girder Fatigue Damage

Case : *Fatigue Cracks in Box Girder*	
1) Brief description of the bridge (type, material, year of construction, …	Provide a short description of the bridge including bridge type, material (steel, reinforced concrete, prestressed concrete, timber, masonry, …), year of construction, span lengths, …
Answer	The bridge built in 1991 is composed of two metal decks (box girders). Each deck supports a direction of the highway with a pavement width of 9.75m. Its total length is 244.4m spread over 4 spans (54.2m – 63.0m – 73.0m – 54.2m).
Picture of the bridge	   
2) Description of the failure.	Provide a detailed description of the failure. Include sufficient relevant context to support the failure being unanticipated or producing unexpected performance.

Case : *Fatigue Cracks in Box Girder*	
Answer	Following a detailed inspection in 2014, transverse cracks were discovered on the bottom plate of a span. Temporary repair work was carried out. But in 2015, fatigue cracks were identified on some transverse stiffeners, mainly on common diphragms. The questionnaire deals with the second family of cracks.
Picture of the failure	 Cracks #1  Cracks #2
3) Investigating organization.	If one or more specific agency or institution has the responsibility to investigate bridge failures in your country, please name them and describe their authorities.
Answer	The bridge is located on the motorway network, under the management of a private concessionaire company. Nevertheless, as it is a major failure and the repair is delicate, the concessionaire company carried out the investigations and repairs with regular exchanges and validation with the Ministry of Transport.
4) Legal constraints.	If there are legal constraints on the transparency or process of a bridge failure investigation in your country, please describe those.
Answer	The motorway company wishes to keep anonymous the bridge that presented the failure described.

Case : *Fatigue Cracks in Box Girder*	
5) Investigative process.	Please describe how the investigation was conducted. If a standardized and documented process or procedure was used to guide or inform the investigation, please also describe it here and include a copy with your response.
Answer	There are no standards or procedures for conducting investigations in 2015. 3 families of investigations were conducted: 1. Structural recalculations 2. Diagnostics of materials (Sample Destructive Testing) 3. Diagnostics of structure (instrumentation, structural tests) Although procedures do not exist to locate the families of causes of failure, documents exist to confirm the causes of failure: • A methodology on the theme “Metallic Structures – Fatigue” was written in June 2018 (in French). (Booklet interactive UGE/CEREMA) • French Technical Guides (Technical Instruction for monitoring and maintenance of briges) trace the history of different constructions and possible causalities of failures.
6) Organizational structure.	Describe the organizational structure used by the investigators.
Answer	The organization is classic for a repair work: contractor (concessionary company), Project Manager and its external control, and the Work Company. The specificity is the validation by the representative of the Ministry of Transport.
7) Investigator qualifications.	Describe the qualifications of those involved in the investigation. Education, licensing, training, experience, etc.
Answer	The construction site required the presence of an International Welding Engineer (IWE certificate). The construction site required the presence of an international welding engineer. He has more than 30 years of experience in the design of metal bridges.
8) Investigation documentation.	a. Describe how the failure was documented on-site?
Answer	Cracks were identified with red paint. Crack bottoms were drilled to limit their spread after penetrant testing.
	b. How was physical evidence collected, documented and controlled?
Answer	The inspectors spotted the cracks on a map, with the date and pictures. Quarterly visits were organised to see the development in number and size of cracks.
9) Testing.	a. What type of physical testing was conducted to support the investigation?

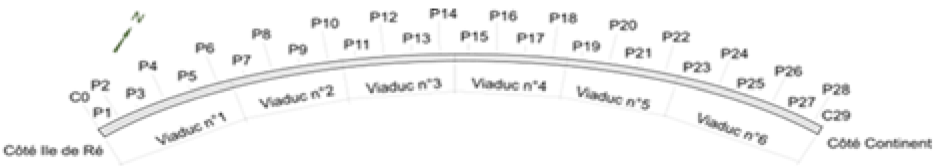
Case : *Fatigue Cracks in Box Girder*	
Answer	The investigations included the following: 1. Steels have been characterized (tensile testing, chemical analysis, charpy testing) 2. After fatigue recalculations, critical areas were identified, such as welds on the connectors. These welds were invesigated. 3. The coating and bituminous concrete thicknesses were checked. 4. Asbestos was also investigated.
	b. If standardized test methods were not used, why not?
Answer	The tests are subject to a test standard.
	c. How was test data stored and documented?
Answer	The recording of the data is carried out on the network of the supervisor. Reports of measurements or tests shall be delivered to the supervisor and contractor.
10) Experimentation.	If experimental testing was conducted, please summarize the need, describe the experiments, and outline how the results were used.
Answer	Instrumentation has been implemented to assess constraints in the structure. This instrumentation allowed the calculation of the traffic factor to be taken into account for each element of metal structures (upper flange, bottom plate and tympanum) (according to the 1996 guide and the EC3) based on histograms collected over the three weeks of measures. Instrumentation was also implemented to assess the constraints in the structure, particularly during repairs. 2 repair prototypes have been made. Deformation gauges were glued on the diaphragms, a loading test to allow 1/ validate the recalculations, 2/ validate the most suitable repair prototype. 

Case : *Fatigue Cracks in Box Girder*	
	
11) Bridge files and records.	a. What records (design, fabrication, construction, inspection, etc.) of bridge were collected to support the investigation, and how where they reviewed?
Answer	The bridge records were complete (drawings, calculation notes, plate acceptance certificates…)
12) Analyses.	What type of analysis or modeling tools (engineering calculation, structural analysis, finite element modeling, others) were used to support the investigation and describe their use?

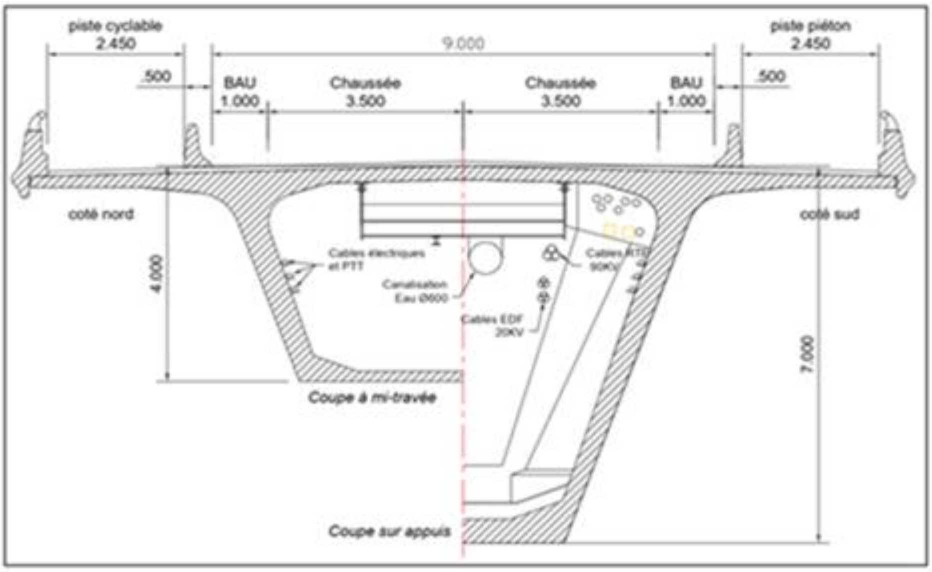
Case : *Fatigue Cracks in Box Girder*	
Answer	A 3D finite element model was conducted to quantify local effects in transverse bending as well as distortion effects. This model confirmed the fatigue phenomenon.
13) Lessons learned.	a. With regard to the cause of failure, what were the findings of the investigation?
Answer	The cause is well known: fatigue. This phenomenon was not taken into account in the design of bridges in 1991 even though the fatigue phenomenon had been known since the mid-1980s. It was taken into account in France in the calculation regulations from 1994. In the present case, the recalculated traffic coefficient changes according to the selected element (more important for the bottom plate than for the stiffeners and upper plates). However, it remains lower or even of the same order of magnitude as the theoretical traffic coefficient normally taken into account at the time of construction. The aggressiveness of the traffic does not seem to be a major parameter in the explanation of the cracking. It is therefore the intrinsic weakness of the geometric configuration concentrating the stresses, coupled with a small category of detail, which explains in the majority the observed cracking.
	b. What lessons learned were derived from the findings?
Answer	Although little observed, the phenomenon is very real. A lack of vigilance was observed at the time with regard to the rules of art not standardized. The importance of periodic visual inspections has been demonstrated.
	c. How were the lessons learned communicated to the bridge engineering, construction and inspection communities?
Answer	A request was made by the Ministry of Transport to all highway companies to identify their pre-1994 metal structures, and to conduct fatigue recalculation and field verification studies to identify potential fatigue cracks.
	d. Describe any changes to the state of practice resulting from the lessons learned.
Answer	The phenomenon of fatigue is now taken into account. But not all fatigue details are listed and justified. The definition of the repair by making 2 instrumented prototypes is an excellent idea to remember.
	e. Identify any challenges the resulted from the process or procedure used to conduct the investigation, and any recommended changes to the approach or methodology used to address those challenges or otherwise result in improvements.
Answer	• Have additional feedback to communicate with design developers, managers on design improvement. • Necessary third party design and repair controls. • Anticipate execution control from the design stage.

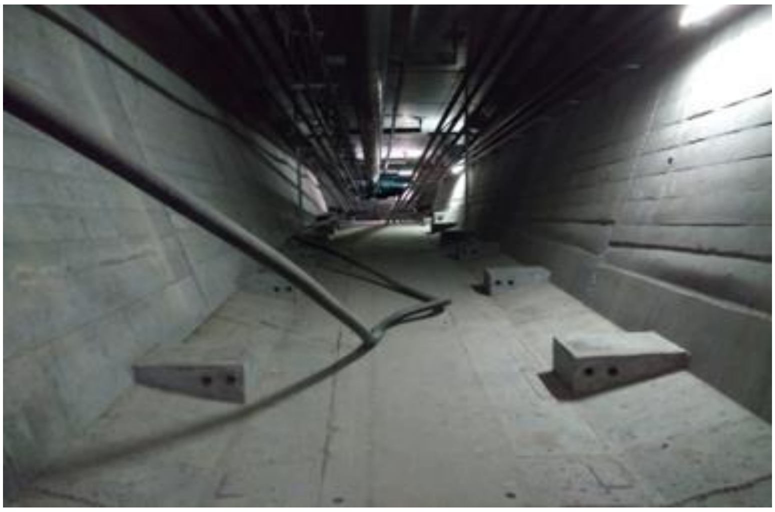
Case : *Fatigue Cracks in Box Girder*	
14) Other impacts on the investigation.	a. If there was a need for a timely repair to address a long detour or simply the restoration of service, please describe how that need impacted the decisions made or process used for the investigation.
Answer	The metallic decks were treated successively, one after the other. Exceptional convoys were banned until final repair.
	b. Please describe how financial considerations (potential cost of the investigation, cost to the traveling public, cost of the repair, etc.) impacted the decisions made or process used for the investigation.
Answer	
	c. Please describe any additional considerations or risks that impacted how the investigation was conducted and what those impacts were.
Answer	The presence of asbestos in the formwork elements remaining in place led to the construction of a preliminary asbestos abatement site.

8.9. Case Study 8: France External Post-Tensioned Tendon Failure

<table>
<tr><th colspan="2">Case : Ré Island Bridge</th></tr>
<tr><td>1) Brief description of the bridge (type, material, year of construction, …</td><td>Provide a short description of the bridge including bridge type, material (steel, reinforced concrete, prestressed concrete, timber, masonry, …), year of construction, span lengths, …</td></tr>
<tr><td>Answer</td><td>
The Ré Island bridge connects the Ré Island to the mainland and crosses four navigable sea passes, with a maximum gauge of 30 m above the sea. It was commissioned in 1988 and has 2 traffic lanes + pedestrian path + cycle path.
It is a bridge of strategic importance, supporting the Departmental Road n ° 735, the only access to the Ré island: around 18,000 vehicles per day, with about 5% of heavyweight lorries and summer peak recorded at 28,000 vehicles in a day.
All the networks (water, electricity, telephone) that supply the Ré island pass through the bridge box girder.
It consists of:
- a box-girder type prestressed concrete deck approximately 3 km long and comprising 6 independent viaducts each approximately 500 m long, separated one from another by half-joints. All of the 6 viaducts form 29 spans with a span varying between 38 and 110 m in length. The box girder bridge was made with high performance concrete (40 MPa strength required) incorporating silica fume, which was innovative for that time.
- 28 reinforced concrete piers and 2 abutments. All the piers are hollow except 2 of them (P11 and P12).
</td></tr>
<tr><td></td><td>


Plan view of the bridge
</td></tr>
</table>

Case : *Ré Island Bridge*	
Picture of the bridge	 **Cross section of the bridge at mid-span and on pier**  **General view of the Ré Island Bridge**
2) Description of the failure.	Provide a detailed description of the failure. Include sufficient relevant context to support the failure being unanticipated or producing unexpected performance.

Case : *Ré Island Bridge*	
Answer	On September 13, 2018, an agent responsible for checking the installations inside the box girder noted the rupture of an external prestressing tendon inside the caisson, the 9.3 South tendon in viaduct 2, between the P7 and P9 piers. The break occurred in a high anchorage on P7 pier. The tendon is a 19 T15S 1770 initially tensioned at 400 T and having an approximate length of 200 m. Although failures of external prestressing tendons have already been observed on a few other box girder bridges in France, the present failure was unexpected. Immediately, the Charente Maritime Department launches: - a technical expertise with the Scientific and Technical Network (RST - IFSTTAR and Cerema) - a tender under "pressing emergency procedure" (to limit the consultation and allocation times according to R2122-1 of the public tender regulations) in order to replace the defective prestressing tendon.
Picture of the failure	 **Photo of the broken tendon**
3) Investigating organization.	If one or more specific agency or institution has the responsibility to investigate bridge failures in your country, please name them and describe their authorities.

<table>
<tr><th colspan="2">Case : Ré Island Bridge</th></tr>
<tr><td>Answer</td><td>At the level of the Ministry of Transport, there is an Office for Investigations on Land Transport Accident (BEA-TT) which is responsible for carrying out technical investigations on land transport accidents and incidents, whether road, rail, river or guided. It was commissioned in 2004, by a decree implementing a law passed in 2002 following the fire in the Mont-Blanc tunnel.

In the event of a serious failure (bridge collapse for example) an administrative investigation may be opened, at the discretion of the Minister of Transport.</td></tr>
<tr><td>4) Legal constraints.</td><td>If there are legal constraints on the transparency or process of a bridge failure investigation in your country, please describe those.</td></tr>
<tr><td>Answer</td><td>There is no legislation that regulates the investigation of a bridge failure.

Nevertheless, the legal authorities in France intervene at several levels:

• criminal court (tribunal pénal) when there are dead people: unequivocal expertise then forwarded to the investigating judge;

• district or high court (tribunal d’instance ou de grande instance): contradictory expertise;

• To settle contractual disputes: administrative tribunal within the framework of public tenders, or commercial tribunal for disputes between private companies.

When the different courts intervene, they appoint experts accredited to the respective courts and who conduct the investigations process; these investigations are then carried out within the framework of the secrecy of the judicial investigation, as long as the judgment is not pronounced.

In the event of a major failure of bridges managed by the French State, the Ministry of Transport is in the habit of setting up technical committees bringing together agents of the manager of the structure and experts from CEREMA and the University Gustave Eiffel. (ex-IFSTTAR). These committees are chaired by a General Engineer. This organization is desirable when there is a major failure. It is set up by other managers such as private motorway companies or local authorities.</td></tr>
<tr><td>5) Investigative process.</td><td>Please describe how the investigation was conducted. If a standardized and documented process or procedure was used to guide or inform the investigation, please also describe it here and include a copy with your response.</td></tr>
</table>

Case : *Ré Island Bridge*	
Answer	In this case, the Charente Maritime Department owns the bridge and administers it under its own and sole authority. The Department immediately set up a technical committee for assistance to the project management which comprises representatives of the Cerema and Gustave Eiffel University (ex-IFSTTAR) and which was formalized by an R&D agreement. The technical committee has developed its own intervention strategy (examinations, reinforced surveillance, repairs). There is no standardized procedure for this, but there is an important technical reference documentation developed over the last forty years: ITSEOA, IQOA, Cahier Interactif sur l'auscultation des Ouvrages d'Art, technical guides of CEREMA and LCPC, repair standards, STRRES guides…
6) Organizational structure.	Describe the organizational structure used by the investigators.
Answer	The investigations (testing and re-calculations) were carried out by CEREMA, Gustave Eiffel University, the SIXENSE company and the STRAINS design office. The repairs were made by the Freyssinet company (dismantling and replacement of tendons, strapping of tendons, etc.)
7) Investigator qualifications.	Describe the qualifications of those involved in the investigation. Education, licensing, training, experience, etc.
Answer	Civil Engineers, Researcher, Research Director, Lecturer, University Professor, Senior Technicians. CEREMA and UGE experts qualified by the “Bridge Domain Committee” which reports to the Research and Innovation Service of the Ministry of Transport. Researchers qualified by the Researchers Evaluation Committee (CEVAL) of the Ministry of Ecology and Transport. Lecturer, University Professor qualified by the National Council of Universities (CNU) Experts, specialists qualified internally by private organizations after possible external evaluation.
8) Investigation documentation.	a. Describe how the failure was documented on-site?

Case : *Ré Island Bridge*	
Answer	- On-site verification by managers - Photographic report (+ reaping of the cut sections of the dismantled tendon during the repair work) - Visit of UGE on site (Center of Nantes) - Removal of the anchor head P7 - Analysis by UGE (Nantes Center) - Examination of the anchor head receptacle - Examination of the bridge documentation
	b. How was physical evidence collected, documented and controlled?
Answer	- Joint visit on site of the manager and the UGE (Nantes Center) - Presentation of the bridge documentation by the manager to the Technical Committee - Analysis and control of documents by the RST within the framework of the Technical Committee
9) Testing.	a. What type of physical testing was conducted to support the investigation?
Answer	Endoscopy Dismantling of the tendon and visual examination or by microscope (optical and SEM) in the laboratory (fractographic analysis, measurement of section losses by corrosion, counting of breaks, etc.). Guided Ultrasonic Wave Reflectometry (USCAN) for examination of other anchor heads. Acoustic monitoring of prestressing tendons Ultra-fast camera during the (man-made) induced rupture of an external tendon to verify the effectiveness of the strapping of tendons and their modelled behaviour during the rupture.
	b. If standardized test methods were not used, why not?
Answer	No such method is standardized.
	c. How was test data stored and documented?
Answer	- Laboratory tests: report from the UGE (Nantes center) - Endoscopy of the receptacle: report from SIXENSE (CONCRETE Nantes)

Case : *Ré Island Bridge*	
	- USCAN and acoustic emission reports by SIXENSE- SYSTEMS - Analysis of USCAN data coordinated between the UGE (Nantes Center) and SIXENSE-SYSTEMS - Ultra fast camera: film by Freyssinet + STRAINS analysis. All reports have been submitted to the manager.
10) Experimentation.	If experimental testing was conducted, please summarize the need, describe the experiments, and outline how the results were used.
Answer	« Surveillance acoustique des câbles : Guide méthodologique du système CASC » – LPC - BRUHAT, Daniel , GAILLET, Laurent , LE CAM, Vincent , MICHEL, Richard , TESSIER, Christian - Techniques et méthodes des laboratoires des ponts et chaussées, Guide technique ACOUSCAB - 35p – 2012 « Surveillance acoustique des câbles : Guide pour la maîtrise d'ouvrage ». – Y. Gautier, J. Dumoulin – Techniques et méthodes des laboratoires des ponts et chaussées, Guide technique CASC2 – 23p – 2013. Fiches du Cahier Interactif Auscultation des Ouvrages d'Art : B-5-3 : « Surveillance acoustique des câbles » B-5-7 : « Réflectométrie ultrasonore par ondes guidées » C-1-5 : « Endoscopie (Application à la recherche de vide ou de zones corrodées dans les conduits de précontrainte). » E-2-4 : « Diagnostic de la précontrainte extérieure protégée par du coulis de ciment au contact des armatures » Results used by the Technical Committee to propose actions to the manager of the bridge.
11) Bridge files and records.	a. What records (design, fabrication, construction, inspection, etc.) of bridge were collected to support the investigation, and how where they reviewed?
Answer	The whole bridge's documentation (design, manufacture, construction, inspection, etc.) was made available to the Technical Committee, which obtained the necessary information (construction weekly reports, drawings, calculation notes, etc.).
12) Analyses.	What type of analysis or modeling tools (engineering calculation, structural analysis, finite element modeling, others) were used to support the investigation and describe their use?
Answer	Use of PCP software by Cerema.

Case : *Ré Island Bridge*	
	Use of structural calculation software, finite element calculation software and a specific calculation program to recalculate the structure in different degraded prestressing configurations and to identify different critical points, as well as to model the whipping of prestressing tendons after breakage.
13) Lessons learned.	a. With regard to the cause of failure, what were the findings of the investigation?
Answer	Corrosion of the strands behind the anchor is the cause of the rupture. The results of the failure assessment by the UGE helped explain the failure process: 1. Rupture during construction of a weld between the HDPE sheath and the trumpet at the anchor. 2. Leak that appeared during the leak tightness tests of the ducts at construction (documented in the bridge weekly reports). 3. Injection of polyurethane foam between the sheath and the concrete to plug the leak, from the injection vents 4. Penetration of the foam inside the sheath. 5. The foam hampered the progress of the grout during injection, absorbed water from the grout and caused segregation of the grout and the development of a very basic humid environment (pH 13.2 to 13.5) allowing corrosion of the wires over a long time. (Formation of a cement grout / PU foam amalgam). The composition of the grout is not in question and no chloride was detected.
	b. What lessons learned were derived from the findings?
Answer	It is therefore an unprecedented corrosion process due to the injection of polyurethane foam in an attempt to stop cement grout leaks during construction. This foam injection operation was carried out on a large number of external prestressing tendons of this bridge. This obviously poses the problem of ensuring the safety of people working inside the box girder and of the investigations to be carried out to assess the state of conservation of the other tendons of this bridge in order to decide on repair actions. For the first time in France, the technique of transversely strapping tendons between them to prevent their whipping was tested during an induced tendon break. The test took place after the design and calculation of the strapping by the STRAINS company with an ad-hoc software. After observation, it appeared that the transverse strapping had to be supplemented by a longitudinal strapping (type cargo net) at the ends of the tendons and at the level of the deviators to better contain the formation of a tendon loop.

Case : *Ré Island Bridge*	
Answer	In addition, it is essential to trace any non-compliance in order to approve each repair procedure.
	c. How were the lessons learned communicated to the bridge engineering, construction and inspection communities?
Answer	Modification in November 2018 of the Note n ° 3 of CEREMA “Awareness note on existing structures with external prestressing” in order to incorporate this case of possible failure. Presentation by Pierre-Marie AUDOUIN-DUBREUIL at LE PONT 2019 Colloquium in Toulouse: "Tendon break at the Ile de Ré bridge" IMGC / AFGC Technical Day on the Durability of External Prestressing (September 2019) at the FNTP Organization of a seminar on 02/05/2020 in La Rochelle “Experience feedback from external prestressing”, bringing together the main French experts in prestressing. Publication of the following article to IABSE: B. GODART, L. GAILLET, L. VAN SCHOORS, L. LABOURIE, D. GERMAIN, B. VAURIGAUD (2021) - Recent failures of external prestressing grouted tendons: the paramount role of the HDPE duct. IABSE Congress, Christchurch, February 3-5. RMC Discovery film on the Ile de Ré bridge (November 2020).
	d. Describe any changes to the state of practice resulting from the lessons learned.
Answer	One should move towards a ban on injecting polyurethane foam to plug any leaks, but it should be noted that, with the improvement of the technology of external prestressing since the construction of this bridge in 1988, this type of defect is no longer found on recent structures. In addition, each repair procedure must be shared and validated before execution.
	e. Identify any challenges the resulted from the process or procedure used to conduct the investigation, and any recommended changes to the approach or methodology used to address those challenges or otherwise result in improvements.

Case : *Ré Island Bridge*	
Answer	Visual analysis of the anchor heads revealed a frequent but not systematic recourse to the use of polyurethane foam. Given the thickness of the anchor blocks, it is not possible to detect the presence of foam in the duct and in the anchorage. Also, we are trying to assess the progress of corrosion due to the presence of this foam. Acoustic monitoring allows good detection of wire breaks and their location. Thus, it makes it possible to determine whether a tendon is in a dynamic breaking. On the other hand, it is essential to determine at the start of the acoustic monitoring the state of the anchor heads, in order to know whether we are at the start of a corrosion process or on the contrary close to a fatal rupture. Based on the 4 disassembled anchorage heads, the USCAN guided ultrasonic wave reflectometry device allows to predict whether the strand wires at the head are in good condition or show corrosion. It does not yet give an accurate result of the extent of corrosion and does not detect with sufficient precision the number of broken wires to have a reliable condition of conservation of the anchor heads. The planned dismantling of the next 3 tendons, 2 of which have a head estimated to be heavily corroded, will allow more sampling to improve the calibration and performance of the USCAN process. In addition, the external prestressing technology with greased sheathed strands (TGG) (considered as an improvement of the technology of clear strands used for the construction of the bridge), makes it possible to reach 85 to 90% of the original tension, given the congestion of TGGs in existing reservations. Depending on the number of tendons replaced, this constraint will potentially requires the use of specific solutions to maintain the current load carrying capacity of the structure.
14) Other impacts on the investigation.	a. If there was a need for a timely repair to address a long detour or simply the restoration of service, please describe how that need impacted the decisions made or process used for the investigation.
Answer	The Ré Island bridge connects the island to the mainland. There is no possible alternative route. It is impossible to cut off traffic for more than a few hours at night and if the cut must be complete, this requires the establishment of medical and rescue teams on the island. In addition, all the networks supplying the island with electricity, water and telephone pass through the box girder of the bridge in the immediate vicinity of the prestressing tendons.

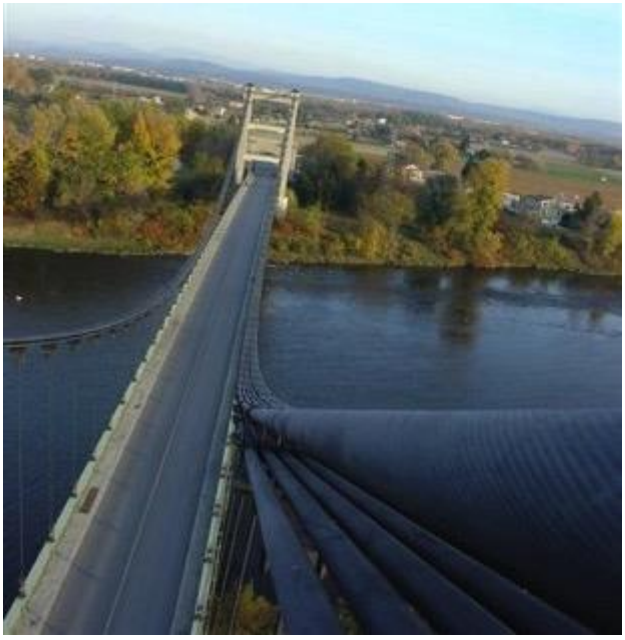
Case : *Ré Island Bridge*	
Answer	It is therefore essential to carry out almost all of the work under circulation. As a result, the only possible entrances into the bridge are through the abutments; these constraints require manual supply on site to replace the tendons. The broken tendon being in the middle of viaduct No. 2, this required securing by strapping and the installation of acoustic monitoring on all tendons between the abutment and the working site, ie nearly a third of the bridge. Simultaneously and prior to the disassembly and replacement of the broken tendon, all the anchor heads were analysed by the USCAN process to determine the ones that were corroded.
	b. Please describe how financial considerations (potential cost of the investigation, cost to the traveling public, cost of the repair, etc.) impacted the decisions made or process used for the investigation.
Answer	The priority of the Charente-Maritime Department, owner and operator of the Ré bridge, is the permanent maintenance of all the functionalities of this structure, both for transit and for the supply networks of the Ré Island. As a result, the financial criterion for urgent or safeguard repairs only comes second. Thus, the Department did not hesitate, in order to guard against the consequences of a new tendon break at: - set up a temporary internal structure at the half joint between viaducts 1 and 2, in order to replace a faulty tendon. - initiate the replacement of strategic tendons at this location. - reinforce deviators liable to be destabilized by re-anchoring of a tendon when it breaks at one of its heads. Given the very high cost of replacing a tendon, the Department cannot preventively replace all of the 218 tendons constituting the external prestressing of the Ré bridge. He wants to replace those showing significant corrosion or those of a strategic nature for maintaining the bridge in service. In order to continuously monitor the progress of corrosion in the tendons, it was decided to carry out a preliminary diagnosis of all the anchor heads throughout the bridge, associated with acoustic monitoring of the tendons. Subject to improving the performance of the methods for analyzing the state of corrosion of anchor heads, a program to replace the most damaged tendons will be implemented with, as a safety measure, reinforcement of the half-joints and all deviators. In order to minimize any impact on traffic, the tendons anchored in the half-joints will be systematically replaced, due to the lack of redundancy.

Case : *Ré Island Bridge*	
Answer	On this occasion, additional work is carried out: change of the bearings in the half-joints, strengthening by composite materials of the webs of the female segment of each half-joint in order to take advantage of the accessibility and structural advantages of the temporary reinforcements put in place.
	c. Please describe any additional considerations or risks that impacted how the investigation was conducted and what those impacts were.
Answer	The only possible entrances into the caissons of the Ré bridge are a service door in each abutment and a manhole in the middle of each of the 6 viaducts located under the roadway. The lack of an alternative road makes it impossible to cut off traffic for more than a few hours at night. Each cut also requires the implementation of very significant police and civil protection resources in order to maintain the safety of the inhabitants of the island. It is also very difficult, except during nocturnal periods, to set up a traffic alternate in order to open manholes without generating, due to the traffic, very heavy traffic jams. These operating constraints require access to damaged tendons only through the abutment on the Ré island side, and thus exclusively manual supply and therefore permanent displacements of workers in the immediate vicinity of the prestressing tendons. Spontaneous tendon breakage in the presence of people working inside the bridge presents a major risk to their safety. To minimize this risk, it was decided before replacing the broken tendon, to install a strapping of all the prestressing tendons in order to limit the consequences of whipping in the event of a possible new rupture of a tendon. This strapping was implemented from the abutment on the Ré island side when moving up to the broken tendon. Simultaneously, and also in progress, an acoustic monitoring device was installed and all anchor heads were analyzed by the USCAN process. A similar safety procedure will be used when work will be done on the 4 other viaducts of the bridge.

8.10. Case Study 9: France Suspension Cable Failure

<table>
<tr><th colspan="2">Case : Teil Suspension Bridge</th></tr>
<tr><td>1) Brief description of the bridge (type, material, year of construction, …</td><td>Provide a short description of the bridge including bridge type, material (steel, reinforced concrete, prestressed concrete, timber, masonry, …), year of construction, span lengths, …</td></tr>
<tr><td>Answer</td><td>The Teil suspension bridge in France, built between 1947 and 1949, crosses the Rhône. With a total length of 317 metres, it consists of a central suspended span of 235 metres and two isostatic spans of 41 metres each. The structure has a roadway of 6.5 metres and two sidewalks of 1.15 m each.

Main cables rest on 2 articulated pylons and are anchored at the ends of the structure. In way of the central span, the 16 cables of each strip are organized into two half strips of 8 cables.

The 32 main cables, each with an external diameter of 82 mm, consist of 217 wires. The retaining cables, located only in the edge span, with an external diameter of 61 mm, consist of 157 wires each. The suspension lines consist of either two full bar bars with 39 mm diameter (15 short lines), or 47 mm diameter cables with 80 wires (28 long lines).</td></tr>
<tr><td>Picture of the bridge</td><td>
</td></tr>
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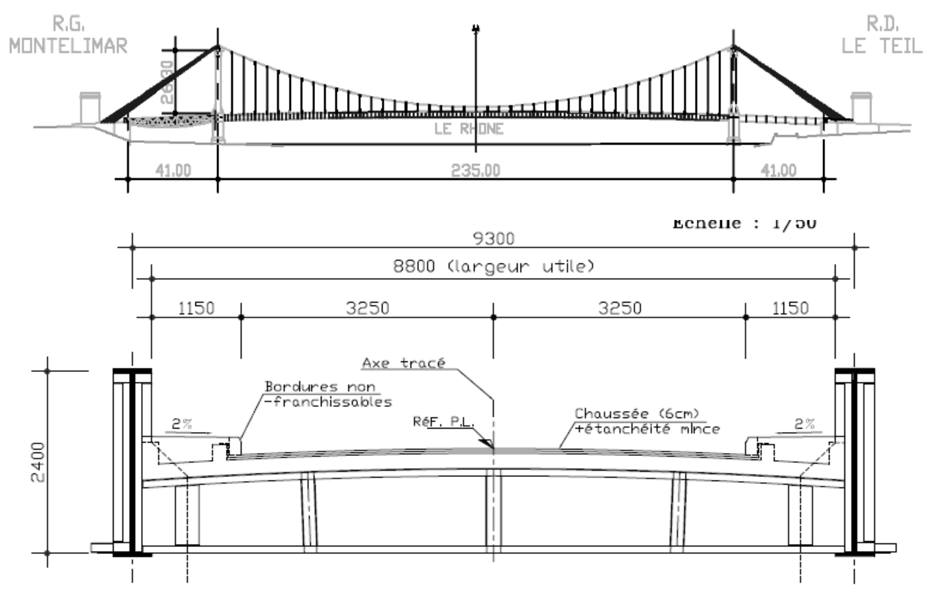
<table>
<tr><th colspan="2">Case : Teil Suspension Bridge</th></tr>
<tr><td></td><td>
</td></tr>
<tr><td>2) Description of the failure.</td><td>Provide a detailed description of the failure. Include sufficient relevant context to support the failure being unanticipated or producing unexpected performance.</td></tr>
<tr><td>Answer</td><td>On 11 September 2007, a failure in a main cable carrying the structure at an anchor base was observed.</td></tr>
<tr><td>Picture of the failure</td><td>
</td></tr>
<tr><td>3) Investigating organization.</td><td>If one or more specific agency or institution has the responsibility to investigate bridge failures in your country, please name them and describe their authorities.</td></tr>
</table>

<table>
<tr><th colspan="2">Case : Teil Suspension Bridge</th></tr>
<tr><td>Answer</td><td> At the level of the Ministry of Transport, there is an Office for Investigations on Land Transport Accident (BEA-TT) which is responsible for carrying out technical investigations on land transport accidents and incidents, whether road, rail, river or guided. It was commissioned in 2004, by a decree implementing a law passed in 2002 following the fire in the Mont-Blanc tunnel. In the event of a serious failure (bridge collapse for example) an administrative investigation may be opened, at the discretion of the Minister of Transport. As Teil bridge is part of the national road network, the State has commissioned the technical bodies of the Ministry in charge of Transport (CEREMA, UGE – ex-LCPC) to carry out the missions of expertise and technical assistance for the phases of repair studies and works. A committee of experts from the Ministry sat from the time of the incident until the definition of the final repair program. </td></tr>
<tr><td>4) Legal constraints.</td><td>If there are legal constraints on the transparency or process of a bridge failure investigation in your country, please describe those.</td></tr>
<tr><td>Answer</td><td> There is no legislation that regulates the investigation of a bridge failure. Nevertheless, the legal authorities in France intervene at several levels: criminal court (tribunal pénal) when there are dead people: unequivocal expertise then forwarded to the investigating judge;
district or high court (tribunal d’instance ou de grande instance): contradictory expertise;
To settle contractual disputes: administrative tribunal within the framework of public tenders, or commercial tribunal for disputes between private companies. When the different courts intervene, they appoint experts accredited to the respective courts and who conduct the investigations process; these investigations are then carried out within the framework of the secrecy of the judicial investigation, as long as the judgment is not pronounced. In the event of a major failure of bridges managed by the French State, the Ministry of Transport is in the habit of setting up technical committees bringing together agents of the manager of the structure and experts from CEREMA and the University Gustave Eiffel. (ex-IFSTTAR). These committees are chaired by a General Engineer. This organization is desirable when there is a major failure. It is set up by other managers such as private motorway companies or local authorities. </td></tr>
<tr><td>5) Investigative process.</td><td>Please describe how the investigation was conducted. If a standardized and documented process or procedure was used to guide or inform the investigation, please also describe it here and include a copy with your response.</td></tr>
</table>

Case : *Teil Suspension Bridge*	
Answer	There was no formal standardized process in France to conduct the investigation. In this case, the investigations were defined to meet several objectives. Some investigations were essential to gather the information needed to repair the structure. Other studies have been carried out to assess their ability to give results for the diagnosis of this type of pathology. The investigations focused on: • the phenomena leading to the rupture, • the extent of this defect on the work, • the condition of the cables and suspension lines as a whole, • the condition of the structure and deck in particular. The purpose of these investigations, in addition to understanding the origin of the incident, is to verify the extent of the repairs to be undertaken and to verify the oppotunity of the repair.
6) Organizational structure.	Describe the organizational structure used by the investigators.
Answer	The owner is the State (DIRCE) The investigations (auscultations and recalculations) were conducted by CEREMA, the Gustave Eiffel University. The repair work was carried out by the company Baudin Chateauneuf.
7) Investigator qualifications.	Describe the qualifications of those involved in the investigation. Education, licensing, training, experience, etc.
Answer	Civil Engineers, Researcher, Research Director, Lecturer, University Professor, Senior Technicians. CEREMA and UGE experts qualified by the "Bridge Domain Committee" which reports to the Research and Innovation Service of the Ministry of Transport. Researchers qualified by the Researchers Evaluation Committee (CEVAL) of the Ministry of Ecology and Transport. Lecturer, University Professor qualified by the National Council of Universities (CNU). Experts, specialists qualified internally by private organizations after possible external evaluation.
8) Investigation documentation.	a. Describe how the failure was documented on-site?
Answer	There was no documentation on site.
	b. How was physical evidence collected, documented and controlled?
Answer	The first concern being to understand the origin of this failure and to assess the risk of similar failure in the other cap assemblies, visual inspections with and without disassembly were completed by non-destructive but sometimes invasive investigations.

Case : *Teil Suspension Bridge*	
	Reports were produced for each investigation, analysis or test.
9) Testing.	a. What type of physical testing was conducted to support the investigation?
Answer	The 2 anchorages of the broken cable were analyzed in the laboratory (the pathological anchorage, and the opposite anchorage). For anchorages still in place on the structure, the cable entry area in the anchorage has been cleaned to check the presence of the zinc ring that is formed during the cable entry and examine the condition of the wires prior to entry into the anchorage. In cases where this ring did not exist, the condition of the wires in the anchor was examined to the extent possible (over a few centimetres). Further tests were conducted on the anchorages: • perforation and endoscopy: inconclusive observations • impact-echo: Inconclusive observations • Ultrasound for wire rupture: Inconclusive observations • Acoustic emission: The aim was to try to compare cables presumed healthy and damaged between them. The results appeared to show significant differences in frequency distribution and salve amplitudes. The cables were also tested: • visual inspection of broken cable • metallographic and chemical analysis of cable wires • mechanical testing of cable wires • in situ electromagnetic campaign of main cables
	b. If standardized test methods were not used, why not?
Answer	Tests used are not standardized. Some have been carried out in the exploratory phase, in particular because the origin area of the failure in the anchorage is very difficult to investigate by non-destructive physical measures.
	c. How was test data stored and documented?
Answer	The results have been documented in reports.
10) Experimentation.	If experimental testing was conducted, please summarize the need, describe the experiments, and outline how the results were used.
Answer	At the time of the investigations, there were no operating procedures. Today, a website collects established procedures: These are the Worksheets of the Interactive Review of Bridges (Gustave Eiffel University and CEREMA). For example: B-5-3: Acoustic Cable Monitoring B-5-7: Ultrasonic guided wave reflectometry C-1-5: Endoscopy (Application for searching for vacuum and/or corroded areas in prestressing ducts)
11) Bridge files and records.	a. What records (design, fabrication, construction, inspection, etc.) of bridge were collected to support the investigation, and how where they reviewed?
Answer	The entire file of the bridge is available.

<table>
<tr><th colspan="2">Case : Teil Suspension Bridge</th></tr>
<tr><td>12) Analyses.</td><td>What type of analysis or modeling tools (engineering calculation, structural analysis, finite element modeling, others) were used to support the investigation and describe their use?</td></tr>
<tr><td>Answer</td><td>Diagnostic studies were also conducted to:
check the stability of the work without and under circulation after the cable breaks,
check the opportunity of repairing the work.
The first approach was to recalculate the safety coefficients of the structure in degraded mode.

In a second phase, a study of the fatigue resistance of the suspended span (excluding cable) was carried out.</td></tr>
<tr><td>13) Lessons learned.</td><td>a. With regard to the cause of failure, what were the findings of the investigation?</td></tr>
<tr><td>Answer</td><td>Very quickly, it was decided:
not open the structure to road traffic without reinforcement,
allow pedestrian traffic on the structure and road traffic on the track being crossed after securing the structure (high surveillance and cable whip protection).
Then, temporary repair work was carried out to relieve the stress in the anchorage bases of the cables.

Finally, definitive work involved replacing the all main cables.</td></tr>
<tr><td></td><td>b. What lessons learned were derived from the findings?</td></tr>
<tr><td>Answer</td><td>This is a conventional corrosion process.

This failure allowed us to explore new methods of investigation, to choose new cables made of galvanized and painted wires, more durable over time.</td></tr>
<tr><td></td><td>c. How were the lessons learned communicated to the bridge engineering, construction and inspection communities?</td></tr>
<tr><td>Answer</td><td>Several presentations in France and internationally were made.

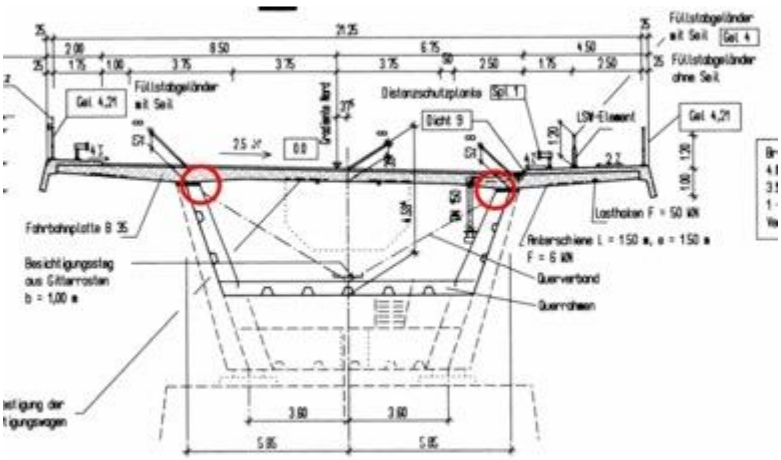
IABMAS 2012, Bridge Characterization and Structural Health Monitoring: A suspension case study

TRB 2015, Damage Characterization and Rehabilitation of the Teil Bridge, Ardèche, France</td></tr>
<tr><td></td><td>d. Describe any changes to the state of practice resulting from the lessons learned.</td></tr>
<tr><td>Answer</td><td></td></tr>
<tr><td></td><td>e. Identify any challenges the resulted from the process or procedure used to conduct the investigation, and any recommended changes to the approach or methodology used to address those challenges or otherwise result in improvements.</td></tr>
<tr><td>Answer</td><td></td></tr>
</table>

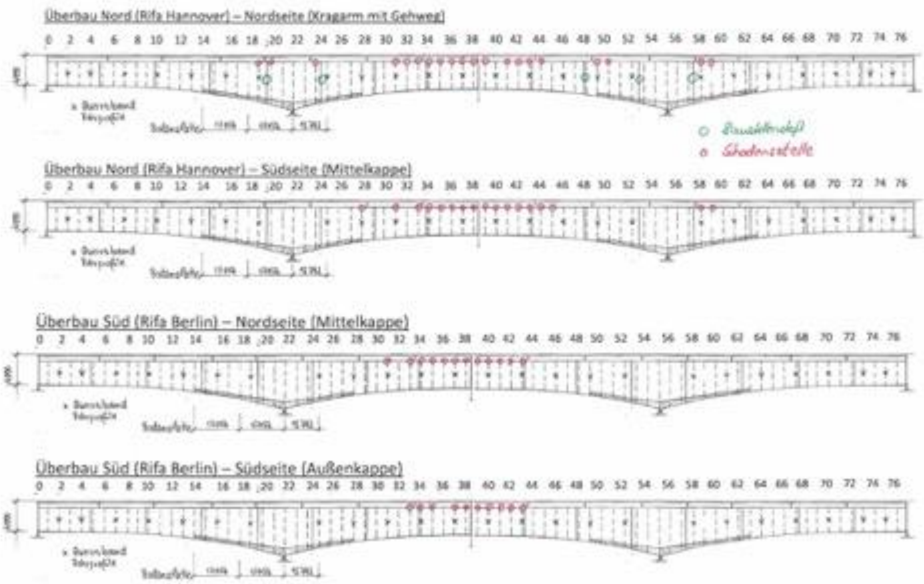
Case : *Teil Suspension Bridge*	
14) Other impacts on the investigation.	a. If there was a need for a timely repair to address a long detour or simply the restoration of service, please describe how that need impacted the decisions made or process used for the investigation.
Answer	The work was stopped for over a year. A deviation was put in place with a river crossing about 10 km north.
	b. Please describe how financial considerations (potential cost of the investigation, cost to the traveling public, cost of the repair, etc.) impacted the decisions made or process used for the investigation.
Answer	The work had to be put back into circulation as quickly as possible because there are few crossings on the river.
	c. Please describe any additional considerations or risks that impacted how the investigation was conducted and what those impacts were.
Answer	

8.11. Case Study 10: Germany Box Girder Fatigue Damage

Case : *Bridge over the river Elbe in Hohenwarthe*	
1) Brief description of the bridge (type, material, year of construction, …	Provide a short description of the bridge including bridge type, material (steel, reinforced concrete, prestressed concrete, timber, masonry, …), year of construction, span lengths, …
Answer	Name: *Hohenwarthe Elbe bridge* Location: Hohenwarthe in Saxony-Anhalt, Germany Total span: 1,170.41 m Foreshore bridge: prestressed concrete bridge, span: 832.2 m Separating pile: concrete frame, span 11.5 m River bridge: Steel with orthotropic deck plate, span: 326.71 m Individual bridge structures for every direction Width between the railings: 21.25 m and 18.75 m Load model: BK 60/30 (DIN 1072) Construction year: 1994-1997 2015: 67,136 adt/24 hours 2015: 14,025 HGVT/24 hours
Picture of the bridge	

Case : *Bridge over the river Elbe in Hohenwarthe*	
	
2) Description of the failure.	Provide a detailed description of the failure. Include sufficient relevant context to support the failure being unanticipated or producing unexpected performance.
Answer	Inspection of 2 September 2014: - circumferential fillet welds of the connection between the stiffener of the cross girder and the upper flange are cracked in many places - cracks of 1m length and 2mm width in the weld at some areas in the connection of the longitudinal weld of the upper flange to the upper flange reinforcement (red circles in the 1st picture) - both directions - extensive damage - similar damage dimension in both parts of the structure - above all, damages at the centre of the span (red circles in the 2nd photo) 

Case : *Bridge over the river Elbe in Hohenwarthe*



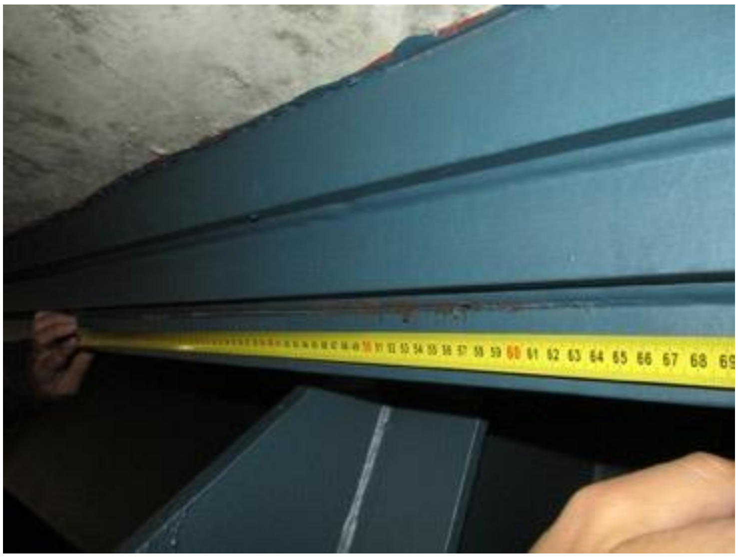
Füllstabgeländer = handrail
mit Seil = with cable
ohne Seil = without cable
Fahrbahnplatte = upper deck plate
Besichtigungssteg auf Gitterrosten = inspection way with grids
Distanzschutzplanke = guardrail

The immediate repair of the damaged areas was done with conventional grinding and re-welding, completed in December 2014. (This measure was not intended to stop the predicted spread of the damage, but to reduce the dimension of the existing damage. The aim was to gain time to determine the cause of the damage.) In the context of monthly special inspections with visual and magnetic particle testing, first new cracks on previously undamaged welds and re-welded welds were already detected in March 2015.

Since the cause of the damage was unclear and in order to determine useful repair options, an expert opinion was commissioned in July 2015, which was available in March 2016.

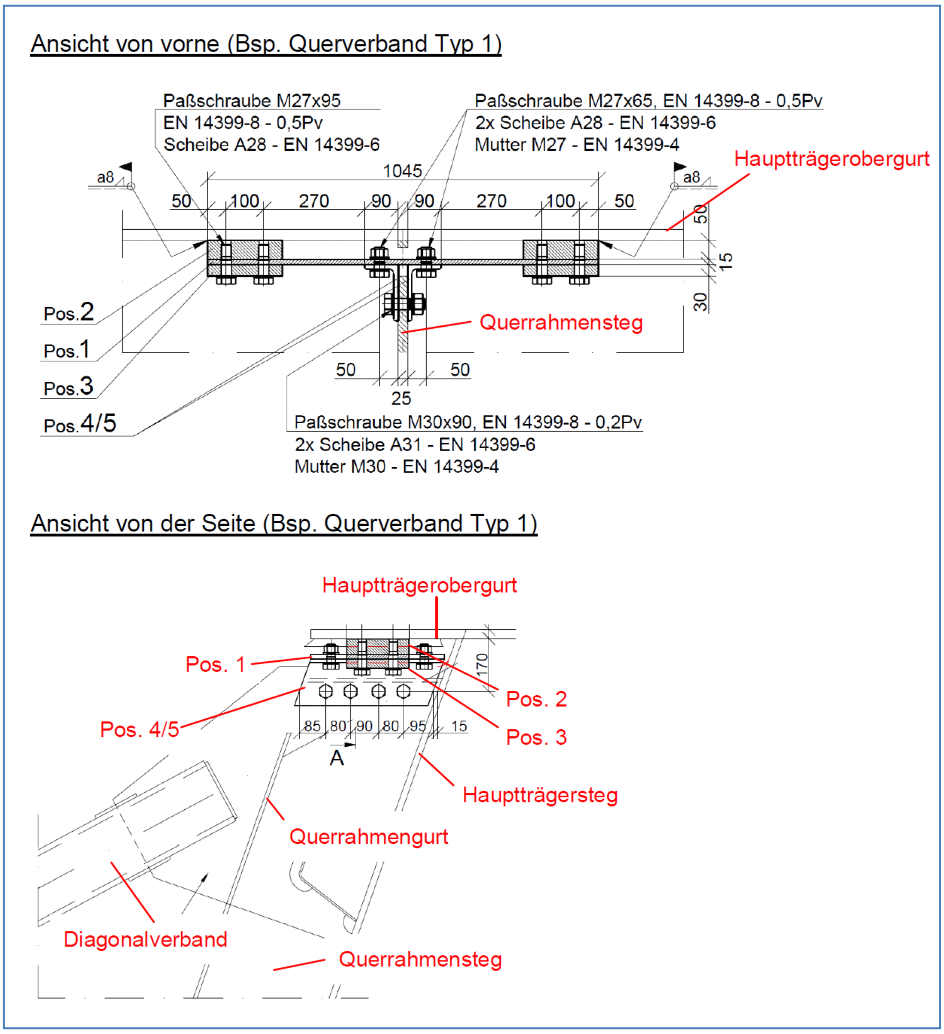
Based on investigations and calculations by experts it was shown that the weld cracks resulted from considerable fatigue action effects in the cross frame joints induced by transverse bending due to the traffic effects, which, in accordance with then applicable provisions, the cross frame joints were not made for. In addition, the formwork carriage supports, cemented in the cross frame and necessary for the structure, were decisive for the damage on the Hohenwarthe Elbe bridge. Due to unplanned composite effects, they strengthen the clamping and thus the transfer of shear and transverse bending loadings from the roadway slab to the transverse frames of the main box section.

Case : *Bridge over the river Elbe in Hohenwarthe*	
	The expert considered the regravelling from 2012/2013 to be the main raison for the timing of the damage as well as for its development. According to the calculations, the heat impact during the construction of the coating most likely led to plasticising of the welding at the connections. Consequently, it is probable that the cracks occurred in the pre-damaged welds due to the significant, construction-related heat impact on the roadway slab, which had not been sufficiently regulated in terms of standards. In summary, it can be said that the existing cross frame joints to the top chords of the main girders of the existing superstructures are not sufficiently fatigue-resistant and durable. Even with the traditional "grinding and re-welding“ weld repair procedures, the joints cannot be sustainably repaired. Therefore, a regeneration strategy was drafted. The idea is that the upper connections to the upper chords are separated and the thrust forces transferred to the upper chord alternatively via a bending plate that is flexible in vertical direction.
	In an expert opinion, the refurbishment of the top chord points of the cross frame was preferred. In order to avoid possible damage from the bottom joints of the formwork carriage supports, the roadway slab was opened in certain areas with hydroblasting, two formwork carriage supports were made accessible and the weld points at the joint were investigated by visual inspection and magnetic particle testing. Considering that inspections in the areas were only possible to a certain extend due to the partially very difficult access, no indications for fatigue cracks were found. In the course of further structural inspections, the situation of the steel top flange and the concrete slab at the joint is to be reviewed. At first, the refurbishment was tested on four joints with corresponding measuring ongoing, before the refurbishment of the other joints was done. The repair of the top flange joints is done by cutting the connections of the transverse stiffeners and their chords to the top chord of the main girder. To relieve the top flange joints, a “hinge” is created so that no significant moments due to transverse bending of the slab can be transferred via the connection. The hinge effect is achieved by inserting a thin spring plate (bending plate) into the slit between the top flange and the transverse stiffener, connecting it by screws to the top flange in a shear-resistant manner using spacer and lining plates. The spring plate is connected to the transverse stiffener (web of transverse frame) using angle profiles. The bending flexibility of the spring plate ensures that it absorbs the greatest possible rotation. In the process of repair of the upper flange joints, the welding at the transverse stiffeners and upper flanges are also strengthened.

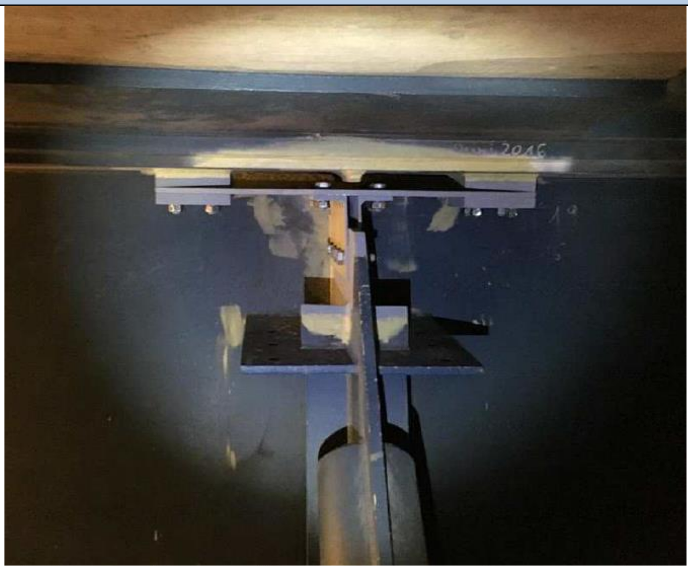
Case : *Bridge over the river Elbe in Hohenwarthe*	
	In order to avoid local plate bending of the main girder web in the area of the free cut during the construction process, temporary bracket plates are connected from outside, which transfer the released horizontal forces from eccentric traffic loading into the transverse frames in a controlled manner. After the repair of the joint, the horizontal loads are taken up by these joints and the bracket plates can be removed. Subsequently and after analysing the four test joints, starting in 2020, the refurbishment of the remaining areas is done. During the construction work, the traffic on the respective structure is limited to two lanes. The vehicles may use the centre of the roadway slab to minimise torsional stress.
Picture of the failure	 

Case : *Bridge over the river Elbe in Hohenwarthe*

Final state after the refurbishment:



Case : *Bridge over the river Elbe in Hohenwarthe*	
	Ansicht von vorne = front view Bsp. Querverband Typ 1 = ex. transverse brace Type 1 Paßschraube = fitting screw Scheibe = disk Mutter = nut Hauptträgerobergurt = main girder top chord Querrahmensteg = cross frame web Ansicht von der Seite = side view Hauptträgersteg = main girder web Querrahmengurt = cross frame chord Diagonalverband = diagonal frame
	 

Case : *Bridge over the river Elbe in Hohenwarthe*	
	
3) Investigating organization.	If one or more specific agency or institution has the responsibility to investigate bridge failures in your country, please name them and describe their authorities.
Answer	In Germany, the federal states are responsible for construction, maintenance and control of federal trunk roads. They are also responsible for guaranteeing the obligation to ensure traffic safety. There is a competent authority in every federal state that takes care of all matters related to engineering structures along the federal trunk roads. However, starting 1 January 2021, a dedicated corporation will be responsible for the motorways.
4) Legal constraints.	If there are legal constraints on the transparency or process of a bridge failure investigation in your country, please describe those.
Answer	If there are people injured the public prosecutor will take over. They appoint experts to examine the failure. This will be the basis for any further investigations. If massive and unexpected damage is detected during the inspection of a structure, Section 4 of the Federal Trunk Roads Act applies, stipulating the obligation to ensure traffic safety. Depending on the dimension and severity of the damage, this requirement can be met directly by the maintenance depots. Otherwise, the transport authorities are responsible for ordering traffic constraints with the purpose of protection that can even include closures, if necessary. The further process is also stipulated in Section 4 of the Federal Trunk Roads Act: structures need to meet the requirements of safety and security. The competent authority then initiates the necessary measures.
5) Investigative process.	Please describe how the investigation was conducted. If a standardized and documented process or procedure was used to guide or inform the

Case : *Bridge over the river Elbe in Hohenwarthe*	
	investigation, please also describe it here and include a copy with your response.
Answer	In order to guarantee the stability and durability of the civil engineering structures and to ensure road safety for the users (vehicles, cyclists, pedestrians, etc.), inspections of the structure need to be carried out regularly. The details are regulated in standard DIN 1076 "Engineering structures in connection with roads - inspection and test".
6) Organizational structure.	Describe the organizational structure used by the investigators.
Answer	The results of the inspections form the basis for decisions taken in the context of the maintenance management of the road construction authorities of Saxony-Anhalt. In order to ensure harmonised and quality-assured inspections of the structures, in addition to DIN 1076, the "Guidelines for the Uniform Documentation, Assessment, Recording and Evaluation of the Findings of Structural Inspections in Accordance with DIN 1076 (Ri-Ebw-Prüf)" apply.
7) Investigator qualifications.	Describe the qualifications of those involved in the investigation. Education, licensing, training, experience, etc.
Answer	Inspections of a structure are carried out only by professional civil engineers with many years of experience and a certification updated every 6 years by the Association for Promoting Quality in Education and Training for Inspection Engineers (VFIB) (https://www.vfib-ev.de/english/)
8) Investigation documentation.	a. Describe how the failure was documented on-site?
Answer	Inspection of a structure in accordance with DIN 1076 + expert opinion + object-related damage analysis
	b. How was physical evidence collected, documented and controlled?
Answer	In a structure inspection report in accordance with DIN 1076.
9) Testing.	a. What type of physical testing was conducted to support the investigation?
Answer	Magnetic particle testing
	b. If standardized test methods were not used, why not?
Answer	

Case : *Bridge over the river Elbe in Hohenwarthe*	
	c. How was test data stored and documented?
Answer	Expert opinion and structure inspection report have been uploaded to Road Information Database, Subsystem on Structural Data.
10) Experimentation.	If experimental testing was conducted, please summarize the need, describe the experiments, and outline how the results were used.
Answer	
11) Bridge files and records.	What records (design, fabrication, construction, inspection, etc.) of bridge were collected to support the investigation, and how where they reviewed?
Answer	Structure inspection reports, as built documentation, structure logs, site logs, static documents.
12) Analyses.	What type of analysis or modeling tools (engineering calculation, structural analysis, finite element modeling, others) were used to support the investigation and describe their use?
Answer	The structure was inspected in mathematical terms on the basis of a comprehensive 3D model. The modelling was carried out on the basis of real cross-sections and dimensions, including the formwork carriage supports. The effects of several different load combinations were investigated.
13) Lessons learned.	a. With regard to the cause of failure, what were the findings of the investigation?
Answer	According to the prepared expert opinion, the following reasons have been identified to be responsible for the cracks: 1) During the construction of the structure, first, the steel components for the box girder were produced and brought into position. To transfer the loads from the formwork carriages required for concreting, steel girders made of double-T sections were welded on the top of the steel flanges at the positions of the transverse frames. These were shortened later, but are mostly concreted into the roadway slab.

Case : *Bridge over the river Elbe in Hohenwarthe*

Based on code assumptions, the structural analysis of the structure assumes hinges between the box girder and the concrete slab. In practice, this assumption cannot be confirmed, because when the steel profiles are set in concrete, there is a rigid joint that can absorb high loadings (moments).

2) In order to keep the roadway slab as slim as possible (d= approx. 40 cm), it was prestressed diagonally.

This leads to considerable creep and shrinkage effects in the roadway slab and thus to its shortening. As a result, constraining stresses occur at the upper corners of the box girder.

3) The renewal of the roadway slab in the summer of 2013, which was considered an unusual event, also played a role for the occurred damage. The temperature with which the material was applied created significant tensions in the roadway slab. Corresponding load assumptions were not taken into account for the original static calculation of the structure. Due to the unequal distribution of temperature in the roadway slab, the roadway slab tries to bulge out. Additional stresses occur in the upper connections of the transverse frames. The thereby induced forces are probably not the main reason for the damage, yet they may have been the reason for visible cracks in the pre-damaged areas and for the acceleration of the damage development. This also explains why no cracks were visible during structure inspections before 2014.

Case : *Bridge over the river Elbe in Hohenwarthe*	
	
	b. What lessons learned were derived from the findings?
Answer	That calculation assumptions and implementation should match. That it is a good idea to plan and construct structures in a way that all areas can be inspected easily and quickly. Particularly for steel bridges, a light inner coating is useful.
	c. How were the lessons learned communicated to the bridge engineering, construction and inspection communities?
Answer	When constructing the upper connections, the guidance of the Federal Ministry of Transport and Digital Infrastructure from 26 April 2016 (letter from the Federal Ministry of Transport and Digital Infrastructure to the federal states) needs to be taken into account. Presentations, meetings between federal states and federation, technical committees, standardisation committee
	d. Describe any changes to the state of practice resulting from the lessons learned.
Answer	The regulations in DIN EN 1994-2 (NA) and DIN EN 1993-1-9 (NA) for large bridges of this kind have been updated. RE-ING 2-2 No. 1.4.1 (7) – formwork carriages lying on the bottom RE-ING 2-2 Annex A QRA 1, page 1 and 2 (standardised cross frame points of composite bridges with open box girder) ZTV-ING 4-3 (light inner coating of steel box girders)

Case : *Bridge over the river Elbe in Hohenwarthe*	
	Research project on the effects of temperature in bituminisation processes (not yet completed) - is to be included in standardisation Research project on clamping of roadway slabs in the area of cross bracing of composite steel bridges (not yet completed) - to be included in standardisation and/or regulations
	e. Identify any challenges the resulted from the process or procedure used to conduct the investigation, and any recommended changes to the approach or methodology used to address those challenges or otherwise result in improvements.
Answer	
14) Other impacts on the investigation.	a. If there was a need for a timely repair to address a long detour or simply the restoration of service, please describe how that need impacted the decisions made or process used for the investigation.
Answer	
	b. Please describe how financial considerations (potential cost of the investigation, cost to the traveling public, cost of the repair, etc.) impacted the decisions made or process used for the investigation.
Answer	
	c. Please describe any additional considerations or risks that impacted how the investigation was conducted and what those impacts were.
Answer	

8.12. CASE STUDY 11: HUNGARY BRIDGE COLLAPSE

Case : *Hernad Bridge at Pere*	
1) Brief description of the bridge (type, material, year of construction, …	Provide a short description of the bridge including bridge type, material (steel, reinforced concrete, prestressed concrete, timber, masonry, …), year of construction, span lengths, …
Answer	The 3 spanned bridge is a serie of simple girders with prefabricated prestressed reinforced concrete beams and cast-in-situ reinforced concrete deck slab. The spans are 16,20 + 15,60 + 16,20 m long. The carriageway is only one lane, its width is 3,00 m. The substructure was built in 1914-15 with wooden piles and concrete pilecap foundation. The bridge was blasted in 1944 when the whole superstructure and the wall of the left bank river-pier were completely destroyed. Reconstruction of the superstructure and the destroyed pier was completed in 1950-51 (the new pier wall was built on the remaining foundation). A complete refurbishment took place in 1994.
Picture of the bridge	
2) Description of the failure.	Provide a detailed description of the failure. Include sufficient relevant context to support the failure being unanticipated or producing unexpected performance.
Answer	A main bridge inspection in 2016 showed that the right bank river-pier has been tilted to the downstream side. Earlier main inspections also showed a tilting tendency but this process reached such an extent in 2016 that annual detailed geodetic (monitoring) survey was prescribed. In 2018 it was proven that the rate of inclination accelerated so that the bridge had to be closed immediately. The river did not show any unusual flow conditions at an average water level, so no degeneration of the riverbed and no undermining of the pier could be inferred.

<table>
<tr><th colspan="2">Case : Hernad Bridge at Pere</th></tr>
<tr><td>Picture of the failure</td><td>

 </td></tr>
<tr><td>3) Investigating organization.</td><td>If one or more specific agency or institution has the responsibility to investigate bridge failures in your country, please name them and describe their authorities.</td></tr>
</table>

Case : *Hernad Bridge at Pere*	
Answer	Regular inspection (or, if justified by an extraordinary phenomenon, targeted inspection) of bridges is the task of the road operator. According to chapter 6 of Technical Specification No. e-UT 08.01.25. bridges shall be inspected every 10 years with the involvement of a bridge expert, supported by geodetic measurements and laboratory tests. The bridge experts are selected by Magyar Közút Co. (state road operator) through a public procurement procedure. The road operator is entitled to impose restrictions or even closure in his or her own competence, the expert performing the bridge inspection can make a similar proposal.
4) Legal constraints.	If there are legal constraints on the transparency or process of a bridge failure investigation in your country, please describe those.
Answer	There is no specific regulation for inspecting bridge failures. Fortunately it has been a very rare event in Hungary in the recent decades.
5) Investigative process.	Please describe how the investigation was conducted. If a standardized and documented process or procedure was used to guide or inform the investigation, please also describe it here and include a copy with your response.
Answer	During the 2018 target inspection, geodetic measurements, riverbed surveys and diving surveys were carried out in the vicinity of the pilecaps. The recorded condition was then compared by the bridge expert with the outcomes of the previous inspections and earlier measurements.
6) Organizational structure.	Describe the organizational structure used by the investigators.
Answer	Head of bridge department of the state road operator (on behalf of the Client); Regional bridge engineer of the state road operator (on behalf of the Client); Bridge experts of MSc Ltd. (private-owned engineering consultant).
7) Investigator qualifications.	Describe the qualifications of those involved in the investigation. Education, licensing, training, experience, etc.
Answer	Compliance with the criteria specified during the public procurement procedure, in particular bridge expert licence registered by the Hungarian Chamber of Civil Engineers (min. 10 years of bridge engineering experience).
8) Investigation documentation.	a. Describe how the failure was documented on-site?

Case : *Hernad Bridge at Pere*	
Answer	expert report with recommendations and photographs; geodetic survey with a measuring station plus Sonar (riverbed survey); diving survey: underwater camera plus video recordings.
	b. How was physical evidence collected, documented and controlled?
Answer	Due to the nature of the failure, no physical evidence was collected. An expert report was compiled based on the above inspections and measurements. The expert compared the measurement results with the previous results and showed them on a diagram over time. The diving survey confirmed the suspicion of pier undermining and, in addition, provided important new information: it shed light on the method of foundation (no drawings were available for this detail, but the Operator assumed a shallow foundation). It turned out from the riverbed survey that due to the extreme amount of sediment deposition on the upstream side of the other river-pier, the drift line shifted into the immediate vicinity of the pillar in question, which caused the undermining.
9) Testing.	a. What type of physical testing was conducted to support the investigation?
Answer	No physical testing was carried out, only the above mentioned visual inspection, geodetic survey and diving survey.
	b. If standardized test methods were not used, why not?
Answer	Not applicable
	c. How was test data stored and documented?
Answer	Expert report (printed and electronic version).
10) Experimentation.	If experimental testing was conducted, please summarize the need, describe the experiments, and outline how the results were used.
Answer	No experimental testing was conducted.
11) Bridge files and records.	a. What records (design, fabrication, construction, inspection, etc.) of bridge were collected to support the investigation, and how where they reviewed?
Answer	The drawings of the bridge built before World War II were lost, so there are no drawings for the foundation. However, drawings of the reconstruction works in

Case : *Hernad Bridge at Pere*	
	1950 and the complete refurbishment in 1994 are available, as are the main inspection reports after the war.
12) Analyses.	What type of analysis or modeling tools (engineering calculation, structural analysis, finite element modeling, others) were used to support the investigation and describe their use?
Answer	No modeling or structural analysis was required to explore the problem. For the design work of the restoration and stabilization, a structural analysis was carried out on the basis of geotechnical excavation with a finite element model.
13) Lessons learned.	a. With regard to the cause of failure, what were the findings of the investigation?
Answer	Due to the accumulation of sediments, the degeneration of the riverbed and the undermining of the foundation were the direct causes of the failure.
	b. What lessons learned were derived from the findings?
Answer	In the case of rivers with strongly variable water flows, it is advisable to implement extraordinary (more frequently than the required 10-years periodic) riverbed surveys.
	c. How were the lessons learned communicated to the bridge engineering, construction and inspection communities?
Answer	The bridge operator and the expert presented the issue on the annual national bridge engineering conference.
	d. Describe any changes to the state of practice resulting from the lessons learned.
Answer	Being a unique case, no system-level change is required.
	e. Identify any challenges the resulted from the process or procedure used to conduct the investigation, and any recommended changes to the approach or methodology used to address those challenges or otherwise result in improvements.
Answer	Invisible structural elements or those with unknown parametres (e.g. missing drawing for the substructures) had to be inspected on the basis of instrument-measurable changes (and their acceleration over time). In similar cases, steps should be taken to get to know the details of the unknown elements in some way.

Case : *Hernad Bridge at Pere*	
14) Other impacts on the investigation.	a. If there was a need for a timely repair to address a long detour or simply the restoration of service, please describe how that need impacted the decisions made or process used for the investigation.
Answer	Due to the real risk of loss of stability due to the continuous tilting of the pier, the complete bridge closure was inevitable, the length of the diversion road and the increased travel time did not influence the decision.
	b. Please describe how financial considerations (potential cost of the investigation, cost to the traveling public, cost of the repair, etc.) impacted the decisions made or process used for the investigation.
Answer	The scope and cost of the target inspection and the decision to close the bridge were not influenced by financial considerations. As the bridge operator does not have financial source for the complete reconstruction of the bridge, the technological drawings and then the construction for the temporary stabilization of the bridge were prepared out of turn.
	c. Please describe any additional considerations or risks that impacted how the investigation was conducted and what those impacts were.
Answer	None

8.13. Case Study 12: Hungary Pier Foundation Failure

Case : *Piliscsaba Masonry Bridge*	
1) Brief description of the bridge (type, material, year of construction, …	Provide a short description of the bridge including bridge type, material (steel, reinforced concrete, prestressed concrete, timber, masonry, …), year of construction, span lengths, …
Answer	The bridge was constructed in 1890 and is a 4 span brick/stone masonry over a small creek. The span are cca 3 metres each. It carries a municipality one lane road with relatively low local traffic. The loadbearing capacity has been reducted to 3,5 tons decades ago due to some hints of deterioration.
Picture of the bridge	
2) Description of the failure.	Provide a detailed description of the failure. Include sufficient relevant context to support the failure being unanticipated or producing unexpected performance.
Answer	In February 2020, one of the spans suddenly collapsed without any prior notice. Approx. half width of the roadway disappeared in the pit formed by the collapse. There was no external effect/impact at the time of the failure (flood, heavy vehicle, etc.). Fortunately, at the time of the collapse, no one was on/under the bridge, so no injuries were detected. The Civil Guard Service quickly closed the road physically in order to prevent any accidents.

Case : *Piliscsaba Masonry Bridge*	
Picture of the failure	  
3) Investigating organization.	If one or more specific agency or institution has the responsibility to investigate bridge failures in your country, please name them and describe their authorities.
Answer	The operator of the bridge is the municipality of Piliscsaba (a small town close to Budapest). Soon after the collapse was noticed, a joint site inspection was called in the presence of the Mayor, the technical administrator of the municipality, the Police and the Civil Guard. The responsibilities in case of a bridge failure are not assigned precisely in Hungary but usually the representatives of the operator, a designer (preferably the original designer – if available), and a bridge expert are involved in such an investigation.
4) Legal constraints.	If there are legal constraints on the transparency or process of a bridge failure investigation in your country, please describe those.

Case : *Piliscsaba Masonry Bridge*	
Answer	No such legal constrains are available.
5) Investigative process.	Please describe how the investigation was conducted. If a standardized and documented process or procedure was used to guide or inform the investigation, please also describe it here and include a copy with your response.
Answer	There was no specific process. After the site inspection there was obvious that no cost-effective repair method can be carried out so it was soonly decided that the rest of the bridge shall also be removed and a new conception has to be designed and constructed.
6) Organizational structure.	Describe the organizational structure used by the investigators.
Answer	No specific organization chart.
7) Investigator qualifications.	Describe the qualifications of those involved in the investigation. Education, licensing, training, experience, etc.
Answer	There is no specification for such a qualification but it is advisable that at least one special bridge expert (structural engineer, licenced by the Chamber of Civil Engineers, with at least 10 years of relevant experience) shall be a member of the investigation staff.
8) Investigation documentation.	a. Describe how the failure was documented on-site?
Answer	Mostly photographs, with some sketches.
	b. How was physical evidence collected, documented and controlled?
Answer	After the quick decision about the complete removal the collection, documentation and control of the physical evidence became unnecessary.
9) Testing.	a. What type of physical testing was conducted to support the investigation?
Answer	No testing has been carried out.
	b. If standardized test methods were not used, why not?
Answer	Not applicable
	c. How was test data stored and documented?

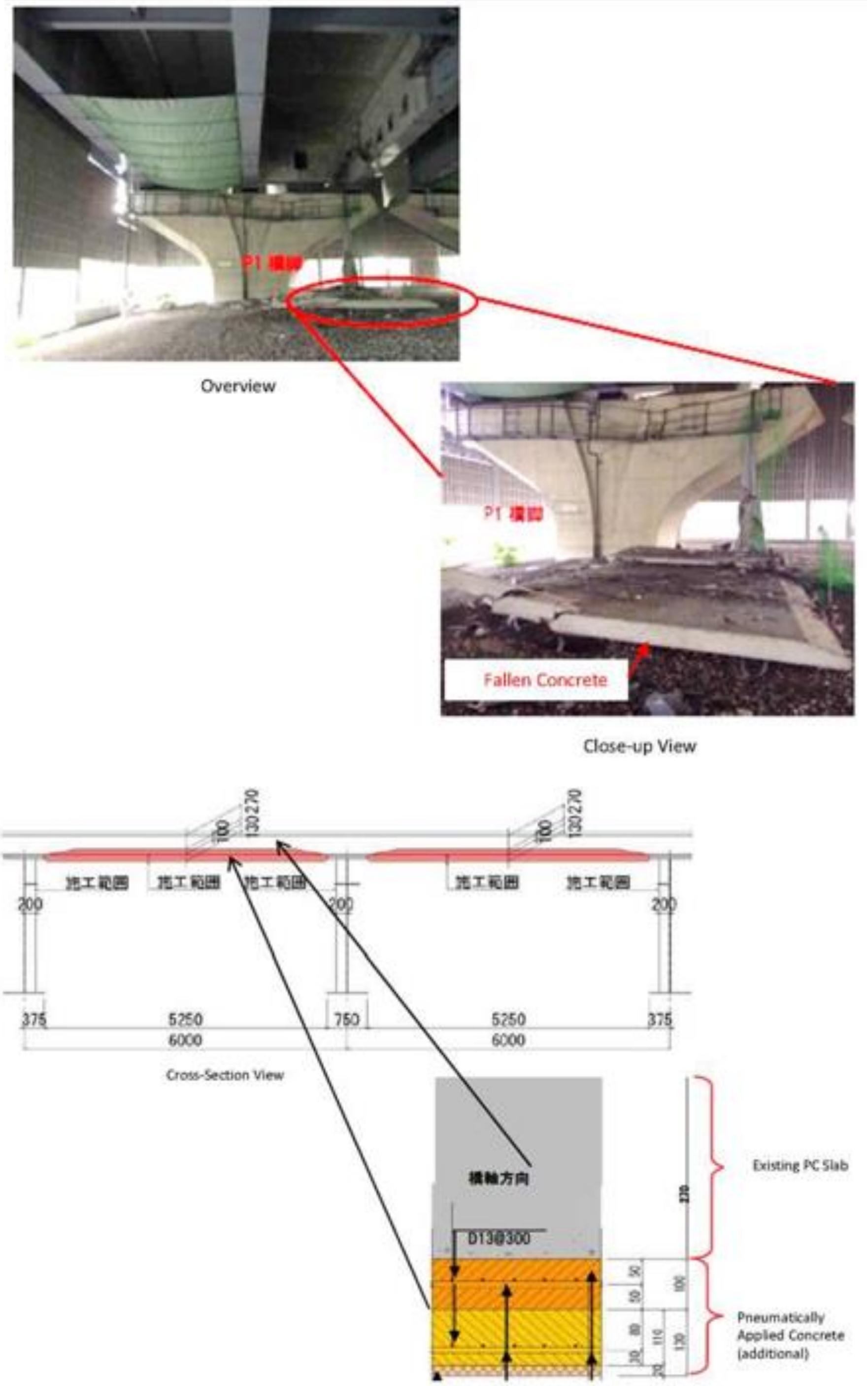
Case : *Piliscsaba Masonry Bridge*	
Answer	No such data were stored.
10) Experimentation.	If experimental testing was conducted, please summarize the need, describe the experiments, and outline how the results were used.
Answer	None
11) Bridge files and records.	a. What records (design, fabrication, construction, inspection, etc.) of bridge were collected to support the investigation, and how where they reviewed?
Answer	Unfortunately no such drawings are available for the structure.
12) Analyses.	What type of analysis or modeling tools (engineering calculation, structural analysis, finite element modeling, others) were used to support the investigation and describe their use?
Answer	None
13) Lessons learned.	a. With regard to the cause of failure, what were the findings of the investigation?
Answer	With regards to the hints of previous deterioration, perhaps more attention should have been paid to more frequent bridge examination regime.
	b. What lessons learned were derived from the findings?
Answer	The municipality roads and bridges need as much care as the ones in state operation.
	c. How were the lessons learned communicated to the bridge engineering, construction and inspection communities?
Answer	Recommendations to the involved organizations that municipality infrastructure requires as much care as state infrastructure.
	d. Describe any changes to the state of practice resulting from the lessons learned.
Answer	Very short time has passed since the incident, so no lessons yet.
	e. Identify any challenges the resulted from the process or procedure used to conduct the investigation, and any recommended changes to the approach or methodology used to address those challenges or otherwise result in improvements.

Case : *Piliscsaba Masonry Bridge*	
Answer	See above
14) Other impacts on the investigation.	a. If there was a need for a timely repair to address a long detour or simply the restoration of service, please describe how that need impacted the decisions made or process used for the investigation.
Answer	No long detour is needed, the road was simply closed.
	b. Please describe how financial considerations (potential cost of the investigation, cost to the traveling public, cost of the repair, etc.) impacted the decisions made or process used for the investigation.
Answer	The Municipality has been applied successfully for financial sources that will cover the costs of the demolition (already been completed) and the design and construction of the new concept.
	c. Please describe any additional considerations or risks that impacted how the investigation was conducted and what those impacts were.
Answer	None

8.14. Case Study 13: Japan Spray Applied Concrete Failure

Case : Spray Applied Concrete Failure	
1) Brief description of the bridge (type, material, year of construction, …	Provide a short description of the bridge including bridge type, material (steel, reinforced concrete, prestressed concrete, timber, masonry, …), year of construction, span lengths, …
Answer	Bridge Type: 7-span continuous steel plate girder bridge with three main girders, Maximum Span Length: 75m Slab: precast pretention prestressed concrete slabs with span length of 2.5m, Completion Year: 2004
Picture of the bridge	
2) Description of the failure.	Provide a detailed description of the failure. Include sufficient relevant context to support the failure being unanticipated or producing unexpected performance.

Answer	In order to mitigate vibration and noise coming from running trucks over the joints, additonal concrete was sprayed on the lower surface of the deck slab in the vicinity of joints (10m-long) with an aim to increase the stiffness of the slab in 2006. On September 2014, the additonal spray-applied concrete fell off at the interface on the ground where the bridge operator manages. Dimention of the spray-applied concrete: length: 10m (L) * 5.25m (W) * *0.23m (T), about 30t (Weight) Inspection way and drain pipe were damaged when the concrete fell.

<table>
<tr><th colspan="2">Case : Spray Applied Concrete Failure</th></tr>
<tr><td>Picture of the failure</td><td>
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</table>

3) Investigating organization.	If one or more specific agency or institution has the responsibility to investigate bridge failures in your country, please name them and describe their authorities.
Answer	Investigation is conducted under the responsibility of the bridge operator. Regulatory agency is Ministry of Land, Infrastructure, Transportation and Tourism. In this case, an accident investigation board was established to examine the cause of the accident and to develop preventive measures. The board was composed of experts from academic and public officials.
4) Legal constraints.	If there are legal constraints on the transparency or process of a bridge failure investigation in your country, please describe those.
Answer	There is no legal constraints.
5) Investigative process.	Please describe how the investigation was conducted. If a standardized and documented process or procedure was used to guide or inform the investigation, please also describe it here and include a copy with your response.

Answer	There is no standardized and documented process or procedure. In this case, the Board was held three times to deliberate the following issues. First: Background of the accident, investigation policy to clarify the cause and response policy after the accident. Second: Analysis of the detailed investigation results and new technical findings. Third: Examination of recurrence prevention measures and organizing new technical findings.
6) Organizational structure.	Describe the organizational structure used by the investigators.
Answer	There was no specific organizational structure in the board.
7) Investigator qualifications.	Describe the qualifications of those involved in the investigation. Education, licensing, training, experience, etc.
Answer	The board was composed of eight experts as follows. Chair: ● Emeritus professor of national university Members: ● Professors of national and public universities ● Head of Bridge and Structures Division of National Institute for Land and Infrastructure Management ● Senior Researcher of Materials and Resources Research Group of Public Works Research Institute ● Director for Bridge research of Nippon Expressway Research Institute Company Limited
8) Investigation documentation.	a. Describe how the failure was documented on-site?
Answer	Photographs, sketches and other measurements/tests used to write the Board report.
	b. How was physical evidence collected, documented and controlled?
Answer	The bridge operator collected the fallen concrete and used for tests to clarify the cause.

9) Testing.	a. What type of physical testing was conducted to support the investigation?

Answer	･Concrete strength of the existing PC slab (Schmidt hammer test) ･Concrete strength of the spray-applied concrete (Schmidt hammer test and compressive test of collected cores) ･Carbonation depth of the spray-applied concrete (phenolphthalein test) ･Peeling situation the spray-applied concrete (impact elastic wave test)
	b. If standardized test methods were not used, why not?
Answer	Not applicable
	c. How was test data stored and documented?
Answer	It was stored and documented in a form of committee report by the bridge operator. It was also disclosed through the operator's web site. https://www.c-nexco.co.jp/corporate/pressroom/survey/pdf/finalreport.pdf (in Japanese)
10) Experimentation.	If experimental testing was conducted, please summarize the need, describe the experiments, and outline how the results were used.
Answer	The cause of the accident was estimated by obtaining detailed findings from experiments and analyses about the event that the spray-applied concrete peeled off and fell from the deck slab. In particular, real-scale reproductive experiments and vibration experiments were implemented to verify the following effects on the accident. ● Effect of concrete volume change due to temperature change and dry shrinkage emphasized by the thick spray-applied concrete ● Effect of vibration during the curing process ● Effect of shear force at the abrupt change point of cross-section emphasized by the thick spray-applied concrete
11) Bridge files and records.	a. What records (design, fabrication, construction, inspection, etc.) of bridge were collected to support the investigation, and how where they reviewed?
Answer	Execution and inspection records about the fallen spray-applied concrete including the test records implemented before the execution.
12) Analyses.	What type of analysis or modeling tools (engineering calculation, structural analysis, finite element modeling, others) were used to support the investigation and describe their use?
Answer	● Finite element analyses to verify shear force at the interface. ● Thermal stress analyses to verify the effect of concrete volume change due to temperature change and dry shrinkage.

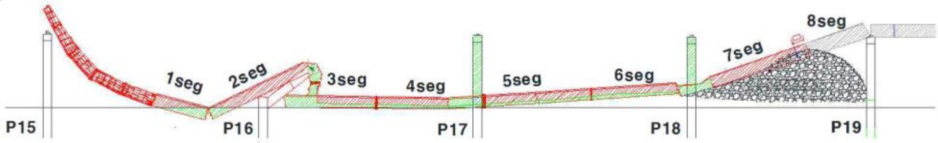
13) Lessons learned.	a. With regard to the cause of failure, what were the findings of the investigation?
Answer	It was concluded that the spray applied concrete peeled off from the slab because of reduced its adhesion due to concrete shrinkage and traffic vibration emphasized by large thickness of the applied concrete, and then, it fell down by its own weight after the progress of peeling.
	b. What lessons learned were derived from the findings?
Answer	Recurrence prevention measures were summarized as follows: ● Repair method for thickness-increased bottom face of RC slab with more than 70mm in thickness should be avoided unless its structural integrity is verified. ● Required safety should be secured not only with just satisfying a safety factor, but with recognizing the following possibility: inhomogeneity of material and strength, ununiformity of load action and stress action caused by temperature change, dry shrinkage, etc. may cause local destruction of structure, and may result in falling of structures with time. ● In design and construction of structural/non-structural members, structures should have redundancy with double safety measures if necessary in view of the possibility of falling of members/parts. In addition, the durability of members and their joints should as well as the ease of inspection should be enough considered.
	c. How were the lessons learned communicated to the bridge engineering, construction and inspection communities?
Answer	● Proceeding of the Japan Road Conference ● The operator's web site
	d. Describe any changes to the state of practice resulting from the lessons learned.
Answer	Not applicable
	e. Identify any challenges the resulted from the process or procedure used to conduct the investigation, and any recommended changes to the approach or methodology used to address those challenges or otherwise result in improvements.
Answer	Not applicable
14) Other impacts on the investigation.	a. If there was a need for a timely repair to address a long detour or simply the restoration of service, please describe how that need impacted the decisions made or process used for the investigation.
Answer	The investigation did not affect traffic since the event occurred within controlled area.

	b. Please describe how financial considerations (potential cost of the investigation, cost to the traveling public, cost of the repair, etc.) impacted the decisions made or process used for the investigation.

Answer	The bridge operator bore the expenses.
	c. Please describe any additional considerations or risks that impacted how the investigation was conducted and what those impacts were.
Answer	Not applicable

8.15. Case Study 14: South Korea Bridge Collapse

Case : *Incremental Launching Failure*	
1) Brief description of the bridge (type, material, year of construction, …	Provide a short description of the bridge including bridge type, material (steel, reinforced concrete, prestressed concrete, timber, masonry, …), year of construction, span lengths, …
Answer	A bridge was designed as a 22 span pre-stressed concrete box girder including an arch-stiffened pre-stressed box girder segment. The total length of the bridge is 1,350m and the following construction methods were employed; - ILM(Incremental Launching Method) : 980m(13@60+4@50, P6~A2) - BCM(Balanced Cantilever Method) : 250m(2@65+120, P2~P6) - FSM(Full Staging Method) : 120m(2@60,A1~P2) The construction was started at June 2013 and supposed to be finished by December 2018. Due to a sudden collapse during the launching, the bridge was redesigned as a steel box girder bridge and opened to the public at January 2020.
Picture of the bridge	 Conceptual drawing of the bridge
2) Description of the failure.	Provide a detailed description of the failure. Include sufficient relevant context to support the failure being unanticipated or producing unexpected performance.
Answer	The portion of the bridge constructed using the incremental launching method was divided into 36 segments for the launching operation. The typical length of the segment was 30 meters. During the launching of a 14th segment (405M), the launched portion of the girder was suddenly collapsed. A Pier 16 was also collapsed. Fortunately, no one was injured or killed. At the time of the collapse, the launching operation was stopped to replace the damaged sliding pad.

Case : *Incremental Launching Failure*	
Picture of the failure	 
3) Investigating organization.	If one or more specific agency or institution has the responsibility to investigate bridge failures in your country, please name them and describe their authorities.
Answer	State agencies have the authority to organize an Accident Investigation Committee to investigate the accidents when a serious accident happens. MOLIT(Ministry of Land, Infrastructure and Transport) and has formed an Accident Investigation Committee(AIC) to investigate main causes of the bridge collapse. The Committee was composed of experts from industry and academic and public officials.
4) Legal constraints.	If there are legal constraints on the transparency or process of a bridge failure investigation in your country, please describe those.
Answer	No such legal constrains are available.
5) Investigative process.	Please describe how the investigation was conducted. If a standardized and documented process or procedure was used to guide or inform the investigation, please also describe it here and include a copy with your response.
Answer	A schematic investigation procedure is stipulated in the operation manual for the AIC. The AIC is required to carry out an initial site investigation to preserve the site and plan field and laboratory tests. After that, the AIC needs to establish detailed investigation procedures and carry out detailed site investigation to collect information. The AIC also performs series of tests, if necessary, and has to publish an investigation report.
6) Organizational structure.	Describe the organizational structure used by the investigators.
Answer	No specific organization chart is available.

Case : *Incremental Launching Failure*	
7) Investigator qualifications.	Describe the qualifications of those involved in the investigation. Education, licensing, training, experience, etc.
Answer	Bridge experts (structural engineers with at least 10 years of experience, professor of relevant experiences) and public officials were a member of the investigation committee.
8) Investigation documentation.	a. Describe how the failure was documented on-site?
Answer	The AIC carried out number of site investigations to determine causes of the failure. They also collected accident related data at the site and construction records, documents on design, and structural analysis results. These information became part of the investigation report.
	b. How was physical evidence collected, documented and controlled?
Answer	The AIC gathered the samples for testing and physical evidence for analysis.
9) Testing.	a. What type of physical testing was conducted to support the investigation?
Answer	Compressive strength of concrete and tensile strength of reinforcements were tested. The quality of grout was also reviewed.
	b. If standardized test methods were not used, why not?
Answer	Not applicable
	c. How was test data stored and documented?
Answer	The test data and resulted were documented by the AIC.
10) Experimentation.	If experimental testing was conducted, please summarize the need, describe the experiments, and outline how the results were used.
Answer	None
11) Bridge files and records.	a. What records (design, fabrication, construction, inspection, etc.) of bridge were collected to support the investigation, and how where they reviewed?
Answer	Every necessary records such as structural analysis results for the completed bridge and the launching operations, drawings, material test data, licencing and approval documentations, communication records between a contractor and a supervisors were collected.
12) Analyses.	What type of analysis or modeling tools (engineering calculation, structural analysis, finite element modeling, others) were used to support the investigation and describe their use?
Answer	Detailed FEM analysis was performed.
13) Lessons learned.	a. With regard to the cause of failure, what were the findings of the investigation?

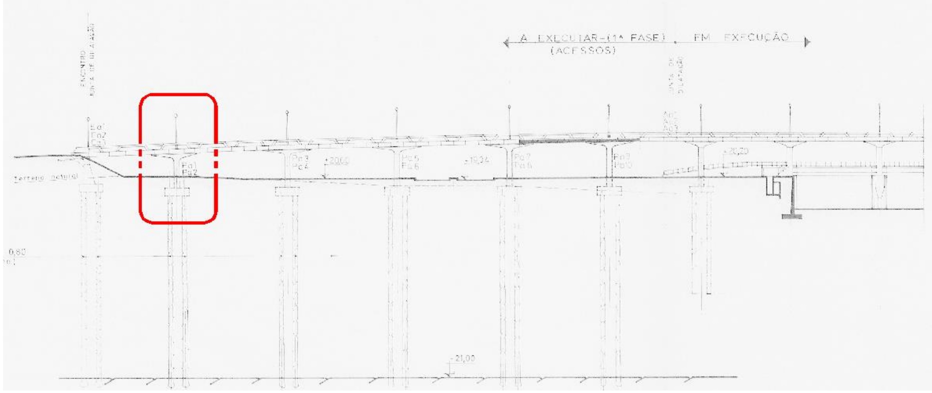
Case : *Incremental Launching Failure*	
Answer	The Investigation Report from the AIC suggested that design and construction errors contributed the sudden failure of the bridge during the launching operations. The Report suggested that the shear strength requirements of concrete box girder was not fully considered for the ILM launching operation. It was also suggested that construction problems such as quality of grouting, cracks at construction joints, couplers for pre-stressing strands and poor shear reinforcement details contributed the failure.
	b. What lessons learned were derived from the findings?
Answer	During the bridge design and construction, constructability needs to be checked in detail.
	c. How were the lessons learned communicated to the bridge engineering, construction and inspection communities?
Answer	At the end of investigation, press briefing was held and the Investigation Report was published.
	d. Describe any changes to the state of practice resulting from the lessons learned.
Answer	No specific information we have.
	e. Identify any challenges the resulted from the process or procedure used to conduct the investigation, and any recommended changes to the approach or methodology used to address those challenges or otherwise result in improvements.
Answer	No specific information we have.
14) Other impacts on the investigation.	a. If there was a need for a timely repair to address a long detour or simply the restoration of service, please describe how that need impacted the decisions made or process used for the investigation.
Answer	To reduce construction time, the failed pre-stressed concrete box girder was totally removed and replaced with a steel box girder. The steel box girder was assembled at the shop and transported to the site.
	b. Please describe how financial considerations (potential cost of the investigation, cost to the traveling public, cost of the repair, etc.) impacted the decisions made or process used for the investigation.
Answer	None
	c. Please describe any additional considerations or risks that impacted how the investigation was conducted and what those impacts were.
Answer	None.

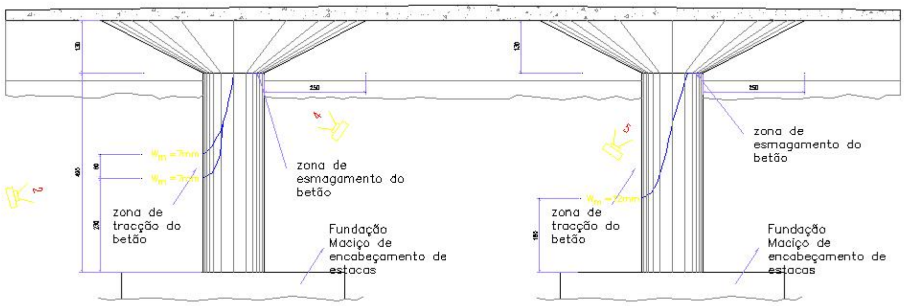
8.16. Case Study 15: Portugal Pier Failure

Case : *Bridge Column Shear Failure*	
1) Brief description of the bridge (type, material, year of construction, …	Provide a short description of the bridge including bridge type, material (steel, reinforced concrete, prestressed concrete, timber, masonry, …), year of construction, span lengths, …
Answer	The first part of this bridge was built in 1980, with a reinforced concrete slab. The second part of the bridge, the North access viaduct, was built in 1991 (Prestressed concrete slab bridge). Bridge continuous multi-span deck (average span length about 25m). This bridge is included in the BMS (Bridge Management System) of IP – Infraestruturas de Portugal. IP is a public company that manages road and rail infrastructure. The purpose of IP is the conception, design, construction, financing, conservation, operation, requalification, enlargement and modernization of the national road and rail networks, including the command and control of circulation.
Picture of the bridge	 
2) Description of the failure.	Provide a detailed description of the failure. Include sufficient relevant context to support the failure being unanticipated or producing unexpected performance.
Answer	Shear failure in 2 piers of the access viaduct (built in 1980). Shear capacity and ductility inadequate for the deformations/displacements imposed by the slab, due to long-term effects of concrete (shrinkage and creep) and temperature variation. It was a situation that suddendly appears.

Case : *Bridge Column Shear Failure*

Picture of the failure





3) Investigating organization.	If one or more specific agency or institution has the responsibility to investigate bridge failures in your country, please name them and describe their authorities.

Case : *Bridge Column Shear Failure*	
Answer	At a national level, LNEC is the institution that has the responsibility to investigate bridge failures or damages in other structures. However, in Portugal, we have some different road infrastructure owners/operators, and when a failure occurs in a bridge (unexpected loss of structural capacity due to unknown or unapparent circumstances), all process of investigation can be conducted by the company that has the responsibility of the infrastructure's management (e.g. Infraestruturas de Portugal, BRISA, etc).
4) Legal constraints.	If there are legal constraints on the transparency or process of a bridge failure investigation in your country, please describe those.
Answer	No.
5) Investigative process.	Please describe how the investigation was conducted. If a standardized and documented process or procedure was used to guide or inform the investigation, please also describe it here and include a copy with your response.
Answer	The investigation was conducted by IP (previously named as EP), following its BMS. Firstly, there are routine and principal bridge inspections, where structural failures and anomalies are detected for the first time, in standardized reports documented in GOA (the BMS adopted by IP). On-site, inspectors fill a bridge inspection form. If there are doubts about structural behavior of any bridge, the final inspection report is the first guide and it is used to inform the investigation. Besides that, there is no standardized and documented process nor procedure to guide/inform investigation. In this process, immediate actions were taken to avoid the failure/rupture of the piers, with local reinforcements.
6) Organizational structure.	Describe the organizational structure used by the investigators.

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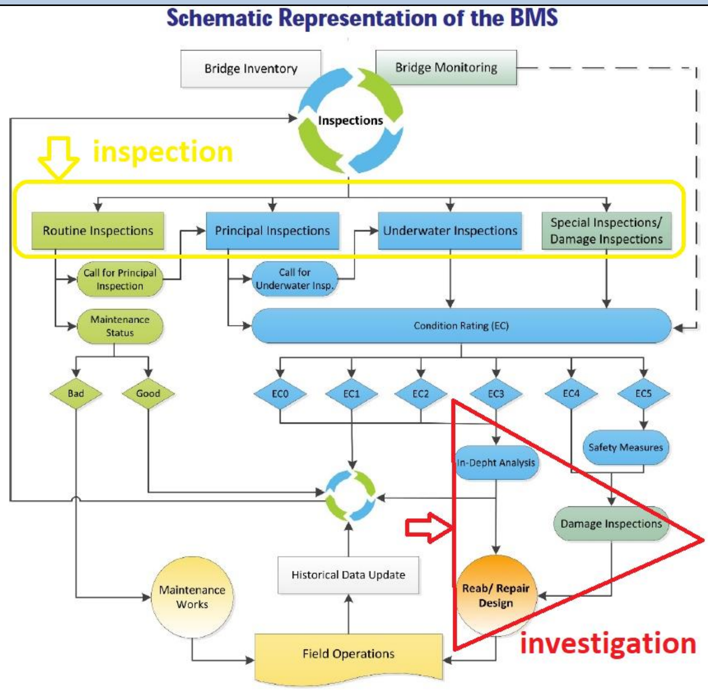
<tr><th colspan="2">Case : Bridge Column Shear Failure</th></tr>
<tr><td>Answer</td><td>


The investigation follows the IP’s BMS.
The organizational structure used by the investigators depends on the type of structural analysis that is needed.
Usually, this is the procedure:

New principal bridge inspection;
In-depth analysis (based on concrete characterization tests, structural modelling, etc);
Repair or rehabilitation design (if necessary).

</td></tr>
<tr><td>7) Investigator qualifications.</td><td>Describe the qualifications of those involved in the investigation. Education, licensing, training, experience, etc.</td></tr>
<tr><td>Answer</td><td>Structural/civil engineers (BSc or MSc) with training on bridge inspections and many years of experience in bridge engineering (design, rehabilitation).</td></tr>
<tr><td>8) Investigation documentation.</td><td>a. Describe how the failure was documented on-site?</td></tr>
<tr><td>Answer</td><td>It was documented with photos and measuring equipment (length and width of the cracks).</td></tr>
<tr><td></td><td>b. How was physical evidence collected, documented and controlled?</td></tr>
<tr><td>Answer</td><td> Physical evidence collected by photos, measuring equipment and a drawing on-site. It was documented in a digital file (drawing with all cracks, including orientation and width of the cracks - values greater than 0,30mm). </td></tr>
<tr><td>9) Testing.</td><td>a. What type of physical testing was conducted to support the investigation?</td></tr>
</table>

Case : *Bridge Column Shear Failure*	
Answer	All the information needed to an in-depth analysis: - Topographical Surveys; - inspection of foundations of the piers (buried zones) to confirm the geometry of the structure; - reinforced concrete characterization tests (Compressive strength test, etc); - geotechnical surveys (SPT); - pavement characterization (thickness);
	b. If standardized test methods were not used, why not?
Answer	It was used standardized methods.
	c. How was test data stored and documented?
Answer	Following normal procedures (stored in laboratory and documented in the BMS data base).
10) Experimentation.	If experimental testing was conducted, please summarize the need, describe the experiments, and outline how the results were used.
Answer	No.
11) Bridge files and records.	a. What records (design, fabrication, construction, inspection, etc.) of bridge were collected to support the investigation, and how where they reviewed?
Answer	Bridge Design Project Bridge Inspections
12) Analyses.	What type of analysis or modeling tools (engineering calculation, structural analysis, finite element modeling, others) were used to support the investigation and describe their use?
Answer	Structural analysis was made by using finite element modelling. This method was used to verify whether the bridge works the way it was designed.
13) Lessons learned.	a. With regard to the cause of failure, what were the findings of the investigation?
Answer	Insufficient shear capacity due to inadequate transverse reinforcement (less than the minimum required according to the national design regulation and the Eurocode 2).
	b. What lessons learned were derived from the findings?
Answer	In short piers located at the end of a long bridge (away from the center of stiffness), it isn’t recommended to be connected monolithically to the deck.
	c. How were the lessons learned communicated to the bridge engineering, construction and inspection communities?
Answer	No official communication. It is possible that this information could be shared at some bridge maintenance and safety conference.

Case : *Bridge Column Shear Failure*	
	d. Describe any changes to the state of practice resulting from the lessons learned.
Answer	Nowadays, short piers located at the end of a long bridge, usually aren't connected monolithically to the deck. The design rehabilitation of this bridge established the demolition of those 2 piers and their substitution by 2 new piers connect to the deck with sliding bearings.
	e. Identify any challenges the resulted from the process or procedure used to conduct the investigation, and any recommended changes to the approach or methodology used to address those challenges or otherwise result in improvements.
Answer	Challenge: Not in this case, but sometimes the original design project is not known. Also, there is no final documentation about any changes that could possibly occurred to the original design during the construction of the bridge. Recommendation: This kind of information should be stored in the BMS database.
14) Other impacts on the investigation.	a. If there was a need for a timely repair to address a long detour or simply the restoration of service, please describe how that need impacted the decisions made or process used for the investigation.
Answer	Yes, there was a need for a timely repair. That need had no impacted on the decision or process used by the investigation, because there was an urgent first repair / reinforcement of the 2 piers (even without a completed investigation on the structural behavior of the bridge).
	b. Please describe how financial considerations (potential cost of the investigation, cost to the traveling public, cost of the repair, etc.) impacted the decisions made or process used for the investigation.
Answer	In these cases, when a serious structural failure is detected in a bridge situated under an important national highway (also with economical costs involved), there are no financial restrictions for the investigation nor for the cost of the repair (taking into account that the rehabilitation presented by the investigators has the best cost-benefit solution).
	c. Please describe any additional considerations or risks that impacted how the investigation was conducted and what those impacts were.
Answer	No additional considerations.

8.17. Case Study 16: Spain Truss Chord Failure

Case : *Hoces del Cabriel Viaduct*	
1) Brief description of the bridge (type, material, year of construction, …	Provide a short description of the bridge including bridge type, material (steel, reinforced concrete, prestressed concrete, timber, masonry, …), year of construction, span lengths, …
Answer	The Hoces del Cabriel Viaducts are two twin separate composite structures built in 1999 made of two Warren-type steel trusses supporting a 14.05 m concrete slab each. Each platform is divided into 3-lanes of 3.50 m wide and two shoulders of 1.75 m the outer one and 1.00 m the inner one. The barriers are 0.40 m wide. The total length of both structures is 423.0 m divided into 4 spans (66.0 m corresponding to an isostatic span and 93.5 m – 170.0 m – 93.5 m corresponding to the hyperstatic spans).
Picture of the bridge	
2) Description of the failure.	Provide a detailed description of the failure. Include sufficient relevant context to support the failure being unanticipated or producing unexpected performance.
Answer	In 2013 a crack on the bottom chord was discovered just in the weld between the connection and the chord. A further inspection revealed that the crack may not have occurred recently but during time because of the presence of some rust on parts of the crack. However, the final crack may have appeared recently due to the lack of rust in that area. The crack initiation, propagation, and final fracture of the tensioned chord modificed the structural behaveour of the truss, that unable to resist the bending moment througn its decomposition into tension and compression forces, resulted in the plastic articulation of the connection inmediately above the two affected diagonals, creating an anticlockwise rotation of the right lateral part (supported on the abutment and the plastic articulation) and a clockwise rotation of the left lateral part, clamped on the adyacent pile. This explanation matches the geometry of the observed crack, with a 3-4 cm aperture and a vertical displacement of 2-3 cm measured from the brocken chord and the adyacent one.

Case : *Hoces del Cabriel Viaduct*	
Picture of the failure	 General view of the crack  Detailed view of the crack
3) Investigating organization.	If one or more specific agency or institution has the responsibility to investigate bridge failures in your country, please name them and describe their authorities.
Answer	The bridge is located on the motorway network, depending on the Valencia Road Demarcation, under the management of the Ministry of Transport.
4) Legal constraints.	If there are legal constraints on the transparency or process of a bridge failure investigation in your country, please describe those.
Answer	There are no legal limitations to the investigation of a case of this type. In Spain, on the other hand, there is Law 19/2013 on Transparency, which determines the ambit, with aims to reinforce the right of citizens to access information about public activities. Its full name is Law 19/2013, of December 9, on transparency, access to public information and good governance.
5) Investigative process.	Please describe how the investigation was conducted. If a standardized and documented process or procedure was used to guide or inform the investigation, please also describe it here and include a copy with your response.

Case : *Hoces del Cabriel Viaduct*	
Answer	There were no standards or procedures for conducting investigations in 2013 apart from several inspection guides published by the Ministry of Transpot. 5 families of investigations were conducted: 1. Detailed visual inspection of both structures 2. Diagnostics of the interior of the chords using endoscopy techniques 3. Diagnostics of the welds (Using Ultrasound techniques) 4. Laboratory analysis of the removed member (metallurgical, chemical, mechanical and resisting characteristics of the tested welds) 5. Laboratory analysis of extracted sample pieces from damaged welds
6) Organizational structure.	Describe the organizational structure used by the investigators.
Answer	The bridge is owned by the General Directorate of Roads, of the Ministry of Transport. The latter commissioned a specialized private company to investigate and analyze the damage. This company had the collaboration of accredited laboratories. This analysis was supervised by technicians from the General Directorate. This company also carried out a rehabilitation project. Finally, a construction company was commissioned to repair the bridge
7) Investigator qualifications.	Describe the qualifications of those involved in the investigation. Education, licensing, training, experience, etc.
Answer	The incident was investigated by a group of different technical, Structures Engineer, Industrial Engineer, International Welding Engineer (IWE certificate), etc and by specialist metallurgic laboratory.
8) Investigation documentation.	a. Describe how the failure was documented on-site?
Answer	The crack that initiated the investigation was visible at a simple sight and documented with photographs. The affected chord was removed and taken to the Road Conservation Centre and pictures were taken to register the state of both the chord and failure zone
	b. How was physical evidence collected, documented and controlled?
Answer	The inspectors spotted the welding defects on a map, with the dimensions. A piece of the broken chord was retired and analysed in laboratory. Visual inspection and END test was carried out. All butt welds were tested to evaluate their integrity.
9) Testing.	a. What type of physical testing was conducted to support the investigation?

Case : *Hoces del Cabriel Viaduct*	
Answer	Apart from the crack that initiated the investigation, further tests were performed on other butt welds during 3 different testing campaigns, mainly between tensioned members on site welded, but also on a fraction of the tensioned members welded at the workshop. Ultrasound tests were carried out to inspect the weld roots and to detect discontinuities in them and misalignments between chord plates were detected. All this information was collected on damage maps Laboratory tests on the removed member and on extracted sample pieces from damaged welds were performed. The investigations included the following: 1. Steel samples were characterized (metallurgical, chemical, mechanical and resisting characteristics of the tested welds) 2. After fatigue recalculations, critical areas were identified, such as welds on tensioned members. These welds were investigated. At the end of the testing campaigns, 100% of the tensioned welds, 50-60% of the compressed welds, 100% of the welds in the diagonals close to the piles and 100% of the welds with large misalignments (>5 mm misalignment and >10% of the smaller thickness) were inspected. Afterwards, two endoscopy testing campaigns were carried out in the critical members to verify the state of the weld roots and the presence or absence of backing.
	b. If standardized test methods were not used, why not?
Answer	The tests are subject to a test standard.
	c. How was test data stored and documented?
Answer	The recording of the data is carried out on the network of the supervisor. Reports of measurements or tests shall be delivered to the supervisor and contractor.
10) Experimentation.	If experimental testing was conducted, please summarize the need, describe the experiments, and outline how the results were used.
Answer	No experimental testing was conducted. A Maintenance Plan was developed in order to track the evolution of the defects during time.
11) Bridge files and records.	a. What records (design, fabrication, construction, inspection, etc.) of bridge were collected to support the investigation, and how where they reviewed?
Answer	The main bridge record collected to support the investigation was the As Built project.
12) Analyses.	What type of analysis or modeling tools (engineering calculation, structural analysis, finite element modeling, others) were used to support the investigation and describe their use?

Case : *Hoces del Cabriel Viaduct*	
Answer	A complex model of the bridge was developed to determine the sensibility and the range of stresses to fatige in each welded joint. A rainflow-counting analysis was also developed to evaluate each welded joint the normative fatigue necessary detail to compare with the real existing one, and to design the necessary actuation.
13) Lessons learned.	a. With regard to the cause of failure, what were the findings of the investigation?
Answer	The cause is well known: fatigue. Fatigue in steel railway bridges it´s very common and designs and construction are very conscious about it, but in road bridges fatigue it´s not so determinant and sometimes it`s possible to reduce the exigences. In these case, the transverse section and the high number of trucks of the highway, was determinant for the develop of the incident. In these line, old fatigue normative recommendations in Europe was less exigence than currently.
	b. What lessons learned were derived from the findings?
Answer	Although little observed, the phenomenon is very real. The importance of periodic detailed inspections has been demonstrated. The good conception of the details between the connections and the members is very important to satisfy the minimum Detail Category required to ensure the normal performance of the structure during its lifetime.
	c. How were the lessons learned communicated to the bridge engineering, construction and inspection communities?
Answer	A request was made by the Ministry of Transport to all highway companies to identify their pre-1994 metal structures, and to conduct fatigue recalculation and field verification studies to identify potential fatigue cracks. A Guide for the project against fatigue in steel and composite road bridges was published by the Ministry of Transport to help other engineers in the understanding of the fatigue phenomenon, facilitate the use and interpretation of the Eurocodes relating to the Ultimate Limit State of Fatigue, as well as improve the quality of the steel and composite road bridges projects subjected to this phenomenon.
	d. Describe any changes to the state of practice resulting from the lessons learned.
Answer	Now, details aimed to reduce the effect of the fatigue phenomenon are taken more into account and placed in the project drawings, and a stricter quality controls during the execution phases are performed in critical areas subjected to it.
	e. Identify any challenges the resulted from the process or procedure used to conduct the investigation, and any recommended changes to the approach or methodology used to address those challenges or otherwise result in improvements.
Answer	

Case : *Hoces del Cabriel Viaduct*	
14) Other impacts on the investigation.	a. If there was a need for a timely repair to address a long detour or simply the restoration of service, please describe how that need impacted the decisions made or process used for the investigation.
Answer	The metallic trusses as well as the slab were treated successively, one after the other. Right lane was closed to traffic until final reparations. The traffic load in the center and left lanes supposed a better performance for the structure by distributing the load between the two trusses
	b. Please describe how financial considerations (potential cost of the investigation, cost to the traveling public, cost of the repair, etc.) impacted the decisions made or process used for the investigation.
Answer	
	c. Please describe any additional considerations or risks that impacted how the investigation was conducted and what those impacts were.
Answer	The General Directorate of Highways is claiming the high costs of the repair from the company that originally built the bridge, determining that they were hidden defects. In principle from an administrative claim, and currently through a judicial process.

8.18. Case Study 17: Switzerland Pier Foundation Failure

Case : Bridge over the Reuss River	
Brief description of the bridge (type, material, year of construction, …	Provide a short description of the bridge including bridge type, material (steel, reinforced concrete, prestressed concrete, timber, masonry, …), year of construction, span lengths, …
Answer	The Bridge over the Reuss River at Wassen is a classical twin continuous girder bridge with 4 spans for a total length of 192 m for the bridge in southern direction (Roma) and 5 spans for a total length of 232 m in northern direction (Lora) and main spans for both bridges over the Reuss River of 64 m. The Roma bridge carries 3 lanes and is 12.63 m wide, the Lora bridge carries 2 lanes and is 10.08 m wide. The cross sections of both bridges are box girder designs in prestressed concrete with 2.4 m height, which results in a height/span ration of 1/27, a slim design. The consoles and the box are wider for the Roma Bridge. This bridge was the result of a bridge contest, designed in 1967 by the famous Swiss Bridge designer Dr. Christian Menn; it was executed in the years 1970-74 as part of the challenging construction of the Gotthard National highway from Erstfeld (canton Uri) to Bellinzona (canton Ticino) with the 16 km long Gotthard Road Tunnel as main structure. The place to build this bridge is a young landscape, finally carved out from the Reuss and Meienreuss glaciers and filled with its gravels after the last ice age, ending 10’000 years ago. The solid base rock, granite type, is covered with sand, gravel and younger blocks from erosion processes. After the glaciers, the Reuss River carved out some 30 m in thickness from this base rock in the last 10’000 years. The base rock is covered with sand-gravel-blocks in a layer of 3 to 10 m all along the planned foundation level. Most pillars and the northern abutments where founded with shallow foundation slabs, the southern abutment and the pillars D and J where deeper founded. But no foundation was driven down to the base rock. The Wassen bridge crosses the Reuss river on a famous place, nearby the old church of Wassen, which can be seen several times taking the Gotthard railway which in this place uses two U-turns in short tunnels to climbe up the steep valley.

Case : Bridge over the Reuss River

Picture of the bridge

Picture 1: Photo of the Reuss bridges Wassen taken 1975, while bridge load testing setup is in place, view downstream (northbound), just before taking the motorway in service. The cantonal road up the Reuss valley underpasses the bridge in the left part of the picture, showing parts of its sustaining wall.

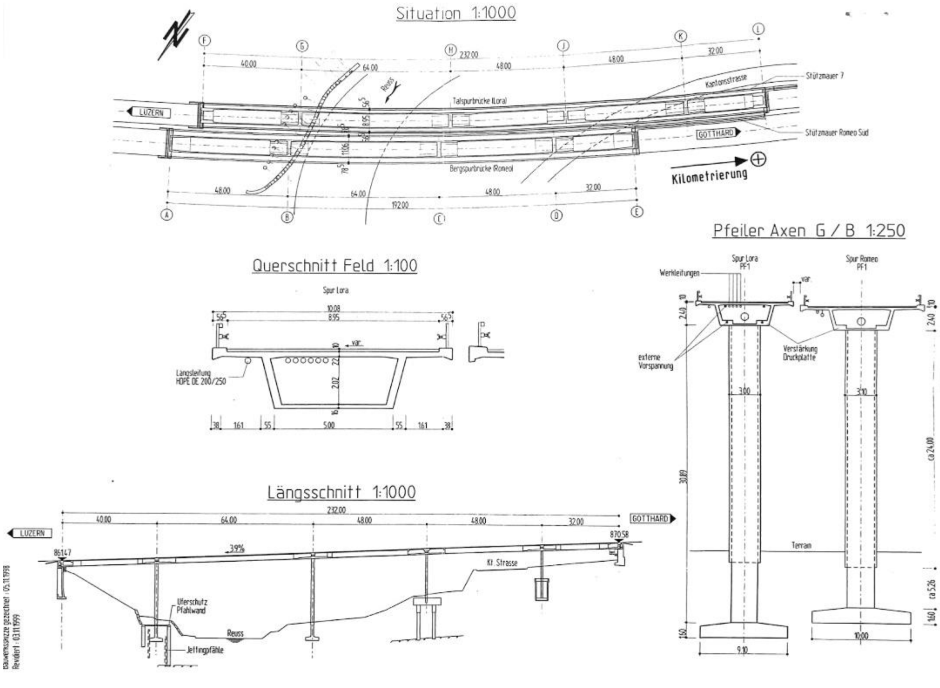


Fig 1: Overview sketch of the bridge, rehab measures introduced

2) Description of the failure.	Provide a detailed description of the failure. Include sufficient relevant context to support the failure being unanticipated or producing unexpected performance.

Answer

1987 was **the** year of the flood catastrophes in the younger swiss history. Several events striked the country, mostly located in the alps. One of this catastrophes was this: In the night from 24. to 25. august, 1987, short but massive rain fall combined with very high temperatures in the central alps led to an extreme flood situation in the whole canton of Uri, parts of the canton Ticion and Valais, in the heart and the southern switzerland. The foregoing weeks where very wet, the ground was soaked with water, and the maximal rain fall occurred at the very end of the event.

The Reuss river delivered a quantity of water to be declared as exeptional high level. Table 1 below shows quantities measured at the delta in Seedorf where the Reuss enters the Lake of 4 Cantons, and statistically expected repeating intervalls in years. This catastrophic quantity was in the range of a 300 yearly interval. It destroyed parts of the Reuss dams constructed 100 years ago, large portions of the cantonal road network and railway network in the canton, and flooded completely two major parts of the liveable area of the canton, one at Andermatt and one on the shore of the lake of 4 cantons – the most populated parts with important touristic facilities, factories and road and railway infrastructure.

HQ 1987 (mit Retention)	820 m^3/s
HQ 1987 (ohne Retention)	1000–1100 m^3/s
Kapazität alter Reusskanal (bordvoll)	rund 600 m^3/s
Grösstes, von 1917-1987 in Seedorf gemessenes Hochwasser:	560 m^3/s
HQ_5	390 m^3/s
HQ_{20}	520 m^3/s
HQ_{50}	620 m^3/s
HQ_{100}	720 m^3/s
EHQ (Extremhochwasser)	1150 m^3/s

Table 1: Reuss river volumes at Seedorf, and yearly intervals

The analysis of historically documented disasters showed that the canton of Uri was repeatedly victim of exceptional flood events, see Fig. 2. The reliable sources end in the beginning 16th century. For the 20th century there was a noticeable "calm before the storm", probably on the one hand in the lower part of the Reuss due to the effect of the dams built 100 years ago, on the other hand in the upper part due to numerous flood protection measures carried out in the course of the construction of the national road and the subsequent optimisation of the cantonal road.

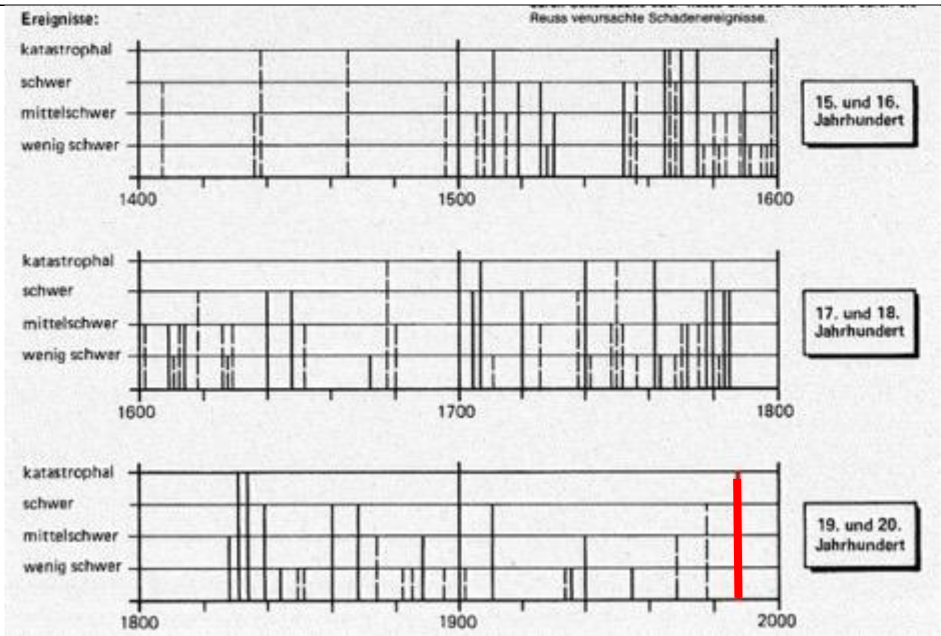


Fig. 2: Documented events caused by Reuss floods with intensity level, red 1987 case

The Reuss river rose and roared down the small valley, raising its bed almost three times wider than before, eroding away tremendous amounts of sand, gravel, blocks under the Wassen Bridge. Fig 3 shows the erosion areas in violet around the Wassen Bridges, and shows locations and designations of their foundations. This erosion pattern, as latter detected in the government sponsored nationwide research, is typical for riverbeds with powerful bedload deposits and long downslope stretches with river loops at the end, as it is found at the Bridges in Wassen. The “regular” Reuss river bed is showed in light blue color. The main streaming direction while the flood is indicated with red arrows.

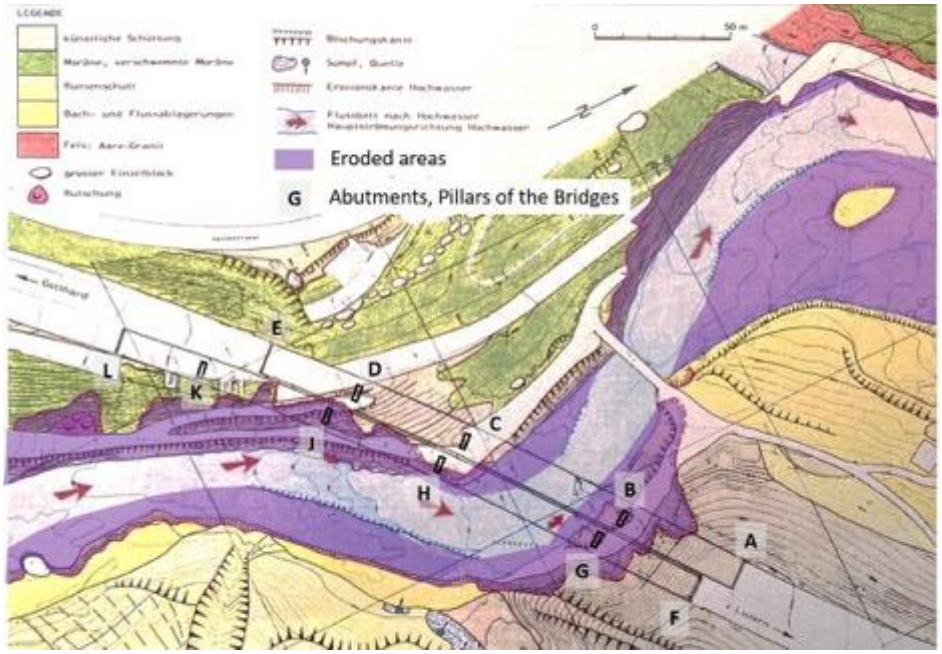
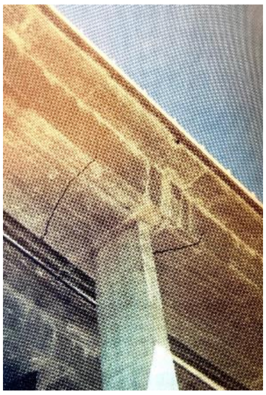
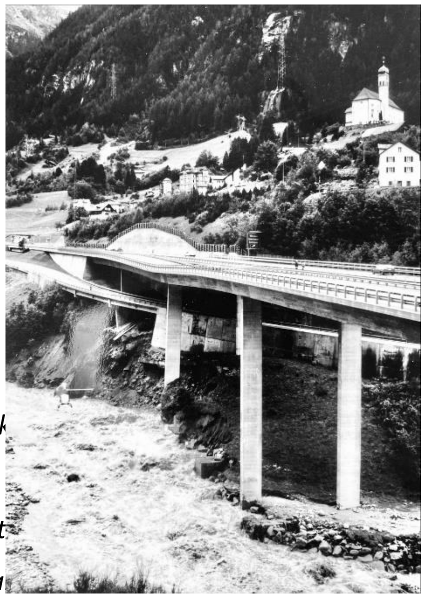
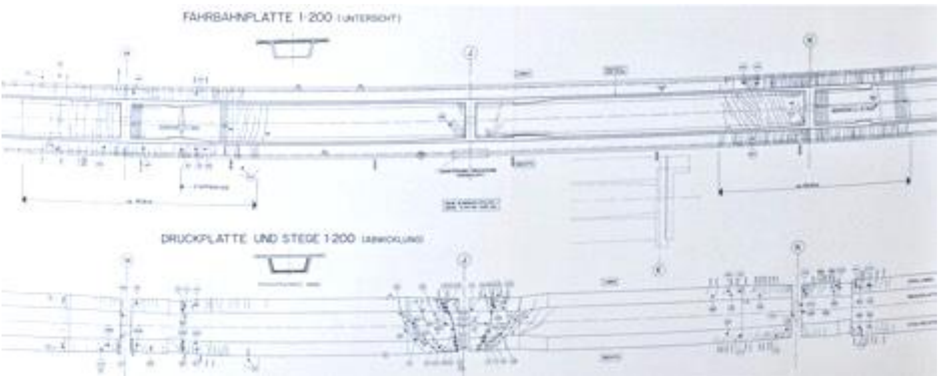
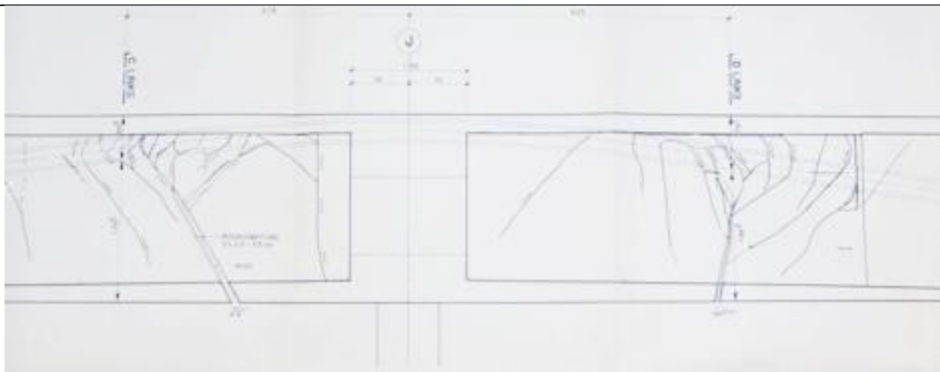


Fig 3: Eroded areas (violet) and foundation of the Wassen Bridge

Case : Bridge over the Reuss River	
	The bended Reuss bed is caused by the rocky hill the Wassen church tops. Because of the right turn the river bed had to do exactly at the place where the bridge is located, the overwhelming waters of the Reuss carved out large portions of the banks under the Lora bridge. The foundation of the first pillar after the southern abutment of the Lora Bridge, axis J, was washed free. While hanging free in the Reuss River after the flood, the foot point of the pillar in Axis J was moved to a point 1.2 m deeper and 0.6 m in transversal direction to the river. The main girder of the Lora bridge over the pillar in axis J was bent downward and rotated. The pillar J was integral part of the structure, with no bearings. Two main cracks opened the box girder on both sides near the pillar end, 70 mm wide on the under side of the lower box girder plate, ending at the post tensioning cables. At this point, the cables where 0.3 m below the deck. One of the two main structural members of the box girder, the outer web, was seperated from the girder with cracks between it and the deck and lower plate, at both sides on a length of about 4 m from the pillar. The outer curb over this area was destrojed because of concrete pressure overload. At the neighboring axes K and H, the deck was cracked over a total length of about 34 m (Axis H) and 28 m (Axis K). This cracks where well distributed, rectangular to the bridge axis and mostly between 0.1 and 0.3 mm. Only a small amount of wider cracks until 3 mm where present, located at concrete pouring joints or places where the post tensioning cables were in a lower area. The web members were cracked from the deck to almost the lower plate in the same areas. This cracks where wider, until 2 mm at the top end, but fewer. The lower plates of the box girder in this areas were without damages. Parts of the foundation of the sustaining wall above the pillar J and parts of the county route under the bridge were washed free, too. The first conclusion was: this bridge, the LORA bridge, has to be replaced.

Picture of the failure	  *Picture 2: Girder Box cracked over Pillar J* *Picture 3:Superstructure lowered by 1.2 m and rotated counterclockwise*  *Picture 4: washed-out foundation Pillar J;* *In the foreground a washed-out framework foundation that remained there.* *In the background the washed-out foundat of the sustaining wall carrying the cantona route.*  *Picture 5:The Reuss bridge Wassen, wounded*  *Picture 6: Supervision of the deck (atop) and folded view at webs and under plate of box girder with marked cracks. In the center Pillar J.*



Picture 7: Main cracks in the web in axis J, largest opening 70 mm

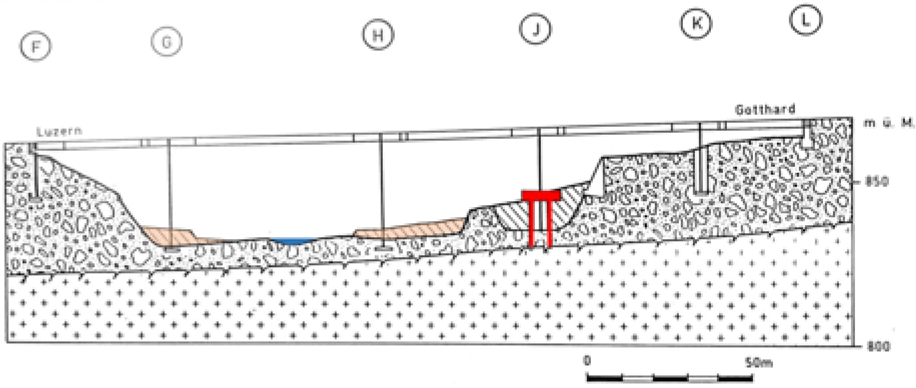
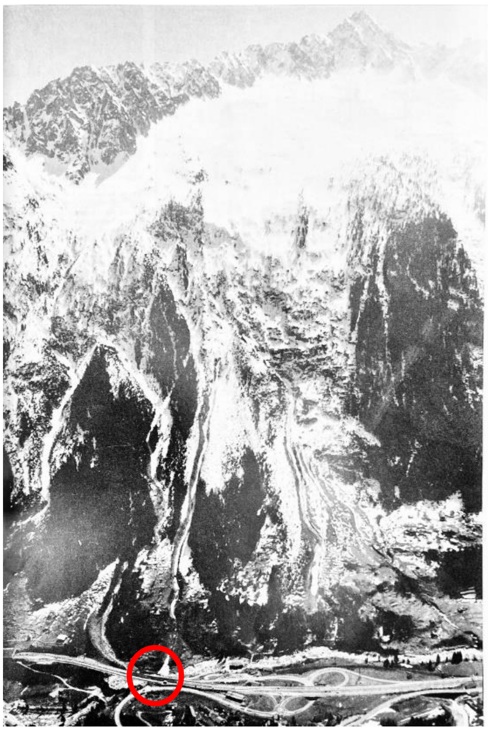
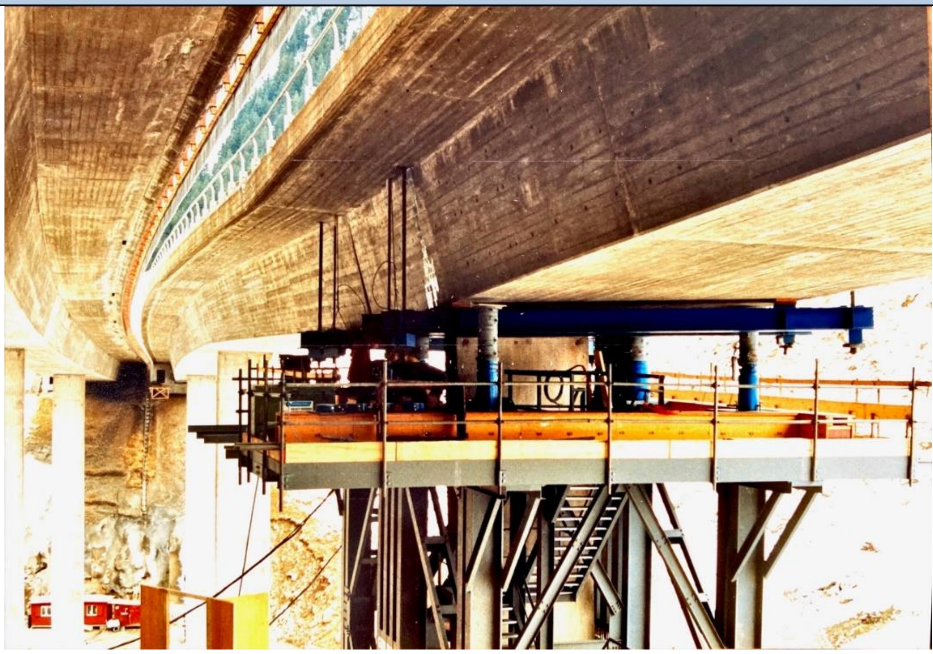


Fig. 4 longitudinal section; base rock, atop gravel, in light brown filled material, in red new foundation of Pillar J. The Reuss is indicated in blue.



Picture 8: The Reuss bridge in Wassen inside the red ring: the potential avalanche situation.

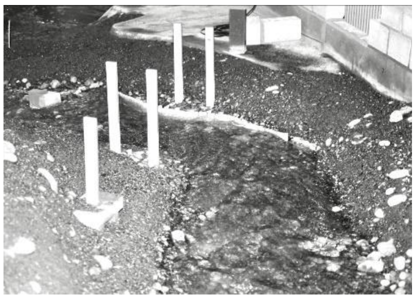
<table>
<tr><th colspan="2">Case : Bridge over the Reuss River</th></tr>
<tr><td></td><td>
Picture 9: Lifting setup, detail. The blue beams and hanging rods are part of securing the broken beam.

Picture 9: Reverse displacement device in place bevore lifting operation. Pilar J with new foundation.</td></tr>
<tr><td>Investigating organization.</td><td>If one or more specific agency or institution has the responsibility to investigate bridge failures in your country, please name them and describe their authorities.</td></tr>
</table>

Case : Bridge over the Reuss River	
Answer	Bridge collapses are very rare events in Switzerland. Therefore, there is no nationwide and specially authorized authority that has the responsibility to investigate such events. On the other hand, due to the liability of the owner of the works, which is laid down in the Swiss Code of Obligations, Article 58, in the case of extensive damage and usually associated with personal injury for which the owner of the works is responsible, an investigation is carried out by the authorities. According to article 58, paragraph 1 of the Swiss Code of Obligations, the owner of the works is liable for the damage caused by faulty installation or poor maintenance of the works. This is a so-called simple causal liability. If a work is defective, the owner of the work is liable, even if he is not at fault. Even proof of due diligence does not exonerate the owner of the work. If there is a defect in the work, he is also liable for an accidental event. Thus, the owner is liable for the defective condition, regardless of whether he knew it or not and whether he would have had the opportunity to avoid it. The owner of the work is liable. It is a prerequisite that the defect in the work is to be regarded as causal for the damage, i.e. causing it. The standard of adequate causality applies. This means that the defect in the work must be suitable, according to the usual course of events and general experience of life, to cause or at least favor damage such as that which has occurred. If the damage is caused by natural events - such as floods - the cantonal authorities are responsible for taking reasonable and possible preventive measures. There are working groups set up by the authorities that can have events of this kind investigated in the sense of research commissions if they are of particular interest. One such group is the Working Group for Research in Bridge Construction, Geotechnics and Tunneling, AG BGT. This group is able to recommend further research, the creation or revision of standards (usually in construction) and publications.
4) Legal constraints.	If there are legal constraints on the transparency or process of a bridge failure investigation in your country, please describe those.
Answer	If an investigation has to be initiated by the authorities - because personal injuries are involved - the results of the investigation are not accessible to the public until the authority has completed the investigation and reached a decision. If an investigation is ordered without an official order, it is the responsibility of the affected work owner who ordered the investigation to regulate the accessibility of the investigation results. Public owners of works are obliged by law to disclose the information at the latest upon completion of the investigation, unless this would involve unreasonable effort.
5) Investigative process.	Please describe how the investigation was conducted. If a standardized and documented process or procedure was used to guide or inform the investigation, please also describe it here and include a copy with your response.

Case : Bridge over the Reuss River	
Answer	There is no standardized method of investigating bridge (partial) failures in Switzerland because, on the one hand, such events are fortunately very rare and, on the other hand, the circumstances are too varied to proceed according to predefined rules. In this case, shortly after the event, the affected canton of Uri set up a superordinate operational organization that had to deal with the following tasks over the entire cantonal territory, divided into two phases according to their priority: Phase I, Immediate Measures, Part Ia: - Saving lives - Establish and secure contact with the upper part of the canton of Uri Phase I, further immediate measures, part Ib: - Close dam breaches - Temporarily restore traffic connections if possible (the Wassen bridge is part of this step) - Remove carcasses - Start clean-up operations - Provisional measures to ensure at least the same level of protection as before the event. This phase began on 25.8.1987 and ended in February 1988 with the reopening of the destroyed cantonal road. In these phases I, emergency law was used in a fast-track procedure; usual project planning steps, plan approvals, and procurement procedures were dispensed with. Phase II, stabilize and improve safety with permanent structures - Project measures for improved flood protection, based on investigations, model tests, overall concept (the Wassen bridge is part of this step) - Present a further flood protection program, based on the latest findings, a higher level of safety with consideration for nature and near-natural hydraulic engineering and the minimization of protective structures; take spatial planning measures such as flood zones. In this phase II, all procedures were implemented within the usual framework, i.e. without emergency legislation.
6) Organizational structure.	Describe the organizational structure used by the investigators.

Case : Bridge over the Reuss River	
Answer	The superordinate organization of the canton of Uri that was deployed had the primary purpose of securing the damage sites, saving human lives and restoring stable conditions to general life, as described above. After initial helicopter inspections, an overview of the situation could be presented on the evening of 25.8.1987 and subsequently the organization presented could be set up. For the reconstruction of the Wassen bridge, a separate, small organization was set up by the cantonal government of Uri at the beginning of September 1987: Superintendent: Federal Office for Road Construction ASB (today ASTRA) Owner: Canton of Uri Project management: Construction Office Uri, Department of Artificial Structures, Altdorf Expert, conceptual design: Prof. Dr. C. Menn, ETH Zurich Geologist: Dr. T.R. Schneider, Altdorf Project author: Ernst Winkler + Partner AG, Wassen General contractor: AG Conrad Zschokke, 8045 Zurich Various laboratories and specialists were consulted, which are not listed here. Certain services were provided by the canton of Uri itself with its own personnel and equipment, such as the permanent overall monitoring of the displacement work with high-resolution measuring sensors in the sub-millimeter range in 3 axes over a period of months. A second project organization was set up for the restoration of flood safety in three phases in the entire bridge area. Specialists in hydraulic engineering, geology, surveying, vibration measurements and contractors in special civil engineering were represented here. The project management was the same as for the bridge reconstruction. In the first phase, the existing situation before the event was reviewed and immediate measures to secure the bridge were designed and implemented. In a second phase, protective measures were designed to preclude damage to the bridge in the event of a recurrence of the August 1987 event. These were checked and optimized using a hydraulic engineering model at a scale of 1:60. This stage revealed the need for scour protection in front of piers B and G, which was constructed in the form of a pile wall. In a third stage, the entire stretch of the Reuss was rehabilitated, including the protective effect of the measures from stages 1 and 2 in the area of the bridge.
7) Investigator qualifications.	Describe the qualifications of those involved in the investigation. Education, licensing, training, experience, etc.

Case : Bridge over the Reuss River	
Answer	The main actors involved in the condition assessment, the design of the reconstruction and the investigation of the hydraulic causes as well as the test-based development of the flood protection measures were trained as civil engineers with a master's degree in civil engineering. The former project author and now expert for the conceptual design, Prof. Dr. Christian Menn, received his doctorate from the ETH Zurich and was at that time full professor for bridge construction. The specialist for geology was a geologist with a doctorate in earth sciences. The laboratories were staffed by people with a wide variety of educational backgrounds. Experts from the Laboratory of Hydraulics at the ETH Zurich were involved in the project to improve flood safety.
8) Investigation documentation.	a. Describe how the failure was documented on-site?
Answer	- Photos were taken in all stages of the event and the reconstruction - Conventional land measurements with tachymeters were used to detect the bridge's actual physical position, the erosion the Reuss created - Crack meters were used to document crack widenings after the event - After a first phase of securing the bridge structure, exploratory drillings were made in the area of the foundations of the bridge in order to find out the exact foundation conditions and the course of the rock surface.
	b. How was physical evidence collected, documented and controlled?
Answer	All findings were collected conventionally and documented in report form. The verification of the facts was done in different ways. For example, the behavior of the Reuss in the event of a flood was checked with a 1:60 model, and subsequently measures to improve flood safety were also tested on it.   Picture 10: high water level, no measures Picture 11: high water level, with protection wall
9) Testing.	a. What type of physical testing was conducted to support the investigation?

Case : Bridge over the Reuss River	
Answer	Hydraulic erosion tests were carried out at the Experimental Station for Hydraulic Engineering of the ETH Zurich to simulate the behavior of the Reuss River in the event of a flood and to confirm planned protective measures. The following construction material tests were carried out on the bridge: - Concrete compressive strengths, concrete tensile strengths, E-moduli - concrete cover measurements - Determination of chloride contents, carbonation depths. Subsoil investigations were carried out to determine the foundation conditions and to determine the position of the rock surface.
	b. If standardized test methods were not used, why not?
Answer	All used laboratory testing methods based on standards, exempt the hydraulic, experimental testing of the flood situation.
	c. How was test data stored and documented?
Answer	At that time, most of the work was still paper-based. The laboratory results and measured variables were recorded in the form of reports, with all the associated supporting documents.
10) Experimentation.	If experimental testing was conducted, please summarize the need, describe the experiments, and outline how the results were used.

Case : Bridge over the Reuss River	
Fragekatalog Answer	Primarily hydraulic tests were carried out in connection with the new design of the protection of the foundations against undermining. The focus was on evaluating measures in three stages and confirming their effectiveness on the basis of tests. In the first stage, the actual situation and immediate measures were modeled, planned and verified. In a second stage, definitive flood protection measures for the foundation of the Wassen bridge were planned, verified on the 1:60 model, optimized and implemented. In a third stage, definitive flood protection measures were planned and implemented in the entire course of the Reuss, taking into account the effect of the measures from the second stage. For the reconstruction of the bridge, the rotation and displacement operations on the superstructure were accompanied by measurements and controlled based on the responses from the structure. After separation of the column from the foundation, the bridge was first rotated back until the compression forces would have resulted in too large an additional torsional effect on the beam. Lifting was then carried out in several phases before the large cracks were closed with injection resin. Subsequently, further lifting was carried out. The non-proportional increases in force found during this process were checked with structural calculations. It was possible to move the bridge back by almost 90%. Further lifting could have overstressed the bridge girder due to redistribution effects. Back creep effects increased these initial back displacements somewhat before the girder over pier J was strengthened and its final position was reached. The measurement campaign was continued in order to control the commissioning of the bridge in the summer of 1988, because the pier was not concreted in again until later. During this time, the bridge was supported on the lifting setup devices in J axis.
11) Bridge files and records.	a. What records (design, fabrication, construction, inspection, etc.) of bridge were collected to support the investigation, and how where they reviewed?

Case : Bridge over the Reuss River	
Answer	Used documents: All drawings, static calculations of the construction time (10-15 years ago) where present and were used. All reports from inspections, performed measures and visits before the failure where analysed: - Full Bridge inspection, performed by the road authority, 15.3.1978 - on-site visits 7.3./2.4.1985 - Full inspection Bridge Romeo, 9.5.1985 - Report of performed repair work, 10.3.1986 - Report of adaptions on installation parts, 196.1986 - Inspection of pillars and sustaining wall, 26.6.1986 - Report of performed repair work nr 13, 19.2.1987 Those reports figured out the following defects and damages: - Pavement displacements on Bridge Romeo - Leaking Expansion Joints (sealing) - Drainage inlets defective; drainage pipes defective in abutments - Concrete of curbs with freeze-thaw damages - Water from drainage of pavement along deck underside - retaining walls adjacent to the bridge with problems of cantilevers, joints, tightness - Chloride-contaminated Pillars nearby the county road - Areas with not good compacted concrete show carbonation until the reinforcement level - Beginning corrosion on bridge bearings The geometry and position of the (now displaced) bridge were surveyed conventionally by measurement (total station, levelling) and compared with the nominal values in situ after the release of the bridge for investigations. Pillar J was measured all along its height to figure out the bending line. Deviations from the design were found up to approx. 5 cm, including differences between the nominal position of the foundation and that of the superstructure. Larger, undocumented deviations were also found in the thickness of the pavement on the deck. The lack of position and settlement measurements immediately after construction or during the operational phase made it difficult to determine the more accurate deformations of the bridge. In order to clearly delineate the effects of the event, extensive crack investigations were carried out on all damaged areas and compared with the investigations from the inspections. In order to determine the exact geotechnical conditions in the area of the foundation of the piers, exploratory drilling was carried out and compared with the assumed conditions at the time of construction. The positions of the expansion joints and the bridge bearings of this floating structure were surveyed and compared with the results of the measurements from the construction period and the position after reconstruction.

Case : Bridge over the Reuss River	
12) Analyses.	What type of analysis or modeling tools (engineering calculation, structural analysis, finite element modeling, others) were used to support the investigation and describe their use?
Answer	For the initial assessment of the condition of the structure in its damaged state, the project author at the time and meanwhile responsible professor for bridge construction at the ETH Zürich, Prof. Christian Menn, and his team carried out considerations based on the damage pattern and simple hand calculations. These showed the urgent need for securing measures on the box girder above column J because, on the one hand, this part of the bridge was only hanging on part of a girder web and, on the other hand, the shear and torsional load-bearing capacity was greatly reduced as a result. The static system was modified in such a way that flow joints were formed above the neighboring supports K and I. The bridge was then strengthened by means of the reinforcement measures. For the strengthening and foundation improvement measures, comprehensive static calculations were carried out to take into account the different stress conditions. Conventional static calculations were performed for the planning of back displacement device, taking into account measured concrete compressive strengths and E-moduli and already realized creeping in the concrete. The stability of the foundations during the event, with the immediate measures and for definite improvements of the foundations as well as the flood protection measures were calculated with soil analysis software. Hydraulic calculations of the actual situation as well as the different project stages were verified on the 1:60 model.
13) Lessons learned.	a. With regard to the cause of failure, what were the findings of the investigation?

Answer	In 1977, after devastating floods in the Schächen valley and on the lower valley floor, the canton of Uri launched a major flood protection program. The accumulation of the flood events and their very large volume of damage within one year – 1987 - prompted the federal government to carry out a nationwide investigation in the sense of a cause analysis. This major work, which took 3 years and showed, among other things, that the event of August 24/25, 1987, will extremely rarely reoccur, but that various favorable factors, such as only partly filled large reservoirs, large karst areas with natural storage volumes and already existing protective structures, were able to prevent even greater damage. Based on the intensive and long-term investigations of various institutes, the main cause is the overestimation of the recurrence period of an event that causes the river Reuss to erode the banks at this river bend to such an extent during the planning in the 1960s. Historical pictures show that the riverbed at this location has not changed much for almost 250 years. This gave the planners and local builders a sense of security. Therefore, these planners and decision-makers cannot be blamed. Possibly, relatively short deep foundations with in-situ concrete bored piles embedded in the granite base rock could have avoided the partial failure, although these would also have been exposed. Today, such deep foundations are usually subjected to a variant study with the criteria of construction time, construction costs, execution risks, long-term reliability. In this case, with a relatively thin gravel layer above the rock, additional costs would hardly be decisive today. In February 1988, model tests were carried out at the Experimental Institute for Hydraulic Engineering of the ETH Zurich in order to verify flood protection measures planned in the meantime for all rows of piers. The very comprehensive flood protection measures carried out from early summer until the end of 1989 in the vicinity of the bridge, such as protecting all pillar rows with comprehensive erosion protection block nets, a protecting pillar row G-B with bored pile walls for a Reuss level bringing twice the amount of water as in august 1987 show the quick reaction to the deficits identified. Other bridge designs also investigated by the project author (i.e. arch bridges, framework structures) would have resulted in foundations in similar locations and possibly even failed in the event 1987. These statements are easily made after the knowledge of the events and the existence of the investigations and are in no way able to do justice to the good basic design of the bridge, the good execution as well as the great effort of all those involved in the excellently set up, well managed and brilliantly executed accomplishment of the reconstruction. This cleverly conceived reconstruction saved a bridge 3/4 of its originally attributed service life, led to a quick reopening after 11 month in July 1988 and saved a far more expensive new construction. The convincing of those responsible on site that the bridge could be pushed back into its original position without being completely broken had to be able

Case : Bridge over the Reuss River	
	to be accepted by all decision-makers first. This decision to investigate in a reconstruction was driven from the superintendent. The exceedingly robust structural design based on the redundant, continuous composite prestressed concrete box girder proved to be very ductile and capable of being almost completely relocated during this partial failure. This, combined with the very daring, rapidly implemented decision to protect the base of the pillar J and the sustaining wall, and the immediate start of securing measures on the superstructure, meant that a catastrophic complete structural failure could be avoided.
	b. What lessons learned were derived from the findings?
Answer	The deficit in determining estimated levels of natural forces and their possible effects on settlements and infrastructures was recognized throughout the country - although not only based on the events of 1987, which, however, intensified the effort. The studies subsequently led to further programs for the preparation of nationwide hazard maps, from which protection concepts for settlements, infrastructure and other areas of use were derived. These concepts resulted in protective measures whose implementation will occupy several generations. In this case, a pile foundation with integration into the rock, which is nevertheless quite close to the surface and of high quality, would be considered in order to reliably avoid settlements on the one hand and to improve the behavior under seismic effects on the other hand. Additional costs compared to the foundation concept used would be low compared to the total investment. It was also known to the planners at the time that these gravel materials covering the rock were all deposited by erosion processes. This also meant that it was only a matter of time before they were further displaced again. The only unknown, then, was the recurrence period of such a large event – which was overestimated, as in answer 2 described. Alternatively or complementarily, far more extensive scour protection measures would be taken today, as they were also subsequently constructed in 1989 and are now standard for foundations in watercourse areas. As a result of these and other – earlier - events, gaps in the responsibility of preventive measures were closed in laws. The management of natural hazards, the planning, construction, monitoring and maintenance of protective structures was recognized as a permanent task of responsible infrastructure owners and municipalities.
	c. How were the lessons learned communicated to the bridge engineering, construction and inspection communities?
Answer	The events of 1987 - not of this individual case, but this one also helped - and their processed findings were reflected in many lecture series and publications, some in standards.
	d. Describe any changes to the state of practice resulting from the lessons learned.

<table>
<tr><th colspan="2">Case : Bridge over the Reuss River</th></tr>
<tr><td>Answer</td><td>From the design phase of the bridge in 1966 to the completion of construction in 1974, no documents have been filed with respect to geology-geotechnics-hydrology-hydraulics-natural hazards. The only references that can be found regarding subsoil are assumed limits of soil pressures under the foundations. These were also cited in the test engineer's report, but not commented on. No geotechnical report is found. The technical work was concentrated on the structure in reinforced and prestressed concrete, in the preparation of the necessary technical drawings and lists. The structural analysis is excellently structured and amazes in its logical, comprehensible presentation and readability. Construction conditions are very well covered. One can see at 1st glance that structural experts were at work here.

Today, subsoil investigations are carried out well in advance in order to have clarity about the foundation of the definitive as well as the construction state. Today, construction in the water space requires that the construction and final condition is also controlled in the case of a flood event, for recurrence periods of at least 100, rather 300 years and for structures of special importance of up to 1,000 years (extreme events). It may also be the case that it is consciously accepted that flooding of individual construction sites may occur during construction if the cleanup effort is in a favorable ratio to otherwise more costly protective measures.

These are general developments in the handling of projects that have found their way into standardization in the course of the last 50 years.

The lessons learned from this case may be drawn from the incredible reserve resulting from the ductile behavior of prestressed concrete construction - assuming a clean structural design.

Also impressive is the possibility of being able to shift heavily deformed structural components that are already creeping almost completely back to their original state. In this process, back creep processes again take place, which benefit this approach.

The documented good behavior after the complex but successful reconstruction is a further lesson in how good-natured and "forgiving" reinforced and prestressed concrete structures react to such unusual actions.

All this is only possible if good but feasible concepts can be implemented – this are experts tasks.

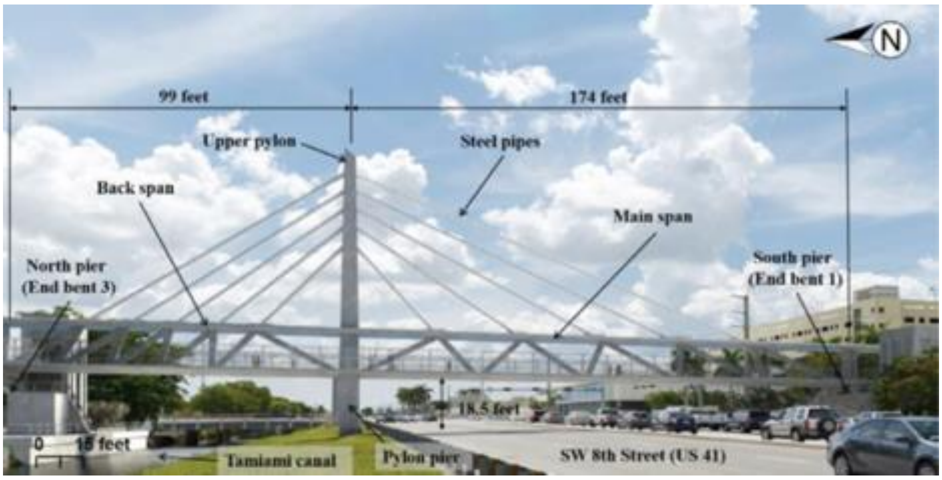
This prestressed concrete structure - like prestressed and most reinforced concrete construction in general, provided that it is carefully designed and implemented - can therefore justifiably be regarded as extremely robust.</td></tr>
<tr><td></td><td>e. Identify any challenges the resulted from the process or procedure used to conduct the investigation, and any recommended changes to the approach or methodology used to address those challenges or otherwise result in improvements.</td></tr>
</table>

Case : Bridge over the Reuss River	
Answer	The biggest challenge was the enormous time pressure. This resulted not only from the economic and construction situation, but also because the coming winter with not only very cold temperatures but the high risk of avalanches usually makes all construction activities in this region impossible, sometimes for weeks. No recommendations can be made for other types of investigation procedure; exemplary work and documentation were carried out here.
14) Other impacts on the investigation.	a. If there was a need for a timely repair to address a long detour or simply the restoration of service, please describe how that need impacted the decisions made or process used for the investigation.
Answer	The failure of the foundation in Axis J of the Lora Bridge in Wassen, the washed and partly destroyed local road and local as international railway system reduced the infrastructure to only one remaining path from upper to lower canton Uri and directly to Ticino (if a detour over several high pass roads (which are closed in winter) and more than 100 km was not acceptable): the Romeo Bridge in Wassen, part of a divided motorway, which had no other major defects. Therefore, not only the increased commuting costs were a decisive factor, but the entire interrupted economic logistics, security logistics. So, a quick solution to reopen the motorway in both directions was essential and a very high priority in the process of mastering this crisis. Investigation and construction costs were not top criteria. One of the first steps was to protect the Lora Bridge from collapsing, in case the now unstable sustaining wall of the county road would slip down and bend the Pillar in Axis J more, tearing it down in the river and completely breaking the box girder. With this done, a small portion of time was gained to decide whether there is a solution to reconstruct the bridge, to replace it partly or to replace it completely. The steps taken, the measures evaluated, the setup of the organisation: all focused to find a quick way to prevent a complete collapse of one of the bridges, but in a safe way. Second goal was to find a quick was for a reopening. Third goal was to investigate how to prevent a 2nd failure. Fourth goal was to improve the security levels, based on the investigations.
	b. Please describe how financial considerations (potential cost of the investigation, cost to the traveling public, cost of the repair, etc.) impacted the decisions made or process used for the investigation.

Case : Bridge over the Reuss River	
Answer	The investigation costs where not a topic, because the almost complete out-of-use of all transportation in this time of the year entailed very costly measures to keep life above Wassen going halfway. The measures taken to investigate had two aspects: do they deliver useful facts and do they so in a reasonable time? The main objective was to be able to put this highway link back into operation as quickly as possible. It was therefore necessary to find out whether the bridge could be repaired, whether the superstructure and parts of the foundation had to be replaced or whether a complete new construction had to be considered. The background to this objective was, of course, user costs for the immense detours, at least for the local population, as long as the cantonal road was also not passable. The maintenance or construction costs were of secondary importance. The costs for necessary improvement measures to increase the safety against such natural events had to be spent in any case, whether repair or new construction, and played no role in the investigations.
	c. Please describe any additional considerations or risks that impacted how the investigation was conducted and what those impacts were.
Answer	In the first hours after the flood, the risk of a complete collapse of the Lora Bridge was unpredictable. To reduce this risk, which hindered all actions around the bridges, the deciding committee found only one way: To prevent the sustaining wall from sliding down in the Reuss river, moving Pillar J further and raising the rotation in the box girder. The committee figured out only one feasible measure: to bring in as much gravel and rock material as possible in front of the pillar J foundation and the sustaining wall as quickly as possible – even if this is a high danger mission for all people involved in the execution. In fact, 15’000 m3 of rock and gravel was unloaded to enclose the pillar foundation and support the sustaining wall in 4 days working round the clock after the decision was taken. After this first high-risk but in the end risk-reducing task, investigations and rehabilitation studies started. Further risks were additional, possible flood events and avalanches, which occur regularly and lead to complete shutdown of all activities in the endangered areas for days or even weeks in Winter. Picture x gives a good impression of the potential avalanche risks around the bridge.

8.19. Case Study 18: United States Bridge Collapse

<table>
<tr><th colspan="2">Case : Florida International University Pedestrian Bridge</th></tr>
<tr><td>1) Brief description of the bridge (type, material, year of construction, …</td><td>Provide a short description of the bridge including bridge type, material (steel, reinforced concrete, prestressed concrete, timber, masonry, …), year of construction, span lengths, …</td></tr>
<tr><td>Answer</td><td>The Florida International University (FIU) Pedestrian Bridge was a single-plane prestressed concrete truss with a main span of approximately 53m. The bridge was under construction in March 2018 when it collapsed.</td></tr>
<tr><td>Picture of the bridge</td><td>The following is an architectural rendering of the completed bridge:



</td></tr>
<tr><td>2) Description of the failure.</td><td>Provide a detailed description of the failure. Include sufficient relevant context to support the failure being unanticipated or producing unexpected performance.</td></tr>
<tr><td>Answer</td><td>The FIU Pedestrian Bridge experienced a catastrophic structural failure within the node connecting truss members 11 (diagonal) and 12 (vertical) and the bridge deck at the north end of the main span. As a result, the bridge span fell about 5.5m onto SW 8th Street, which consists of four through travel lanes and one left-turn lane in the eastbound direction, and three through travel lanes in the westbound direction. Two of the westbound lanes below the north end of the bridge were closed to traffic at the time of the collapse; however, one westbound lane and all five eastbound lanes were open. At the time of the collapse, a construction crew was working on retensioning the post-tensioning rods within the diagonal truss member 11, connecting the bridge canopy and the deck at the north end. Eight vehicles located below the bridge were fully or partially crushed. One bridge worker and five vehicle occupants died. Five bridge workers and five other people were injured.</td></tr>
</table>

Case : *Florida International University Pedestrian Bridge*	
Picture of the failure	This photograph shows the main span shortly after collapse: 
3) Investigating organization.	If one or more specific agency or institution has the responsibility to investigate bridge failures in your country, please name them and describe their authorities.
Answer	In the U.S., the National Transportation Safety Board (NTSB) has the legal authority to investigate all bridge failures. The NTSB is an independent federal agency dedicated to promoting aviation, railroad, highway, marine, and pipeline safety. Established in 1967, the agency is mandated by Congress through the Independent Safety Board Act of 1974 to investigate transportation accidents, determine the probable causes of the accidents, issue safety recommendations, study transportation safety issues, and evaluate the safety effectiveness of government agencies involved in transportation. Although the NTSB has the authority to investigate all bridge failures, it does not have the obligation. As a result, investigations that do not involve a loss of life or are readily explained are often left to be investigated by the public owner or authority.
4) Legal constraints.	If there are legal constraints on the transparency or process of a bridge failure investigation in your country, please describe those.

Case : *Florida International University Pedestrian Bridge*	
Answer	The Federal government and each State government have freedom of information or transparency laws that typically make all information developed during an investigation available to the general public after the deliberative process is completed and findings have been made. For NTSB investigations, the digital files of all data and information developed are available in a single docket through their website. Investigations lead by others have disseminated this information in a variety of ways, generally upon request, but sometimes also through publishing on a dedicated website. By law, NTSB has the authority to determine all facts for investigations in which they lead.
5) Investigative process.	Please describe how the investigation was conducted. If a standardized and documented process or procedure was used to guide or inform the investigation, please also describe it here and include a copy with your response.
Answer	Once victims are recovered, the accident site is controlled by the NTSB. In general, after a survey of the site and damage to the structure, NTSB gathers the parties involved to develop a course of action. There are generally parallel efforts for each investigation; bridge (structures, geotechnical and hydraulic) factors, human-factors (behaviors), vehicle factors, survival factors, and possibly others. Each line of investigation may rely on interviews of people directly and indirectly involved including witnesses, a review of all documentation relevant to the design, fabrication and construction of the bridge, an observation and assessment of the collapsed structure, standardized testing of the materials and equipment involved, analytical evaluation, and experimental testing or investigation. Once all needed lines of investigation are complete, the NSTB investigation staff conduct an overall analysis of the information developed and present a determination of probable cause to the Safety Board (an appointed 5-member panel of safety experts). Once the Board accepts the determination and recommendations, the information developed and relied upon for that determination become the facts of the investigation.
6) Organizational structure.	Describe the organizational structure used by the investigators.

Case : *Florida International University Pedestrian Bridge*	
Answer	The NTSB uses a party system to investigate failures. While NTSB maintains the lead, all interested parties are invited to participate and contribute, including parties that may or are likely culpable. For this investigation, the parties included several Federal, State and local public agencies, law enforcement, the owner, the design consultant, the construction contractor, construction inspectors, and others. All parties share in the information and data developed and all have the opportunity to submit an analysis of that information and data for consideration by the NTSB.
7) Investigator qualifications.	Describe the qualifications of those involved in the investigation. Education, licensing, training, experience, etc.
Answer	The investigative staffs of the NSTB are made up of high technical engineers, scientists, psychologists and others. The NSTB supplements there staff by leveraging expertise from other Federal agencies when elements of the accident being investigated fall outside of their core competencies.
8) Investigation documentation.	a. Describe how the failure was documented on-site?
Answer	Photographs, videos, LIDAR, laser scanning, surveying, notes and other measurements where used to document the site.
	b. How was physical evidence collected, documented and controlled?
Answer	Samples of the bridge materials where collected as well as entire elements. In addition, some of the construction equipment was impounded. All materials and equipment were catalogued and stored in a controlled access facility.
9) Testing.	a. What type of physical testing was conducted to support the investigation?
Answer	The concrete and steel, both passive and active, used in the construction of the bridge were tested to verify properties. Also, the hydraulic equipment was used was tested to be sure it was operating within expected parameters.
	b. If standardized test methods were not used, why not?
Answer	The material testing all utilized standardized test methods.
	c. How was test data stored and documented?
Answer	All test data and specimens were stored in a controlled access facility. The data produced was documented in reports and submitted to the NTSB to share with all parties to the investigation.

Case : *Florida International University Pedestrian Bridge*	
10) Experimentation.	If experimental testing was conducted, please summarize the need, describe the experiments, and outline how the results were used.
Answer	There was no need for additional experimental testing during this investigation.
11) Bridge files and records.	a. What records (design, fabrication, construction, inspection, etc.) of bridge were collected to support the investigation, and how where they reviewed?
Answer	The documents identifying the standards required for design and construction, design calculations, construction plans, construction inspection reports, email, text messages, material certifications and test results, contract documents, financial documents, project status reports and others. All parties to the investigation had access to this information.
12) Analyses.	What type of analysis or modeling tools (engineering calculation, structural analysis, finite element modeling, others) were used to support the investigation and describe their use?
Answer	Both engineering calculation and analytical modelling were used to support this investigation. After errors were found in both the original design calculations and the original analytical modelling, additional calculation and modelling were conducted to verify and identify the source of those errors.
13) Lessons learned.	a. With regard to the cause of failure, what were the findings of the investigation?
Answer	The investigation determined that design and analysis errors made by the Engineer of Record were the probable cause of the accident.
	b. What lessons learned were derived from the findings?
Answer	The lessons learned included the need for more rigorous evaluation of analytical results and for a proper independent evaluation of design calculations.
	c. How were the lessons learned communicated to the bridge engineering, construction and inspection communities?
Answer	Through the NTSB public hearing and accident report. The design specifications have been updated to provide more emphasis in areas where errors were made. A training course on the use of advanced analytical methods was promoted.

Case : *Florida International University Pedestrian Bridge*	
	d. Describe any changes to the state of practice resulting from the lessons learned.
Answer	No significant changes.
	e. Identify any challenges the resulted from the process or procedure used to conduct the investigation, and any recommended changes to the approach or methodology used to address those challenges or otherwise result in improvements.
Answer	The control of the use of information and data did become a challenge during this investigation due to some of the parties involved violating their written agreements. Those parties were appropriately admonished during the public hearing.
14) Other impacts on the investigation.	a. If there was a need for a timely repair to address a long detour or simply the restoration of service, please describe how that need impacted the decisions made or process used for the investigation.
Answer	N/A
	b. Please describe how financial considerations (potential cost of the investigation, cost to the traveling public, cost of the repair, etc.) impacted the decisions made or process used for the investigation.
Answer	N/A
	c. Please describe any additional considerations or risks that impacted how the investigation was conducted and what those impacts were.
Answer	Once the results of the investigation started to indicate the source of the probable cause, not all parties to the investigation acted in good faith in producing data and information that was complementary and not simply an intended distraction.

GLOSSARY

Term	Definition
ADT	Average Daily Traffic
AIC	Accident Investigation Committee
CEREMA	Centre for Studies and Expertise on Risks, the Environment, Mobility and Urban Planning)
DIN	German Institute for Standardization Registered Association
FEM	Finite Element Model
FHWA	Federal Highway Administration
FIM	Forensic Information Modeling
GRDR	Gestión de Riesgo de Desastre Regional
HIC	High Income Country
IFSTTAR	French Institute of Science and Technology for Transport, Development and Networks
LMIC	Low- and Middle-Income Countries
NDE	Non-Destructive Evaluation
NDT	Non-Destructive Testing
NTSB	National Transportation Safety Board
PIARC	World Road Association
TC	Technical Committee
USA	United States of America
3D	3 Dimensional

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