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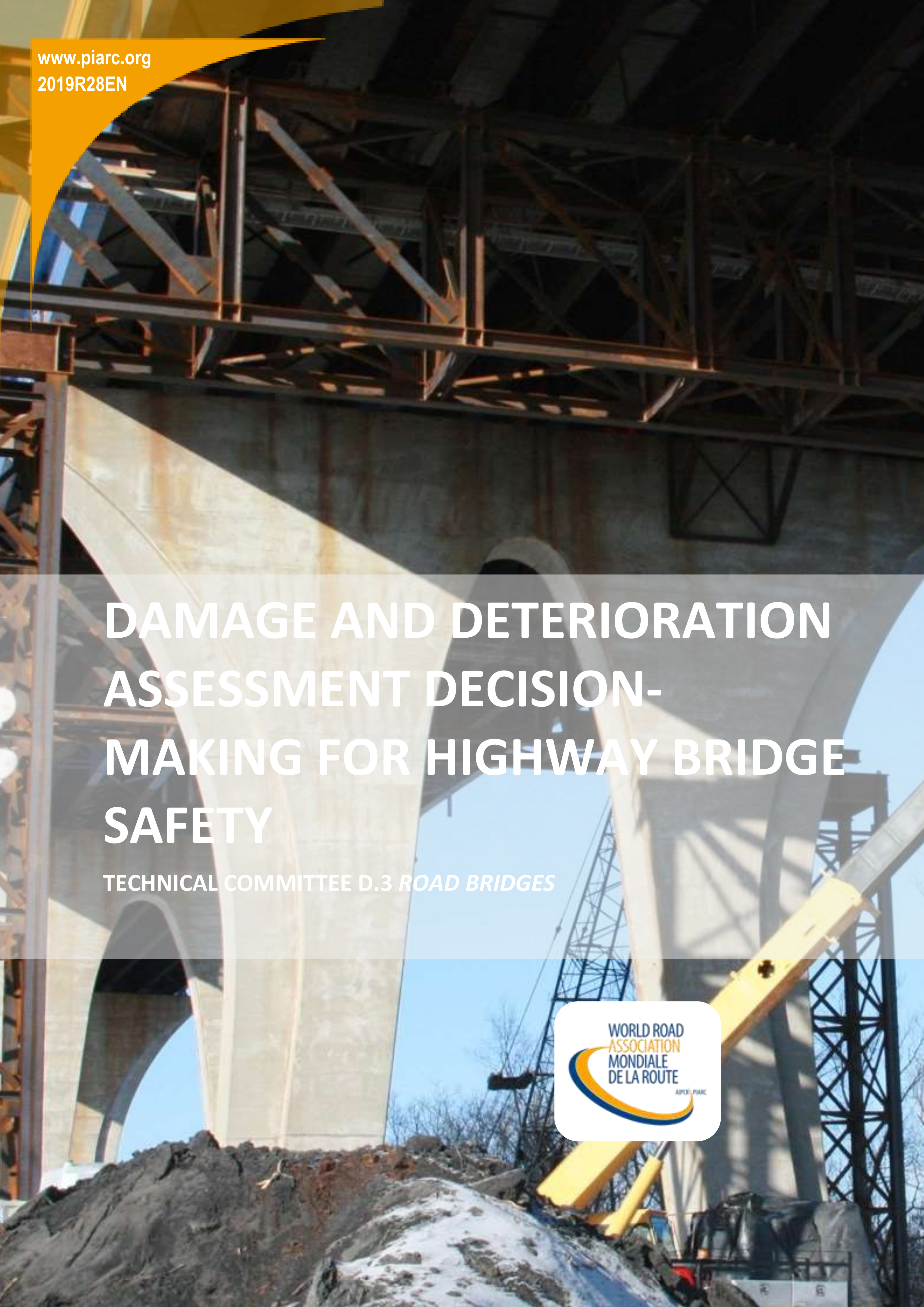

DAMAGE AND DETERIORATION ASSESSMENT DECISION-MAKING FOR HIGHWAY BRIDGE SAFETY

TECHNICAL COMMITTEE D.3 *ROAD BRIDGES*

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 2016– 2019 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

2019R28EN

DAMAGE AND DETERIORATION ASSESSMENT DECISION-MAKING FOR HIGHWAY BRIDGE SAFETY

Bridge owners in most countries routinely assess bridge damage and deterioration to ensure the safety of the traveling public and appropriately manage the service life of a bridge. While in service, bridge owners discover damage or deterioration under two main circumstances. Firstly, damage or deterioration resulting over longer periods of time, and secondly damage or deterioration appearing instantaneously. "Triggers" or causes of this damage or deterioration include; environmental impacts, increased live loads, deicing applications, poor detailing in the design phase, poor construction materials and specifications, severe loading events, natural disasters, impacts, construction defects or by human error. At times, this discovery of damage and deterioration may lead to a bridge closure, traffic restriction, or weight restriction. This will result in damage assessment techniques, load carrying capacity calculations, and subsequent remedial works to return the bridge into service.

The objective of this paper is two-fold; (1) to provide an updated perspective on best practice damage assessment techniques used by bridge owners around the world and (2), to produce a decision process for bridge owners to use as a guide during any damage assessment. The PIARC TC D.3 Bridges Technical Committee workgroup determined a general questionnaire would be required to accomplish the first objective and a diverse collection of worldwide case studies was necessary for the second objective.

The bridge damage assessment techniques were evaluated from responses from 14 countries whom provided several techniques employed in their respective countries. The bridge assessments techniques were compared to results from the 2011 RO7 "Inspector Accreditation, Non-Destructive Testing and Condition Assessment for Bridges" World Road Association report to determine new trends or confirm exiting techniques.

28 worldwide case studies were received from 15 unique countries. The workgroup took a unique approach with these worldwide case studies by using them to evaluate a draft decision-making process. The results of this evaluation were then used to verify, revise and augment the decision-making process. In addition, influencing factors with respect to the decision-making process were identified.

Owners can use the upcoming PIARC produced report decision making process as an important reference with respect to the current damage assessment techniques or to guide them through a bridge incident to ensure the safety of the traveling public.

CONTENTS

1. INTRODUCTION

Highway bridge owners in most countries routinely assess bridge damage and deterioration to ensure safety and structural performance for the traveling public. While in service, bridges experience a variety of incidents involving damage or deterioration. Owners discover this damage or deterioration usually under two main circumstances. Firstly, damage or deterioration resulting over longer periods of time, and secondly damage or deterioration associated with an event or incident. “Triggers” or the initiating actions for these circumstances are described as follows:

Gradually appear over longer periods of time:

Caused by environmental impacts, repetitive or increased live loads, deicing applications, poor detailing in the design phase, poor construction materials and specifications, or insufficient maintenance. Example include:

- corrosion of steel, reinforcement and cables,
- cracks in concrete,
- stone and brick degradation,
- leakages through inadequate joints or poorly maintained drainage systems,
- fatigue cracks due to cyclic loading,
- frozen bearings,
- degradation of materials.

Incident based:

Caused by severe loading events, natural disasters, impacts, construction defects or by human error. Example include:

- extreme weather events,
- earthquakes,
- fires,
- failures or fractures of key structural components, and
- impacts of vehicles or vessels.

Typically, longer term deterioration can be assessed and monitored over a structure’s service life by inspection programs that exist in most countries. The deterioration processes and damage to a bridge structure and/or its components or elements are routinely identified through bridge inspections. Inspections in most countries typically include a condition assessment process that attempts to quantify the state of repair of a bridge. It must be noted that condition rating assessment procedures varied from one country to another. It is important to note that bridge inspections do not provide a direct measure of the load carrying capacity and the associated level of safety for the traveling public. In some countries, a safe live load carrying capacity determination, sometimes called a load rating, is required after an inspection if the conditions of the bridge or the loading on the bridge have changed.

Alternatively, incident based damage or deterioration due to exceptional events usually requires immediate action on the part of the bridge owner, primarily to decide whether a bridge can safely carry the traffic and truck loads to which it is open. Such decisions are generally based on engineering judgement, how well the responsible person/s can assess the effects of damage on performance of the structure and the safety of its users. There are several influencing factors considered in this decision process including: resources, education and experience, data, and risk.

1.1. OBJECTIVES

The objective of this report is two-fold:

1. Provide an updated perspective on best practice damage assessment techniques used by bridge owners around the world, and
2. Produce a decision-making process for bridge owners to use as a guide during any damage assessment. This decision-making process shall elaborate on influencing factors involved and provide guidance to countries on considerations of these factors based on their unique situation, organizational structures and available resources.

1.2. METHODOLOGY

Workgroup 3 from the Bridge Technical Committee (TC) D.3 determined a general questionnaire would accomplish the first objective and a diverse collection of worldwide case studies would be necessary to fulfil the second objective. The workgroup took a unique approach with these case studies by using them to evaluate a draft decision-making process. The results of this evaluation were then used to verify, revise and augment the decision-making process.

A sample case study format and general questionnaire were delivered to all workgroup countries prior to the TC D.3 meeting in September of 2016. The responses were evaluated and the results used to revise the case study format where necessary. A request was then delivered to the entire TC D.3 Bridges Technical Committee to submit two case studies and to complete a general questionnaire. Three sample case studies were provided with this request to assist countries with completing the two case studies of their response.

15 questionnaires were received from the request to the countries. The damage assessment techniques reported were categorized and identified as best practice. Also, as part of this analysis, the RO7 “Inspector Accreditation, Non-Destructive Testing and Condition Assessment for Bridges” of the World Road Association (PIARC, 2012) was referenced to determine the new trends or to confirm the exiting techniques.

In addition, 28 case studies were received in response to the request made to the participating countries. A separate standalone document was created to record these worldwide case studies for future reference. All 28 case studies were evaluated against the draft decision-making process and it was determined that every case study generally followed the series of decisions and actions described in this process. The resulting decision-making process is provided in this document as a guideline for bridge owners to use during damage assessments.

2. DEVELOPMENT OF THE GENERAL QUESTIONNAIRE AND CASE STUDY TEMPLATE

The workgroup determined that the format and complexity of the general questionnaire should reflect the practices, procedures, and experiences shared by group members. This process was also used to determine the case study template. As mentioned previously, the template was finalized by testing it against all case studies and updating it accordingly.

The general questionnaire collected the descriptions of specific techniques and general methodologies used for damage assessment evaluations used by the responding countries. Countries were asked for descriptions of several specific techniques or technologies used in their respective country of the members of the workgroup.

The case study template is based on the application of these rules in practical cases related to recent incidents on bridges. General descriptions of the general questionnaire and case study template follow.

2.1. GENERAL QUESTIONNAIRE

The general questionnaire consisted of two parts:

1. General organization with respect to bridge incidents or events
2. Focus on specific damage assessment techniques or technologies

The general organization section contained the following:

- Description of the bridge management of the bridge procedures and resources available
- List of manuals, flow charts, policies, and forms used in response to incidents and when making decisions for special inspections and/or assessments
- Description and definition of the special inspections and the assessment techniques and technologies employed
- Identification of the special inspections that are most common
- Identification of the damage assessment techniques or technologies that are most common

The focus on a specific assessment technique or technology section contains the following:

- A description of the specific assessment technique or technology
- The type or level of licensing or certification required for the inspector or technician performing the specific assessment technique or technology
- Identification of the organization or party responsible for analysing the results
- Any discussion on how the reliability of results is maintained

2.2. CASE STUDY TEMPLATE

The case study template was developed to capture damage assessment techniques and evaluation models used by countries around the world. In addition, the template was developed to determine how the decisions were made by the owning authority and identify common elements of a decision-making process. This process is intended to provide a framework to develop information to compliment engineering judgement used in decisions. It will identify considerations and influencing factors that can assist bridge owners when they need to react to damage or deterioration events within their bridge inventory.

The case study template collected information with respect to bridge events involving damage and assessments. The architecture of the case study template consisted of four sections. These sections provided more elaborate detail with respect to the event and final resolution. Below is a table representing the case study template:

1.0 Event or incident
- Description of the bridge
- Picture of the bridge
- Description of the event and the trigger that caused the assessment
- Date of the event
- Description of the immediate reactions to this event
- Qualification and organizational responsibility of the agents who made the immediate assessment
- Qualification and organizational responsibility of the immediate decision-maker.

2.0 Decision making process
- Description of the strategies, actions or outcomes in determining what assessments or special inspections were chosen
- Description of the decision-making process
- Qualification and organizational responsibility of the final decision-maker
- Description of the pertinent data available at the time of the decision,
- Influence of the timeframe of returning the bridge to full service,
- Was an engineering calculation made prior to the assessment? If so, in 2D or 3D?
- Description of potential temporary or permanent fixes considered at the time of the decision.

3.0 Description of special inspections, and damage assessment techniques used in this specific case study

4.0 Description of load calculation model and the application of damage or deterioration to that model
- Description of the load model, calculation, 3D versus 2D analysis, methods or techniques used
- Integration of the results of the special assessment or techniques in the load capacity calculation

5.0 Event or Incident Resolution
- Date event or incident resolved
- Results, outcomes, lessons learned

2.3. ANALYSIS OF GENERAL ORGANIZATIONS

The questionnaire was sent to the committee members in January 2017. Answers were received from the following 15 countries:

Austria	Australia	Belgium	Canada
China	France	Japan	Mexico
Netherlands	Norway	Poland	Slovenia
South Africa	Spain	USA - Wisconsin	

Bridge inspection and management practices reported by these countries are rather diverse. Still, several common themes were found in the responses, including:

- Technical regulations for assessment and management of bridges exist or are used in all countries, but with different levels of authority including codes, specifications, guidelines and recommendations.
- These regulations require that inspections or technical visits are performed periodically.
- Inspections are typically divided into:
    - *superficial* inspections, performed on a daily basis by the road maintenance teams,
    - *regular* inspections (also called *periodic*, *assessment*, *general* inspections),
    - more in-depth *major* inspections (also called *main*, *condition* or *principal* inspections), and
    - *special* inspections (also called *emergency*, *specialised*, *exceptional* or *observation* inspections), which are performed on demand.
- The intervals for regular inspection ranged from 1 to 5 years, with 2 years being the most common period.
- The intervals for major inspection ranged from 2 to 10 years, with 5 to 6 years being the most common period.
- Many regulations or guidelines deal with assessment techniques in response to an exceptional or extreme event (natural disaster – flooding or earthquake, structural component failure, discovery of serious deterioration, vehicle impact, etc.). In some cases, policy manuals were prepared for specific structures, such as important tunnels or long-span bridges.
- Each country presented at least one assessment technique that is used in case of exceptional events.
- For safety, most reactions to an exceptional event included an immediate evaluation and precautions such as closure of the bridge or one (or more) of its traffic lane, a restriction on truck traffic, or further assessment. In some cases, no precautions were necessary.
- Assessment techniques, special inspections or investigations are generally used when evaluating damage on a structure.
- All these actions are performed and analysed by specialist engineers, inspectors or technicians. In most cases these were registered engineers or certified inspectors, with minimum required level of experience and appropriate professional qualifications.
- Some countries perform accreditation of these expert's credentials and pursue quality control procedures.

Table 1. summarises the bridge inspection practices and actions in cases of incidents in the fifteen countries that returned answers to the questionnaire.

Table 2. lists the key regulations and guidelines used for inspection and management of bridges, as provided by different countries.

	Regular Inspection (months)		Major Inspection (years)		Special Inspection	Emergency Event Procedure	Prevailing Inspection for Incidents	Technology Employed When Incidents Occur
Australia	Routine	12	Condition Rating	2-5	On Demand	According to App. F of the Structures Inspection Manual	Special Inspection	Special Inspections, material testing, structural analysis, SpaceGass analysis
Austria	Regular	24		6	On Demand	According to ONR 24008	Special Inspection	Special inspections suggested in the inspection report
Belgium	Periodic	12-72			On Demand		Special Inspection	Special inspections, as required: material testing, structural analysis, monitoring
Canada	Regular				Observation Inspection, e.g. Every 6 Months		Regular and Observation Inspections	Load tests, monitoring
China	Periodic	12			On Demand, *Specialized* or *Emergency*	Several Standards	Emergency Inspection	Detailed inspection and any test that may be required
France	Assessment	36	Detailed (some bridges)	6	Exceptional, On Demand	According to ITSEOA	Exceptional detailed inspections by expert or specialist	Reinforced survey (monitoring) or high survey (risk of collapse), IQOA and Risk Analysis
Japan	Periodic	60			Within Periodic?		Additional Inspection	Additional inspection, NDT depending on condition of inspected members
Mexico						According to SIPUMEX BMS		SHM, NDT (UT, PT, AE), material tests, including failure analysis
Netherlands	Condition		Major	6		According to Inspection Framework Rijkswaterstaat	Re-evaluation (recalculation + inspection)	According to Inspection Framework, tests as required (material, X-ray, thermographic, laser scanning, acoustic)
Norway	General	12-24	Major	3-10	On Demand	According to Policy Manual N401	Special Inspection?	Necessary tests and procedures according to Policy Manual N401
Poland	Regular	12	Major	5	On Demand		Bridge inspector visits the bridge and defines further action	As required by special inspection (material properties, proof testing)
Slovenia	Regular	24	Main	6	On Demand		Special Inspection	For critical infrastructure according to policy manuals, otherwise immediate inspection and any test that may be required
South Africa	Routine	24	Principal	5	Emergency, On Demand	According to procedure in National Standard	Special Inspection?	Diagnostic testing services
Spain	Basic	15	Main	5	On Demand		Special Inspection	As required by special inspection, including material testing, underwater inspections
USA - Wisconsin	Routine	24	For Special Structures		In-Depth Inspection, On Demand	According to Section 2.2 of the Wisconsin Bridge Manual	In-Depth, Underwater Diving	Depending on the incident, including NDT, underwater diving

Table 1.Bridge inspection practices and actions in cases of incidents in 15 countries

Country	Regulations or guidelines	Reference
Australia (Queensland)	Structure inspection Manual of the Department of Transport and Main Roads	(DTMR, 2016)
Austria	Bewertung der Tragfähigkeit bestehender Eisenbahn und Straßenbrücken	(ONR 24008, 2006)
Belgium	Règlement de Gestion des Ouvrages d’art	
Canada	Ministry procedure for the monitoring of structures	
China	Code for maintenance of highway bridges and culverts Standard for Technical Condition Evaluation of Highway Bridges and 14 others	(JTG H11, 2004) (JTG/T H21, 2011)
France	Instruction technique d’entretien et de surveillance des ouvrages d’art	(SÉTRA, 2010)
Japan	Guidelines for periodic bridge inspections	(MLIT, 2014)
Mexico	SIPUMEX bridge management system	(SIPUMEX, 2012)
the Netherlands	National law on maintenance of infrastructure	
Norway	Policy manual: Manual N401	(Vegvesen, 2017)
Poland	Management system for bridge structures on national roads SGM	(SGM, 1999)
Slovenia	Methodology for assessing and controlling of capacity of bridges on national roads Policy manuals for individual tunnels	(DRSC, 2010)
South Africa	Manual for the Visual assessment of Road Structures	(TMH19, 2013)
SPAIN	Guide for carrying out the inventory of bridges Guide to basic inspections of bridges Guide for carrying out main inspections of bridges in the state road network	(Mºfomento 2009)
USA, Wisconsin	Wisconsin Bridge Manual and database	(WisDOT, 2017)

Table 2. Key regulations and guidelines used for inspection and management of bridges

3. SPECIAL ASSESMENTS

Objective one was to determine the state of practice for the use of special inspections and assessment techniques when either damage and or deterioration is discovered on a bridge.

3.1. TECHNIQUES AND TECHNOLOGIES

Common inspection methods are normally used to get an overall assessment of the condition state of a bridge. Contrarily, special inspections and assessment techniques are used to get more detailed information to ascertain properties and information that can assist in determining the behaviour and condition of materials, components or systems. There is a wide collection of destructive and non-destructive methods and techniques to apply to bridges. The results of a special inspection could be used as a basis for a further decision or they could be used as an input to support necessary calculations. One example includes quantifying the actual material properties as input to a more accurate calculation model in determining the load carrying capacity.

The PIARC – report 2011 R07 'Inspector accreditation, non-destructive testing and condition assessment for bridges' gives detailed information about the nondestructive methods for inspections.

3.2. SUMMARY OF THE QUESTIONNAIRE RESPONSES

The countries that responded provided a variety of example techniques to determine the material properties for many bridge components. In general, applying one of these techniques is done to refine the nominal material properties used for the initial design or assumed for rehabilitation of the bridge. The most common method reported was core sampling supported by one or more non-destructive techniques. For concrete bridges these non-destructive techniques include: carbonation, ultrasonic transmission velocity, Schmidt Hammer and cover-meter.

For steel bridges, the most employed techniques reported were acoustic emissions, magnetoscope welding test, ultrasonic flaw test and dynamic hardness test instead of traditional hardness test like Brinell. Some countries like Mexico have had success with an acoustic emissions technique in order to evaluate condition of the welds (even taking into account that the welds were embedded in concrete and not directly accessible). Another notable technique was employment of Phased Array Ultrasonic Testing (PAUT), which can offer much more reliable results than traditional ultrasonic testing.

In the case of assessment techniques of cable systems (for suspension and cable-stayed bridges), the most used technique is the determination of the cable load by vibration. Other techniques used for cables are acoustic emission and magnetic flux leakage testing method. However, with regard to the magnetic flux leakage testing, some countries like Belgium highlighted a specific lack of success implementing this method.

For the general assessment of bridges, most countries responded that they used structural monitoring equipment alone and in support of a traditional load test.

Table 3. below shows the summary of the questionnaire dealing with the applied methods of special inspections.

Country	Techniques and technologies
Australia	Monitoring equipment; Space Glass software
Austria	Monitoring equipment; Radiographic examination for welded joints; Material property evaluation
Belgium	Material property evaluation; Load in cables by vibration; Electromagnetic method to locate wires ruptures; Carbonation; Radar, Ultrasonic; Infrared thermography; Monitoring equipment; 3D Modelling
Canada	Magnetoscopic testing for steel; Electrochemical corrosion potential; ground penetrating radar (GPR); Material property evaluation (Steel and concrete cores);
China	Material property evaluation; testing; Carbonation; Chloride; Cover thickness; Resistivity; Corrosion potential; Steel structure flaw detection; Steel structure painting thickness measurement; Stay cable force measurement; Monitoring equipment; Rebound method for concrete strength test
France	Monitoring equipment; Risk analysis
Japan	Dynamic loading test; Standard inspection methods (visual inspection, test hammer, crack gage, visual line level); Nondestructive inspection (ultrasonic, eddy current, magnetometer, fiber scope; magnetic particle testing, infra-red thermography); Inspection of Suspender Ropes by Main Flux Method; Chemical composition testing; Charpy impact test
Korea	Instrumented indentation technique for steel; Concrete carbonation test
Mexico	Acoustic emissions; Welding inspection; Vibration and modal analysis; Dynamic Loading test
Netherlands	Acoustic emissions; X-ray inspection fatigue cracks in steel bridges
Norway	Rapid Chloride Test of Concrete; Carbonation test; Measure the cover thickness
Poland	Profometer; Borescope; Impact Echo; Evaluation of concrete carbonation; Material property evaluation
Slovenia	Load testing; Carbonation; Chloride; Cover thickness; GPR, Profometer, Electro-potentials; Cable force measurements
South Africa	Visual assessment, Material property evaluation, Sample extractions, Analytical calculations
Spain	Magnetic detection of reinforcement steel; Rebound method for concrete strength test; Pulse velocity; Load testing; Core sampling
USA	LiDAR scanning; Magnetic particle testing; Phased Array Ultrasonic Testing (PAUT); Radiography; High Energy X-ray Testing (HEX); Visual assessment
USA (Wisconsin)	Infrared Thermography for bridge deck delamination; Ultrasonic testing; Magnetic particle testing; GPR for bridge decks ; Resistance Micro-Drill for Timber

Table 3. Applied Techniques and Technologies used in Special Inspections

3.3. QUALIFICATIONS

The PIARC report 2011 R07 'Inspector accreditation, non-destructive testing and condition assessment for bridges' gives detailed information about the qualifications of the personal working with inspections of bridges. The responses show similar results to this report with respect to qualifications of these personnel. It is essential that the personnel are well educated to understand the implications of damages and deteriorations. As table 3 illustrates owners will need to work with personnel having several different types of expertise to perform these special assessments. Owners must employ good quality assurance protocols and assessment procedures to ensure quality data and accurate results from these assessments.

The inspector performing the detailed inspection or assessment technique must be qualified, primarily on an educational basis, and more specifically with the expertise required to perform the special assessment. For example; an owner that requires a bridge detailed inspection and special assessment including a load capacity calculation would hire an engineer. This engineer should have experience with material defects that can be encountered on bridges and their origin, coupled with structural analysis of bridge elements and their behaviour. This would be deemed a basic requirement.

The detailed bridge inspection including special assessments is the responsibility of an engineer. However, to be able to fulfil this complete inspection task, engineers generally have the assistance of specialised technicians. The personnel who undertake detailed bridge inspections can be in-house and/or external. Most of the organisations still have in-house staff qualified to undertake inspections, but they are greatly supported by external personnel, mainly from engineering consultancy firms or specialized testing firms. This would suggest that owners want to retain a certain amount of internal expertise to be able to manage and critically analyse external inspection data, specialized assessments, and load carrying capacity calculations.

3.4. APPLICATIONS OF ASSESSMENT TECHNIQUES

The first and basic damage assessment technique used in all countries is visual assessment. It's very important, because all the actions will be dependent on its results. In some countries, specialized equipment such as drones or fiberscope are used to support the visual assessment of hard-to-reach places.

Other non-destructive techniques are aimed for obtaining specific information. For example, ultrasonic methods are widely used in steel bridges for detecting fatigue cracks and other defects in welds and structural elements.

Some countries used more advance ultrasonic testing techniques. In USA the PAUT (Phased array ultrasonic test) method can detect defects in different directions through use of a phased array instead of using linear ultrasonic emission. Another non-destructive method used in most countries is X-Ray test. The novelty used in USA is that it is a "High Energy" X-Ray (HEX), test. A HEX test uses an order of magnitude more energy than a traditional X-Ray test enabling the X-rays to provide reliable results through thicker sections consisting of multiple steel plates.

In the case of cable systems, the magnetic flux leakage testing method is recommended to detect internal broken wires, section loss and corrosion qualitatively. Nevertheless, some countries like Belgium remark the lack of success of this method to locate wires ruptures. It was commonly reported that use of vibration to measure of the load in cables by vibration was successful in determining tension loss.

Numerous non-destructive techniques were used for determining material properties, combined with destructive methods like core sampling, to gather enough data for the calculations needed to evaluate the load capacity of the bridge or support conducting a load test.

To determine strength of a fire affected steel girder in South Korea, an innovative technique was used for testing the tensile properties in steel. The South Koreans reported that their instrumented indentation technique for steel is an evolution from the conventional Brinell hardness measurement method.

3.5. RELIABILITY

To assure the reliability of the measurements from field tests the most common practice is to check the consistency of the results to those from model analysis, complementary tests (load tests) or design data.

Another frequent practice is to compare two different techniques (i. e. cable tension using vibration and a jack direct measurement) or use redundant instrumentation. Test repetitions and recalculations are standard practice and complemented with a statistical analysis.

For standard NDT, although the inspectors can be certified to different levels (I, II and III) and NDT standards are available, in most cases reliability is mainly based on inspector skills and experience (certification and training are implied but not specifically stated). In some cases it is explicitly stated that the sensors must be calibrated and the laboratory must have accreditation for the specified tests. For some tests, there are specific recommendations to prevent errors or misleading measurements, mostly based on experience and common sense (GPR, magnetic tests, infrared).

Quality assurance methods and risk analysis are mentioned but not specified how they are applied or if there is a manual, standard or recommended practice.

3.6. SUMMARY CONCLUSIONS

Most of the countries that responded to the survey indicated they perform specialized assessments to ascertain material properties by combining destructive with non-destructive techniques. The results of those assessments were used to confirm the materials of construction and to support calculations to determine the safe load carrying capacity of the bridge or structural modelling to better understand behaviour.

Another noteworthy technique is the extended use of monitoring equipment as a general technique to measure displacements, distortions, etc. If the gathered information is not good enough to evaluate or assess a bridge’s condition, a load test is usually performed.

4. CASE STUDY SYNTHESIS

As stated above, 28 case studies from 15 countries were received in response to the survey. A separate standalone publication was created to document these worldwide case studies for future reference (document 29508,2018CS01EN.pdf on the PIARC webside). A summary of each of these case studies can be found in appendix 2. Table 4. below provides brief information about the case studies from the responding countries.

#	Country	Bridge Type	Immediate Reaction	Trigger	Special Inspection
1	Australia 1	Steel Arch -tied truss	No Immediate	Bridge Impact	No
2	Australia 2	Timber Girder	Restricting Heavy	Inspection	Yes
3	Austria 1	Steel Plate girder	Lane Closed	Inspection	Yes
4	Austria 2	Mixed Steel Plate -	Special Inspection	Inspection	Yes
5	Belgium	Asymmetrical Cable	No Immediate	Inspection	Yes
6	Canada (S)	Steel Girder	Closed Bridge	Bridge Impact	No
7	Canada ©	Steel Plate Girder	Closed Bridge	Bridge Fire	Yes
8	China	Cable Stay	Closed Portion	Bridge Impact	Yes
9	France 1	Prestressed Concrete	Special Inspection	Inspection	Yes
10	France 2	Steel Plate Girder -	Closed Bridge	Bridge Fire	Yes
11	Japan (M)	Precast block	Lane Closed	Inspection	Yes
12	Japan (Y)	Steel Girder	Lane Closed	Inspection	Yes
13	Korea 1	Steel Box Girder	Closed Bridge	Bridge Fire	Yes
14	Korea 2	Steel Box Girder	Special Inspection	Inspection	Yes
15	Mexico	Cable Stay	Retrieve SHM Data	Inspection	Yes
16	Norway	Concrete Slab	Special Inspection	Inspection	Yes
17	Poland	Double T Post Tension	Restricting Heavy	Inspection	Yes
18	Slovenia 1	Concrete Box Girder	Lane Closed	Bridge Rating	Yes
19	Slovenia 2	Reinforced Concrete	No Immediate	Bridge Element	Yes
20	South Africa	Post Tension T Beam	No Immediate	Bridge Impact	No
21	Spain 1	Prestress Concrete Box	Closed Bridge	Bridge Impact	Yes
22	Spain 2	Prestressed Concrete	Special Inspection	Bridge	Yes
23	USA-FHWA	Arch Through Truss	Closed Bridge	Inspection	Yes
24	USA-FHWA (75)	Steel Plate Girder	Lane Closed	Inspection	Yes
25	USA-FHWA	Tied Arch Truss Bridge	Special Inspection	Inspection	Yes

#	Country	Bridge Type	Immediate Reaction	Trigger	Special Inspection
26	USA-Wisconsin	Prestressed Girder	No Immediate	Inspection	No
27	USA-Wisconsin	Prestressed Girder	Closed under	Bridge Impact	No
28	USA-Wisconsin	Mixed Truss Bridge	Closed Bridge	Bridge Impact	Yes

Table 4. Case Studies

4.1. CASE STUDY STATISTICS

The case studies represent a variety of bridge types, element materials, traffic levels, and age from many countries around the world. The most common bridge length from the compilation of studies is between 100 meters and 500 meters with the longest being submitted by Korea at 7754 meters. Also, all 28 case studies were multiple span bridges with 17 of the case studies being between two and five spans. The graphs in illustration 1 and 2 display the year the bridge was built and the bridge type respectively.

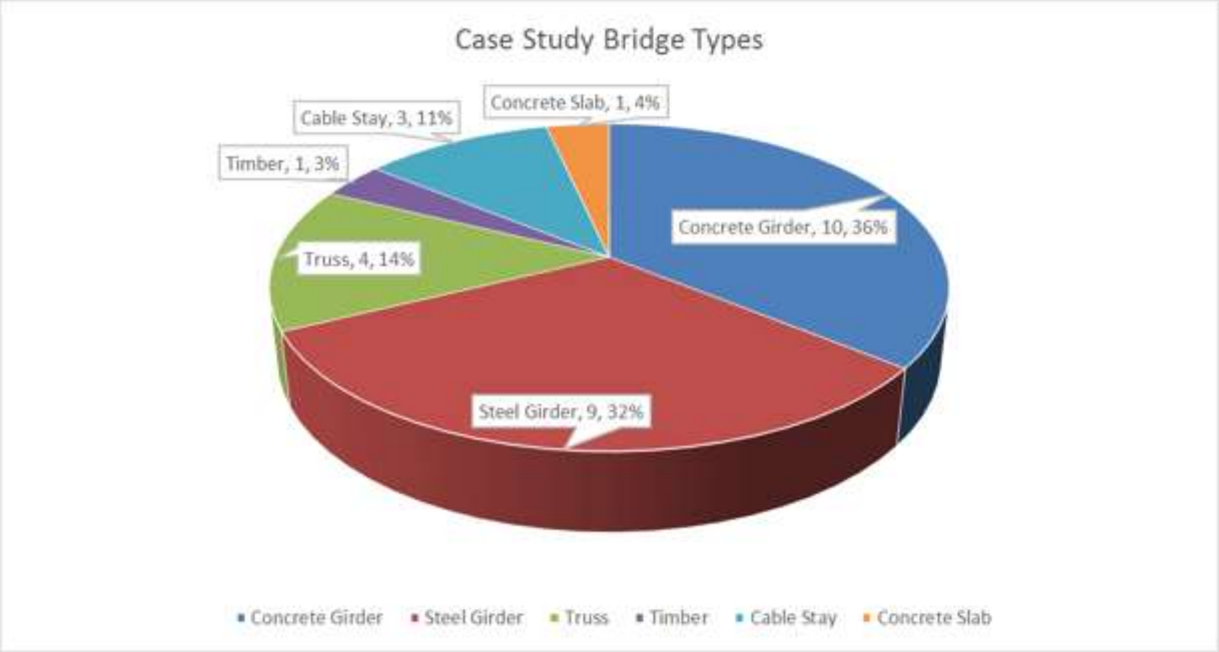

Illustration 1. Case Study Bridge Types

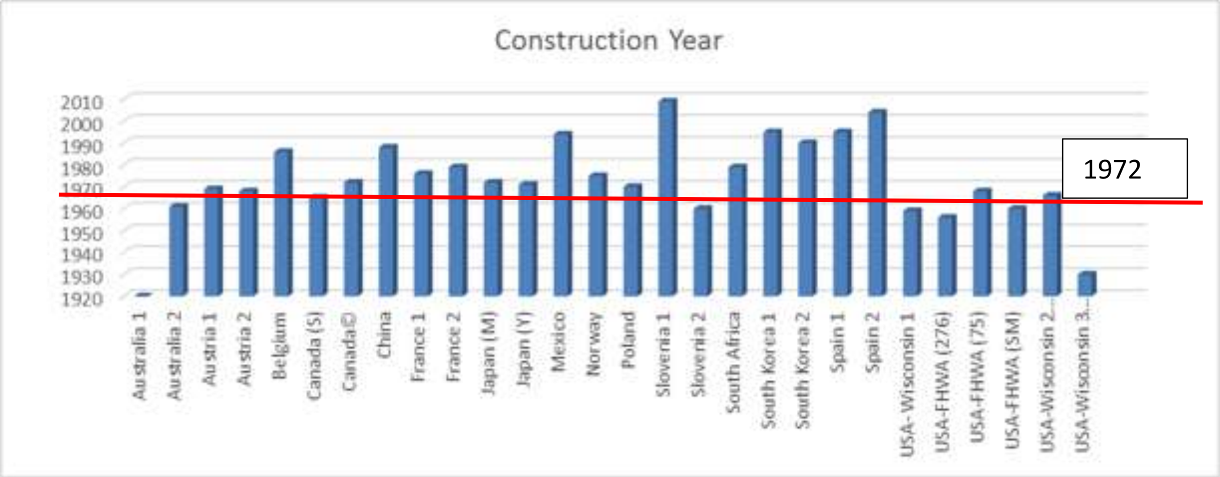

Illustration 2. Year of Construction

The average year of construction for bridges reported in the case studies was 1972. The oldest bridge was from Australia built in 1900, while the newest is from Slovenia built in 2009.

4.2. “TRIGGERS” AND IMMEDIATE REACTIONS

The case studies were categorized by the event that triggered an immediate reaction or special inspection or what caused the event. Illustration 3 shows the case study triggers. Fifteen of the events were discovered during routine or visual inspections, followed by seven events triggered by bridge impacts, and three events triggered by a bridge fire.

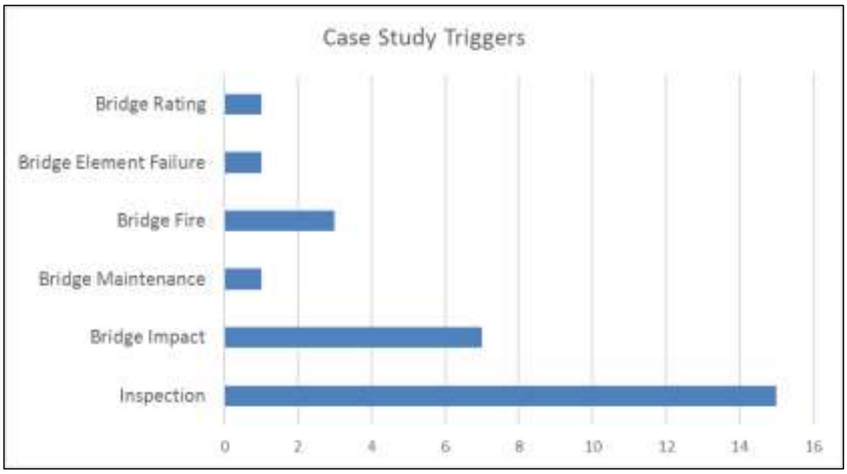

Illustration 3. Case Study Triggers

The most critical aspect to the case study is determining an appropriate timely reaction to the bridge event. These decisions are based on many influencing factors which are described in detail in a subsequent chapter. Along with the influencing factors, engineering judgement is the key component described to ensure safety. These case studies reflect this emphasis on engineering judgement to ensure safety and provide the basis for a decision-making process that can be used by bridge owners worldwide.

As an immediate reaction, many countries closed the bridge, or a portion of the bridge, to ensure safety. Illustration 4 below describes the different immediate reactions taken by owners in the case studies.

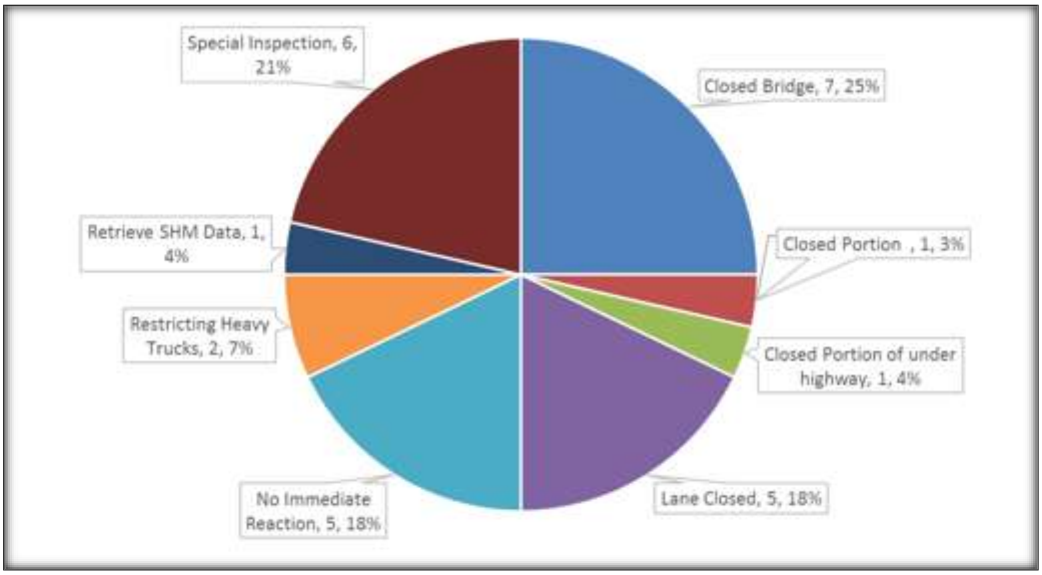

Illustration 4. Immediate Reactions Taken by Owners

4.3. CASE STUDY ANALYSIS

Illustration 4 above shows that 21 of the 28 of case studies involved some type of traffic restriction as part of the immediate reaction. As many of these case studies were on bridges with very high traffic volumes, opening these bridges as soon as safely possible was imperative to the owners. This can produce an increased pressure on the decision-making process.

For instance, Japan had discovered a fatigue crack and immediately shut down the road for 23 hours. During that time, traffic was backed up over 6 Km. A temporary rehabilitation measure was performed in a very short time to return traffic back to the bridge. In doing so, a slight but acceptable risk was assumed by the owner, until more rigorous, time consuming finite element modelling could be performed to verify the temporary repair.

Both, South Korea and France provided a case study with a fire on or under a bridge that resulted in these bridges being shutdown to assess the fire damage. Both bridges were compromised to the extent that prolonged closures were required.

The USA- FHWA case study of the Sherman Milton bridge provides a unique example of an event of cracks discovered during an “arm’s length” or very close inspection. This resulted in a plan of action to perform a special inspection and monitoring program. A later discovery made during the special inspection resulted in the closure of the bridge before a permanent fix could be performed.

Many of the countries made their immediate decisions based on structural engineering expertise of teams that followed a vetting process to close the bridge or restrict traffic on the bridge.

One such example of a vetting process is the case study example provided by US – Wisconsin on a pier cap. They followed a defined “critical findings process” and it was determined that no immediate action needed to be taken (like close or restrict the bridge). Subsequent steps were taken to determine if a rehabilitation was required which resulted in no remedial action being needed before the bridge was to be replaced in the next few years.

Another example of this vetting process is in the case study from Canada (1). During a repair project on a bridge, a fire started on the temporary works that reached the girders. The bridge was closed immediately by law enforcement. An inspection was performed which resulted in leaving the bridge closed. A repair and reinforcement of the girders was completed in 14 days. Canada had put an incident response protocol together after the collapse of a bridge in 2006. They described this as an example of following that protocol successfully to reach the ministry and assigned experts.

Data that aided in making the initial assessment included plans, calculation models, current condition assessments and safety evaluations. An initial load carrying capacity calculation was performed in half of the case study responses. However, most countries performed a final load carrying capacity calculations to support their final decisions (see Illustration 5 calculation of load carrying capacity)

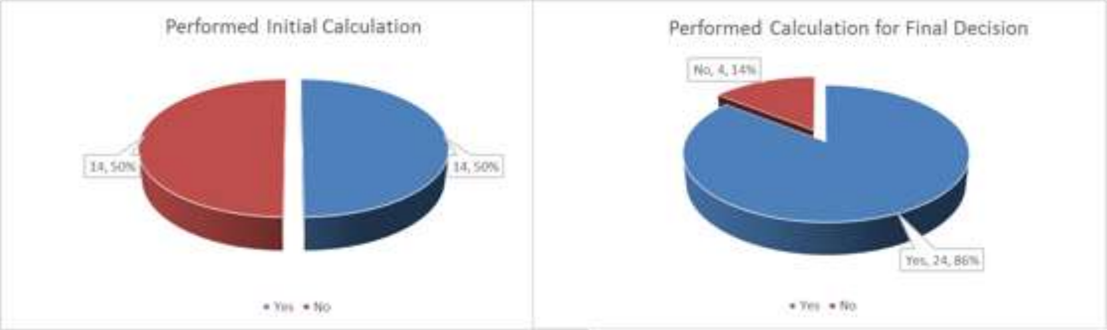

Illustration 5. Calculation of Load Carrying Capacity

One factor in the use of data in calculating an initial load carrying capacity was the availability of a load model or calculation that could be accessed and executed very quickly.

One example of this is the Australia – 1 case study. A vehicle impacted one of the diagonal steel components in the truss. The member fractured at the rivet level and deformed. A rehabilitation project was under way, so the Finite Element Analysis model was used to determine the impacts to the capacity. After evaluation, a 30-ton posting sign was installed. The member was replaced and the sign removed in approximately one month.

Another such example is the USA- Wisconsin – 2 case study. The bridge was hit by a back hoe on a trailer and it damaged girders causing several prestressing strands to be severed. Bridge inspectors closed the ramp pending further evaluation. The bridge was re-opened to legal traffic after an engineering analysis was performed within hours of the event. The final repair used fiber reinforced polymers (FRP) and was completed in the summer of 2016.

Once the immediate action was taken, owners and their perspective teams determined information needed to resolve the issues and bring the bridges back to safe operating service. Often, countries determined they would need additional data to perform load carrying capacity calculations and determine the final repair to restore the bridge. Examples of assessment techniques were provided in responses to the general questionnaire. The specific case studies provide practical examples of what types of data countries wanted to help in the decision-making process. Often, the additional data would be used in the load capacity calculations.

These case studies also illustrate different levels of sophistication or complexity used for the load carry capacity calculation. Many times, a 3D Finite Element load analysis was performed to assist in the decision-making process. Fifteen of the 28 case studies describe the type of model built and the additional data that was provided to the model from a special inspection. This describes the iterative process in determining the problem, acquiring data, and refining the analysis, to understand the issues and provide solutions.

An example of this is described in the Spain -2 case study. A curved bridge had “shifted” or displaced from its original position and was discovered by maintenance team. The owner’s team of experts provided immediate actions for a traffic restriction and a hold down device to ensure the bridge did not keep translating. Afterwards, the investigation used a complex finite element model to isolate the root cause of the issue.

A unique opportunity was provided by the compilation of case studies. That opportunity was to evaluate a draft decision process and determine if the elements identified in the process were apparent in the specific case studies. The result of this evaluation performed by the workgroup provides a decision process that has been validated against the 28 case studies. The elements of this decision process and the influencing factors involved is described in detail in the next chapter.

5. DECISION-MAKING PROCESS

This decision-making process was initially speculated by the workgroup (see appendix A) and then evaluated using the case studies. The evaluation revealed some common characteristics and details in both the decision-making process and in those making the decisions in the case studies. In this section those characteristics and details are identified and discussed.

5.1. 5.1. INFLUENCING FACTORS

5.1.1. Education and Experience

There is no standard or degree which solely prepares an engineer to exercise judgment in making decisions that potentially affect public safety. Newer engineers are less likely to trust their education than those that have routinely applied it to determine load path, interpret behavior or quantify stress. While it is difficult to argue that engineers are not constantly adding to their education throughout their careers, a formal education generally provides the best foundation upon which the building blocks of professional practice are typically laid.

Although not always necessary, the experimental component of typical post-graduate engineering curriculums provides exposure and even familiarity with how materials, components and systems fail. Understanding each of these and their potential relationship to the others is often of vital importance to the engineer reacting to a critical inspection finding on a highway bridge. As such, earning advance degrees can better equip an engineer to influence and make decisions.

Professional licensing can also be a reflection of the level of education and experience an engineer has. For example, in the United States it is common that engineers apprentice under a licensed Professional Engineer for approximately 5 years and submit a brief portfolio of work before qualifying to sit for the licensing examination themselves. While these examinations generally explore an engineer’s level of expertise employing a combination of design standards and specifications, they inherently draw upon an engineer’s understanding of mechanics, limit states and failure modes.

Breadth and depth of experience can also play significant influencing roles in an engineer’s decision making. Engineers with design, construction, inspection and management backgrounds have typically developed a level of understanding and familiarity with a bridge type that informs timely decision making. This familiarity usually includes the level of effort, time and costs associated with rigor of modeling and analyses, repair or rehabilitation activities and/or reconstruction of a bridge.

When that familiarity extends to multiple and complex bridge types, the engineer is generally recognized as an expert by the profession. While experts can be made in many different ways, engineers with advanced degrees, a professional license and experience with the life cycle of multiple highway bridge types are often those trusted to concur or make decisions for critical inspection findings on highway bridges.

5.1.2. Data

When making decisions, generally the more data an engineer has the better. A typical challenge for engineers is accepting that they will not have access to all of the data ideally needed to address an issue. Accepting that likelihood and knowing what level of data is sufficient to influence or support a corresponding level of decision making is part of engineering judgment. Knowing when the level of data collected is enough to support a relevant action also tends to come with practice and experience.

The sources of data generally available include the design plans and specifications updated for any as-built alterations, fabrication and construction documentation on materials and methods, in-service inspection reports, maintenance action statements, and any plans or specifications used to rehabilitate or reconstruct the bridge. In the United States, the data available typically includes a load rating which is a determination of a bridge's safe live load carrying capacity considering the current conditions of the bridge's components and any alterations that have been made to the bridge over time.

The data available might also include strain or other displacement measurement data from a live load or structural behavior study. This type of data can be invaluable when finite-element modeling is used to understand behavior or estimate capacity.

Temporal data tends to be the most influential as it establishes a history of facts or performance for a bridge. If a bridge has been regularly inspected and routinely maintained, and if those actions are well documented through the life of the structure, that data provides a proven basis from which expectations can be built to inform decision making. However, the accuracy and consistency of inspection data can vary significantly from inspector to inspector or region to region. The most consistent inspection data was generated in countries where bridge inspector qualifications are mandated or certified and quality assurance programs are in place.

5.1.3. Risk

In context, risk in this document uses a generally accepted definition; risk is the product of the impact of consequence and the likelihood of occurrence. While the impact of a consequence may be the same when viewed from an engineering and political perspective, when considering likelihood engineering perspectives generally consider probabilities, while political perspectives generally consider possibilities. Both approaches are defendable and the approach chosen likely has as much to do with the experience of the engineers involved as it has to do with the audience that will be evaluating the responses.

Decisions are influenced by knowing what question is being asked – probability or possibility. It is both societally and politically unacceptable for a bridge to collapse. However, bridges are designed and evaluated for a probability of failure, not the possibility of failure. Societally, highway bridges have become ubiquitous and are often treated as constants. The notion of a bridge collapse would not be a consideration for many if not all of those that use these structures daily. That comfort comes from the familiarity individuals develop with these structures through routine interactions and from the diligent and responsible work of bridge owners, inspectors and managers.

Approaching risk from an engineering perspective is often reasonable and pragmatic, but it does not support wide ranging statements of absolute certainty. Engineers usually talk within their profession with the understanding that the safety of a bridge is typically established by using well vetted design and construction methodologies, and supported by routine and regular in-service inspections and evaluations. The traveling public and their elected officials expect and believe that open bridges are always safe and that unsafe bridges are always closed. While this level of certainty is not achievable, the belief does influence engineers when considering risk in making decisions.

5.1.4. Resources

Reacting to a critical finding or failure requires resources. At a minimum, reactions require staff time and travel. However, it is also common to restrict, shore or close a bridge and/or establish a temporary detour. Depending on the complexity of the issue faced, contracted expertise may be needed to advise, augment or conduct an investigation. All of these efforts and activities incur either direct or indirect costs, or both. Also, these costs are incurred before those associated with engineering and implementing a repair.

The indirect costs of reacting to a critical finding or failure are mostly associated with time and mobility. In general, time is the most valuable resource and minimizing the time of reduced operation or closure of a bridge is typically fundamental to a successful response. If a bridge is closed in an urban environment, the pressure to reopen it typically comes from the inability of the network to adequately compensate for the closure resulting in gridlock and a significant impact to both local and regional mobility. In a rural setting, a bridge closure can mean the isolation of households or communities, or detour lengths that are excessive or unworkable for certain types of vehicles.

Before embarking on a detailed investigation, critical thought needs to be given to what information is likely to be produced and how the information might influence an action or repair. If the outcome is not in doubt, minimizing the delay until a repair is made should be the goal. For example, if the source of cracking in a steel beam is not understood, but the only solution is to remove the crack tips and create an alternate load path (plate over the affected areas), if conducted, an investigation of the cracking should at most parallel the repair effort and not precede or delay it.

When bridges are compromised on national level highway systems the quality and capacity of the roadways and bridges on the detours can also impact mobility. Despite the costs associated with longer routes, lower quality roadways can result in slower travel times, and vehicle maintenance and repair needs.

Of course, repairs also incur costs. The engineering and construction activities associated with any repair are relatively simple costs to identify, but can be excessive. Consideration should be given to the service life expectancy of the bridge and match the method or materials of the repair accordingly when possible.

In some situations, repairs can be delayed or mitigated through monitoring a defect. However, monitoring is generally a short-term solution that does incur costs. If monitoring is selected as a response, be careful to define what is being monitored, what the action thresholds are, the actions to be taken, and who is responsible for the actions and communicating the outcomes.

5.2. 5.2. IMMEDIATE REACTION TO ENSURE SAFETY (ENGINEERING JUDGEMENT)

Evaluation of the case studies revealed that engineering judgment was typically employed at all levels of decision making. The weight of that judgment was directly related to both the qualifications and experience of the engineers involved and the availability and reliability of the information on the design, construction and history of performance of the effected bridge.

For bridges that were designed and constructed to a known set of standards and for which past performance had been documented through regular and routine inspections, engineers typically had the information and data needed to leverage a judgment based decision for an immediate reaction. More experienced engineers tend to triage a critical inspection finding on a bridge through a similar series of questions.

- What is the structure type?
- What is the material of construction and when was it produced?
- What element or component of the bridge is effected?
- What is the defect, damage or deterioration?
- Is the defect, damage or deterioration related to a failure mechanism ?
- What are the characteristics (location, orientation, etc.) of the defect, damage or deterioration?
- When was the last inspection and was the defect, damage or deterioration documented then?
- Is there a history of similar defect, damage or deterioration on this or similar bridges?
- How many vehicles use the bridge every day and what is the most reasonable detour route?

With answers to these questions, most experienced engineers can use judgment to determine whether many bridges can remain open, can remain open but restricted for specific vehicles, a reduced number of lanes or to specific load levels, must be shored to remain open, or must be closed until a more detailed analysis can be performed or temporary or permanent repairs are made. This essentially corresponds to a “Level-0” analysis as defined in “Procedures Required for the Assessment of Highway Structures,” (PROVIDE REFERENCE).

The survey data indicated that for 14 of the 28 bridge incidents reported in the case studies, no calculations were made to support an immediate reaction. Of those 14, four bridges remained open to all legal loads, 5 were restricted from some loading and 5 were closed. Although the information gathered did not support the immediate reaction, three of those case studies called for a special inspection in order to support a decision on a near term action. As half of the initial reactions did not involve an engineering calculation and relied solely on the engineer’s judgment, indicates how important past experiences are for of those making decisions.

Although it is difficult to infer too much from the data reported, looking solely at the description of the title and qualifications for those involved with making decisions concerning an initial reaction in the case studies, 20 of the 28 were made by individuals with titles or qualifications that included the word “engineer,” another 4 were made by individuals described as having some level of bridge expertise, 2 were made by law enforcement, and 1 each by a maintenance crew and an owner. However, in 24 of the 28 case studies it was reported that the decisions on initial reactions were supported by a team of others. What this information strongly suggests is that, for a large majority of the case studies, the initial reaction was a considered, measured and reasonable action identified by an individual or team with the appropriate education and background.

5.3. 5.3. ENGINEERING CALCULATIONS

Depending on the redundancy and complexity of a bridge, a determination of load carrying capacity for the compromised state may be made to determine or guide whether restrictions are needed or if a bridge can remain open. At the most basic level, these calculations typically involve the use of a design or evaluation standard to analyze a 2-dimensional (sectional) model for static loading from a linear-elastic analysis. At the next level of rigor, a 3-dimensional model that may account for geometric or material nonlinearities (or both) and the dynamic effects of loading is typically employed. Stepping up again to a model that uses information on the as-built material properties, dimensions or behavior as verified through either non-destructive or destructive testing (sampling) can produce the most accurate predictions of capacity, but also require much more investment in time and resources to produce and interpret. Finally, with an understanding of the statistical backbone used to establish target reliability of a design or evaluation standard, knowledge or data can be used to justify modifying partial safety factors in an effort to quantify unaccounted for capacity reserves that can be leveraged to satisfy an engineering limit state.

5.3.1. Nominal Calculation

When the bridge type is nonredundant or noncomplex and a component can easily be decoupled from the system effects, a sectional capacity calculation can be made for the component that accounts for the defect, damage or deterioration at a critical section. These calculations are more easily made for components that can be isolated from the remaining structure and generally leverage the established standards that were used to design the bridge or for evaluation of the affected bridge. Standards for evaluation of existing bridges often use a lower reliability index to account for the reduction in uncertainty associated with the known characteristics of as-built structures.

Depending on the assumptions made, these calculations are generally conservative enough to produce a lower bound of capacity. If that lower bound still envelopes the internal force effects caused by all legal or unrestricted truck weights and configurations, the bridge can remain open and unrestricted. If not, the bridge can be restricted to a safe load level by eliminating a lane of traffic, confining trucks to operate in only certain lanes, or posting the bridge at a lower truck weight limit. Or, the investigator may choose to do a refined analysis in order to capture additions in capacity provided by system effects or redundancy.

5.3.2. Refined Analysis

When a bridge has significant redundancy or is comprised of a complex structural system, a refined analysis is often necessary to capture the system contribution to overall capacity of a component or a redistribution of loads. These analyses typically use mathematical models that attempt to mimic the physical 3-dimensional behavior of a bridge under load. Whether a first order or second order analysis, these models can have a wide range of level of rigor depending on the methodology employed. The more rigorous, generally the more time consuming and costly. Engineering judgment is needed to assess whether increasing the level of rigor is likely to produce results of value to the investigation in a timely manner before investing. Engineering judgment is also needed to interpret the results and in particular the uncertainty associated with inherent variability, imperfect modeling and estimation error.

Although not always possible or available, refined analyses are best employed when there is a physical anchor (an experimental dataset that captured one or more behavioral characteristics of the bridge) which can be used to compare predictions to reality before the model is used to assess capacity. When a physical anchor is not available, an independent mathematical model built around the same set of known data can be used to corroborate the reasonableness of a prediction.

A caution with independent models, due to the inherent differences in methodologies, modeling techniques and interpretation of results, investigators should not expect duplicative predictions but rather reasonable agreement. Also, the differences from too many independent models can unnecessary distract an investigation from arriving at a corroborated prediction. That is, significant effort can be wasted trying to identify the source of disagreement in the predictions from multiple independent models. It is recommended that the focus remain on the level of agreement and that the number of independent models be limited as to avoid distraction and the possible need to explain differences to the uninformed.

When refined analyses do not predict adequate capacity, the same methods for restricting the load on a bridge mentioned in the previous section are still an option, or a special assessment can be made to improve the data or assumptions considered in the modeling.

5.4. 5.4. SPECIAL ASSESSMENT

Special assessments generally are used to improve the information being leveraged by an engineer to support a decision on a reaction or course of action. They typically involve the application of technology to learn more about the affected bridge. Among other things, special assessments can confirm the behavior of a bridge, the operation of bearings, as-built component dimensions and material properties, and site-specific traffic loading of a bridge. After generation, these data can be used to improve the refined analysis to more accurately predict the structural safety of a bridge.

It is important to note that for the suite of technologies generally referred to as non-destructive evaluation or non-destructive testing, it is often necessary to verify the reliability of the results through some minor destructive testing (sometimes referred to as material sampling) and improve the consistency of the results by certifying technicians through appropriate performance testing.

This level of assessment also includes the option to determine and use structure-specific loading, based on weigh-in-motion measurements, which, particularly for bridges on lightly trafficked routes, can result in sufficient structural safety of the bridge despite lower bearing capacity due to its age or deterioration.

Finally, if the data produced from special assessments does not improve a model’s prediction of the structural safety of a bridge enough to accommodate all legal and unrestricted vehicle loads, the same options discussed previously to restrict load from a bridge are still available. However, a special assessment technique, load testing, can also be used to establish the structural safety of a bridge. Procedures for load testing of this type generally call for critical members of a bridges be monitored while the bridge is loaded in increments up to a level well above legal load. If that specified load level is reached without causing any local non-linear behavior, the bridge is generally acknowledged as being safe for all legal and unrestricted loads.

The disadvantage of establishing capacity via load testing is that if the defect, damage or deterioration progresses, additional load tests will be needed to again confirm capacity. These tests can be costly and typically require closure of the bridge to perform. These closures can be sustained as there is also a need to proceed very carefully under controlled conditions to be sure that those conducting the load test remain safe and that additional damage is not caused to the structure.

As a result, a similar method based on bridge weigh-in-motion measurements, called soft load testing, has been proposed and is used in some countries (ARCHES D16, 2009). This method measures the key performance parameters (influence lines, load distribution factor, dynamic amplification factors) from the bridge responses to normal traffic. Due to the lower level of loading they are appropriate for analyses at serviceability limit states for current traffic, which often is sufficient to extend the life of a bridge.

5.5. 5.5. ADVANCED ANALYTICAL TECHNIQUES

5.5.1. Partial Safety Factors

The previously discussed levels of assessments are based on design or evaluation code implicit levels of reliability, incorporated in the nominal values of loads and resistance parameters and the corresponding partial safety factors. The corresponding target reliability is typically related to past satisfactory performance of an inventory of bridge through calibrations where these have been carried out.

Advanced assessments can take advantage of any additional safety characteristic to that structure and amend the assessment criteria accordingly. It can apply modified partial factors based on information available and safety characteristics specific for a bridge in terms of dimensional surveys, material testing, age, consequences of failure, reserve strength and redundancy, etc. These modifications are derived using reliability analyses to ensure consistency between the two methods. One note of caution when using a reliability analysis, care should be taken not to double count bridge-specific benefits which have already been considered in earlier stages.

5.5.2. Probability Analysis

Reliability analyses that consider the demonstrated variability in the load and resistance data to project a probability of failure require significantly more information than is often routinely available. Although generally an option for bridges that can remain open at some level of service, in most cases it is likely that collecting the data and identifying the expertise needed to conduct the analyses will require more time than is available for an immediate reaction. As such, it is recommended to leave these types of investigations to inform decisions on longer term solutions where the previous assessment levels discussed did not demonstrate adequate capacity to restore service without significantly effecting mobility.

Probability assessment involves reliability analysis of particular structures or types of structure. Such analyses require statistical data for all the variables defined in the loading and resistance equations. The techniques for determining the probability of failure from such data are now available and can be undertaken relatively easily in modest time frames. However, these assessments require advanced specialist knowledge and expertise.

5.6. 5.5. SUMMARY CONCLUSIONS

The levels of assessment discussed in this chapter have been presented independently for ease of communicating their commonly understood characteristics. In practice, influenced by the experience and judgment of the engineers involved, the methods and rigor of multiple levels of assessment can be employed concurrently.

Ultimately, these types of engineering calculations are simply tools to be used by engineers capable of competently interpreting the results to support decision making for action or inaction in response to a bridge inspection critical finding or failure.

Illustration 6 is intended to depict a continuous process to support intermediate decisions, and final decisions to bring the bridge back into safe service for the traveling public.

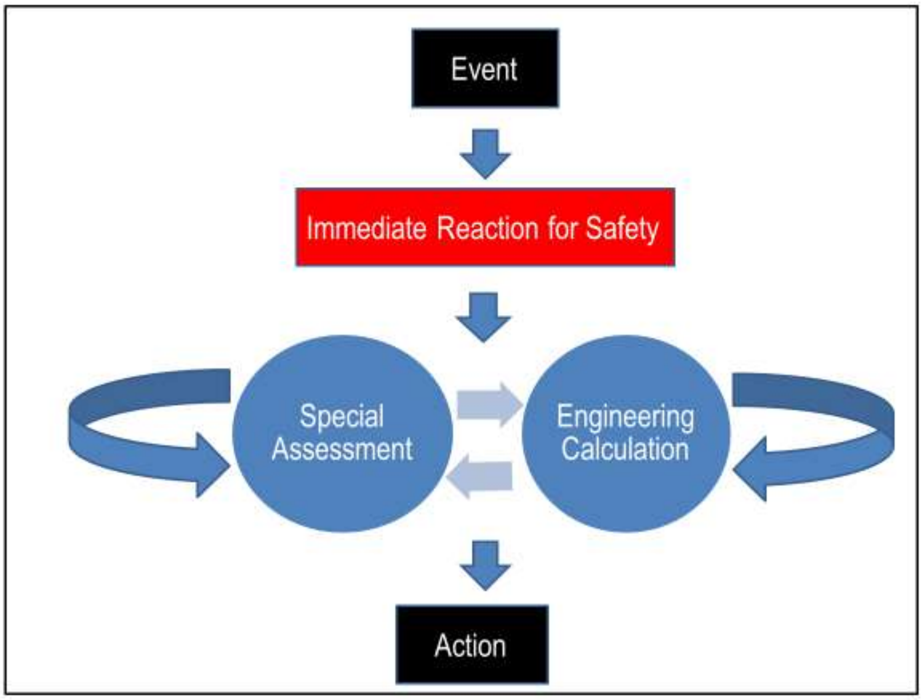

Illustration 6. Illustrative graphic of the Decision-Maxing Process

6. FINDINGS AND RECCOMENDATIONS

Most of the countries responded that they perform specialized assessments to ascertain material properties by combining destructive with non-destructive techniques. The results of the assessments are implemented in performing calculations in the load carrying capacity and structural modelling.

Another noteworthy technique is the extended use of monitoring equipment as a general technique to measure displacements, distortions, etc. If the gathered information is not sufficient enough to evaluate the bridge condition, a load test is usually performed.

The levels of assessment discussed in the preceding chapter have been presented independently for ease of communicating their commonly understood characteristics. A review of that discussion has resulted in several recommendations:

- Engineering judgment plays an invaluable role in both the initial reaction to a bridge issue and follow up actions. It is recommended that owners include newer or less experienced engineers in the decision making process or at a minimum in an observational role for their exposure to the incident and the experienced professionals that determine actions. These opportunities provide irreplaceable lessons for maintaining the competency of the workforce.
- In order to appropriately rely on inspection data, it is recommended that bridge inspectors have a defined knowledge set and training which is verified through applied and/or performance testing.
- In all cases, time is the most important resource but safety is the primary objective. It is recommended that any compromises to the routine level of safety provided by actions taken in response to a bridge issue be well understood and qualitified.
- It is recommended that owners remain mindful of the likely outcome to a bridge issue response as further levels of analysis are employed. Special assessments and inspections can be costly and time consuming. Success is generally associated with timeliness of identifying a solution and implementing the repair.

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8. APPENDIX A: EVENT DECISION TEMPLATE

Event Decision Process - Information

- Engineering Judgment
    - What is the element/component damaged, defect or deteriorated?
    - Average Daily Traffic (ADT) / percentage of truck traffic
    - Detour Possibilities
    - What is the potential temporary / permanent fix or monitoring
    - Costs
    - Time/mobilization to conduct Special Inspection / Analysis v. temporary or permanent repair?
    - Time constraints
    - What is the damage/defect/deterioration?
        - Location
        - Orientation
        - Characteristics

- Topology of the bridge
    - What is the structure type?
    - What is the specified material?
    - Number Spans
    - What was in the last inspection report?

- Cause
    - Accidental
        - Bridge Hit
        - Fire
        - Scour
    - Extensive degradation
    - Construction defect
- Application of regulation / operational methodologies
    - When decisions are made by policy versus expert judgement

- Immediate reaction
    - Shoring, Cribbing Blocking
    - Restrict lanes – shoulder, restrict type (example no trucks), restrict load (example Up to 10 Tons) Close?
    - Do Nothing

- Nominal Calculation (element/component)
    - Satisfied?
    - Likelihood that a refined analysis will be satisfactory?
    - Typical temporary or permanent repairs?
    - Will repair require a refined analysis?
    - Time for refined analysis v. temporary or permanent repair?

- Refined Analysis (element/component or system behaviour…3D)
    - Satisfied?

  - Likelihood that an updated analysis will be satisfactory?
  - Time/mobilization to conduct Special Inspection v. temporary or permanent repair?

- Special Inspection – behaviour, constraints, material properties, actual sizes
  - What information is needed?
  - NDE technologies used?
    - Level of reliability?
    - Performance testing?
    - Validation…destructive testing?
  - Material testing?
  - Proof/load test?

- Revised Refined Analysis or Rigorous Analysis (geometric, material or fully non-linear?)
  - Update model from special inspection data
  - Satisfied?

9. APPENDIX B: SUMMARY OF CASE STUDIES

	Event Date	Trigger Category	Country	Page
#1	March 2017	Bridge Impact: Vehicle impact with one of the diagonal steel components in the truss	Australia	33
#2	September 2010	Inspection: Inspection after soil washed away discovered rotten timber piles	Australia	34
#3	2009	Inspection: Floor panel plate buckling	Austria	35
#4	2013	Inspection: Gaps near prestressed cable couplers were detected	Austria	36
#5	2001	Inspection: Cable partial rupture and deteriorated	Belgium	37
#6	July 2016	Inspection: The impact damaged both exterior girders	Canada	38
#7	December 2013	Inspection: Fire reached the girders	Canada	39
#8	June 2007	Bridge Impact: Vessel Collision with a Pier	China	40
#9	2011	Inspection: Bending Cracks Discovered	France	41
#10	October 2012	Bridge Fire: Truck overturned and caused a fire on bridge	France	42
#11	2009	Inspection: Cracks Spalling and Flaking found led to discovery of fracture of PC Cables	Japan	43
#12	2006	Inspection: Crack of one meter found from the welding connection	Japan	44
#13	December 2010	Bridge Fire: Tanker truck below bridge caught fire	Korea	45
#14	January 2014	Inspection: Severe corrosion in box girders from de-icing agents	Korea	46
#15	June 2015	Inspection: Fatigue crack discovered of anchor system	Mexico	47
#16	2015	Inspection: Expansion joint failure damaging side wall of abutments	Norway	48
#17	September 2014	Inspection: Part of bridge portion appeared to have sank	Poland	49
#18	-	Rating: 200 older bridges designed and deteriorated assessed for safety	Slovenia	50
#19	2009	Bridge Element Failure: An element of the expansion joint failed	Slovenia	51
#20	November 2014	Bridge Impact: Pedestrian bridge hit above freeway	South Africa	52
#21	July 2002	Bridge Impact: Bridge hit by a vehicle knocking out a column	Spain	53
#22	September 2016	Inspection: Deck moved transversely 20 cm caused from rotational instability from bearing devices	Spain	54
#23	January 2017	Inspection: Inspector During Painting Work Discovered a Full Depth Fracture	USA	55
#24	June 2014	Inspection: Fracture in Web and Bottom Flange Discovered	USA	56
#25	February 2011	Inspection: Cracks in Tension Tie Discovered	USA	57
#26	September 2015	Inspection: Excessive Pier Cap Deterioration	USA	58
#27	February 2016	Bridge Impact: Bridge Hit Severed Prestress Strands	USA	59
#28	February 2016	Bridge Impact: Truss Member Hit and Fractured	USA	60

#1 AUSTRALIA (1)

Event Date	Trigger Category: Bridge Impact
March 2017	Vehicle impact with one of the diagonal steel components in the truss

Bridge Type	Immediate Reaction	Special Assessment	Construction Year	Total Length (m)
Steel Arch -Tied Truss	No Immediate Reaction	No	1900	416

Description: A vehicle impacted one of the diagonal steel components in the truss. The member fractured at the rivet level and deformed. A rehabilitation project was under way, so the FEA analysis model was used to determine the impacts to the capacity. After evaluation, a 30-ton posting sign was installed. The member was replaced and the sign removed in approximately one month.

#2 AUSTRALIA (2)

Event Date	Trigger Category: Inspection
September 2010	Inspection after soil washed away discovered rotten timber piles

Bridge Type	Immediate Reaction	Special Assessment	Construction Year	Total Length (m)
Timber Girder	Restricting Heavy Trucks, and a lane	Yes	1961	27

Description: During an inspection after soil had washed away, a decayed timber pile was discovered. In addition, the part of the bridge deck had sunk. The Bridge was restricted to over legal heavy vehicles, one lane, and put on a 3-month inspection monitoring program. The permanent solution was completed in 2016.

#3 AUSTRIA (1)

Event Date	Trigger Category: Inspection
2009	Floor panel plate buckling

Bridge Type	Immediate Reaction	Special Assessment	Construction Year	Total Length (m)
Steel Plate girder	Lane Closed	Yes	1969	13290

Description: A main bridge inspection identified floor panel plate buckling. The security lane was closed immediately. The decision was made to replace the bridge in a future year and leave the security lane closed.

#4 AUSTRIA (2)

Event Date	Trigger Category: Inspection
2013	Gaps near prestressed cable couplers were detected

Bridge Type	Immediate Reaction	Special Assessment	Construction Year	Total Length (m)
Mixed Steel Plate - Prestressed T Girders	Special Inspection	Yes	1968	1800

Description: A main bridge inspection identified open gaps near prestressed cables where they are coupled together. A gap surveillance monitoring system was installed. Some of the members were reinforced after the engineering analysis calculations were performed.

#5 BELGIUM

Event Date	Trigger Category: Inspection
2001	Cable partial rupture and deteriorated

Bridge Type	Immediate Reaction	Special Assessment	Construction Year	Total Length (m)
Asymmetrical Cable Stay	No Immediate Reaction	Yes	1986	232

Description: A cable inspection identified a cable with some wires ruptured. Two strands were installed next to the cable in case of complete rupture. An analysis was done to verify the bridge would be serviceable with one less cable.

#6 CANADA 1(S)

Event Date	Trigger Category: Inspection
July 2016	The impact damaged both exterior girders

Bridge Type	Immediate Reaction	Special Assessment	Construction Year	Total Length (m)
Steel Girder	Closed Bridge	No	1965	

Description: The bridge girders was impacted by an over height vehicle. The bridge was closed immediately by law enforcement. After an inspection, the bridge was open with one lane running in the center portion. A normal repair of the girders was completed in November.

#7 CANADA 2(C)

Event Date	Trigger Category: Inspetion
December 2013	fire reached the girders

Bridge Type	Immediate Reaction	Special Assessment	Construction Year	Total Length (m)
Steel Plate Girder	Closed Bridge	Yes	1972	483

Description: During a repair project, a fire started on the temporary works that reached the girders. The bridge was closed immediately by law enforcement. A inspection was performed and resulting in leaving the bridge closed. A repair and reinforcement of the girders was completed in 14 days.

#8 CHINA

Event Date	Trigger Category: Bridge Impact
June 2007	Vessel Collision with a Pier

Bridge Type	Immediate Reaction	Special Assessment	Construction Year	Total Length (m)
Cable Stay	Closed Portion	Yes	1988	1675

Description: A vessel collided with a pier and caused a portion of the bridge to collapse. The bridge was closed and a damage inspection was performed. This was major event and a rehabilitation project was completed in three steps. The steps included removing the sunken ship and collapsed portion of the bridge, followed by the final repair and rehabilitation. This was completed by August 2008.

#9 FRANCE 1

Event Date	Trigger Category: Inspection
2011	Bending Cracks Discovered

Bridge Type	Immediate Reaction	Special Assessment	Construction Year	Total Length (m)
Prestressed Concrete Box Girders	Special Inspection	Yes	1976	204.50

Description: During an in-depth inspection several bending cracks were discovered. A special evaluation and site assessment was performed. The findings resulted in a permanent fix by adding additional prestressing and composite materials. This work was completed in 2011.

#10 FRANCE 2

Event Date	Trigger Category: Bridge Fire
October 2012	Truck overturned and caused a fire on bridge

Bridge Type	Immediate Reaction	Special Assessment	Construction Year	Total Length (m)
Steel Plate Girder – Mixed Concrete	Closed Bridge	Yes	1979	585

Description: A an overturned truck caused a fire on the bridge. This fire ignited parked trucks below the bridge increasing the fire damage and impact to the bridge. The bridge was immediately closed and boat traffic below was restricted. The deck was heated to avoid brittle collapse in cold temperatures. A permanent fix was performed by removing the damaged metallic portion and replacing it. This work was completed in August 2013.

#11 JAPAN 1(M)

Event Date	Trigger Category: Inspection
2009	Cracks Spalling and Flaking found led to discovery of fracture of PC Cables

Bridge Type	Immediate Reaction	Special Assessment	Construction Year	Total Length (m)
Precast block segmental	Lane Closed	Yes	1972	300

Description: In 2006, cracks, spalling and flaking in concrete were found in the bottom flange of the PC box-girder during a bridge inspection. Repair work was started in September 2009. When a part of the covering concrete with rust stains was removed for repair, the fracture of some PC cables was discovered. The owner immediately restricted traffic on the bridge by closing the lane above the damage. After the assessment, the traffic was removed by setting up a special monitoring program. The final repair consisted of carbon fiber sheet reinforcement and external PC tendons were installed. This work was completed in 2011.

#12 JAPAN 2(Y)

Event Date	Trigger Category: Inspection
2006	Crack of one meter found from the welding connection

Bridge Type	Immediate Reaction	Special Assessment	Construction Year	Total Length (m)
Steel Girder	Lane Closed	Yes	1971	128

Description: During a routine inspection, the inspector found a crack with a length of 1m developing from the welding connection around the slit between main girder and transverse girder to the girder. The following day in-bound traffic was closed an emergency procedures were executed for 23 hours. The repair consisted of splicing metal plates from both side of the crack. Additional material was added to stiffen lower flanges. This was completed during the closure.

#13 KOREA 1

Event Date	Trigger Category: Bridge Fire
December 2010	Tanker truck below bridge caught fire

Bridge Type	Immediate Reaction	Special Assessment	Construction Year	Total Length (m)
Steel Box Girder	Closed Bridge	Yes	1995	380

Description: A tanker truck, which was illegally parked underneath the bridge, caught fire. The fire lasted for about an hour and caused severe damages. The high temperature flames substantially reduced stiffness and strength of steel box girders. The bridge was closed immediately and a special inspection was performed. Temporary supports were placed to avoid larger deformations or partial collapse of the bridge. The damaged portion was removed and precast sections with steel beams were installed to expedite the fix.

#14 KOREA 2

Event Date	Trigger Category: Bridge Inspection
January 2014	Severe corrosion in box girders from de-icing agents

Bridge Type	Immediate Reaction	Special Assessment	Construction Year	Total Length (m)
Steel Box Girder	Special Inspection	Yes	1990	7754

Description: Severe corrosion in the box girders were discovered during an initial inspection. An expansion joint leaked de-icing agents into large areas of the box girders. Traffic was not restricted. A special inspection and model were built. It was concluded to plate the lower members where there was severe section loss.

#15 MEXICO

Event Date	Trigger Category: Inspection
June 2015	Fatigue crack discovered of anchor system

Bridge Type	Immediate Reaction	Special Assessment	Construction Year	Total Length (m)
Cable Stay	Retrieve SHM Data	Yes	1994	422

Description: A defective weld in the upper anchoring element of one cable, with initial cracks that evolved due to fatigue was discovered after failure. Traffic was restricted to the left side of the bridge. A special inspection was performed in addition to data being retrieved from the structure health monitoring (SHM) system to assess the rest of the bridge. A temporary supporting system was installed. This work was completed in August 2016.

#16 NORWAY

Event Date	Trigger Category: Inspection
2015	Expansion joint failure damaging side wall of abutments

Bridge Type	Immediate Reaction	Special Assessment	Construction Year	Total Length (m)
Concrete Slab	Special Inspection	Yes	1975	214

Description: During a simple inspection in 2015 it was found that the bridge deck had no more expansion room at the joints and that the concrete was damaged along the side walls of the abutments (spalling). The immediate reaction was to remove the back wall and build one 10 cm behind the original one. Traffic was removed during work and special investigations. The permanent fix will include many more repairs and remediation. This work is ongoing.

#17 POLAND

Event Date	Trigger Category: Inspection
September 2014	Part of bridge portion appeared to have sank

Bridge Type	Immediate Reaction	Special Assessment	Construction Year	Total Length (m)
Double T Post Tension Girders	Restricting Heavy Trucks	Yes	1970	233

Description: During a routine inspection, an observation of the barriers and edge beam showed the portion of the bridge was sinking. The owner restricted heavy trucks immediately. It was determined a default in the girders and the bridge stabilized. Proof testing was performed and no repairs were made. Heavy truck traffic remains restricted.

#18 SLOVENIA 1

Event Date	Trigger Category: Rating
	200 older bridges designed and deteriorated assessed for safety

Bridge Type	Immediate Reaction	Special Assessment	Construction Year	Total Length (m)
Reinforced Concrete Beams	No Immediate Reaction	Yes	1960	0

Description: Over 200 older bridges were assessed for structural safety. A program of different analysis and assessment techniques was used to determine what bridges would need posting or strengthening. Load posting of the bridges was to be mitigated based on the program assessment techniques. Of the 200 bridges that were evaluated 13 needed actions in form of strengthening or load posting.

#19 SLOVENIA 2

Event Date	Trigger Category: Bridge Element Failure
2009	An element of the expansion joint failed

Bridge Type	Immediate Reaction	Special Assessment	Construction Year	Total Length (m)
Concrete Box Girder	Lane Closed	Yes	2009	91

Description: An element of an expansion joint failed. The driving and emergency lanes were closed immediately. An expansion joint expert was called in to evaluate all other elements and expansion joints. As an element was not in stock the replacement took four weeks.

#20 SOUTH AFRICA

Event Date	Trigger Category: Bridge Impact
November 2014	Pedestrian bridge hit above freeway

Bridge Type	Immediate Reaction	Special Assessment	Construction Year	Total Length (m)
Post Tension T Beam	No Immediate Reaction	No	1979	95

Description: A pedestrian bridge was struck by a vehicle. The owner decided to jack up the bridge by .5 meters as a temporary solution before making a permanent repair. The jacking of the bridge was completed in December of 2015 and the permanent repairs of the damaged area was completed in October 2015.

#21 SPAIN 1

Event Date	Trigger Category: Bridge Impact
July 2002	Bridge hit by a vehicle knocking out a column

Bridge Type	Immediate Reaction	Special Assessment	Construction Year	Total Length (m)
Prestress Concrete Box Girder	Closed Bridge	Yes	1995	60

Description: A heavy vehicle hit one of the columns of the pier, causing the collapse of it. The girders supported by this column were hanging on the deck. The bridge was closed and traffic was restricted underneath. Big hydraulic jacks were installed to replace the collapsed column as a temporary fix. A new column was formed and installed and tests were performed for the deck to ensure adequate serviceability. The work was completed in 42 days.

#22 SPAIN 2

Event Date	Trigger Category: Bridge Inspection
September 2016	Deck moved transversely 20 cm caused from rotational instability from bearing devices

Bridge Type	Immediate Reaction	Special Assessment	Construction Year	Total Length (m)
Prestressed Concrete Beams	Special Inspection	Yes	2004	215

Description: The road maintenance personnel had detected a transverse displacement of the deck. A special inspection and several assessment techniques were conducted to evaluate the bridge. In addition, traffic was restricted from the wider shoulder. The permeant fix consisted of replacing the bearings and the repositioning the deck. The work was completed on January 27, 2017.

#23 USA – FHWA (1) (276)

Event Date	Trigger Category: Inspection
January 2017	Inspector During Painting Work Discovered a Full Depth Fracture

Bridge Type	Immediate Reaction	Special Assessment	Construction Year	Total Length (m)
Arch Through Truss	Closed Bridge	Yes	1956	2058

Description: A construction inspector during painting of the truss noticed a full depth fracture of the top chord on one of the spans. The bridge and roads underneath were closed to all traffic. The determined repair was to splice the chord to restore it. The bridge was repaired and returned to service in March, 2017.

#24 USA – FHWA (2) (75)

Event Date	Trigger Category: Inspection
June 2014	Fracture in Web and Bottom Flange Discovered

Bridge Type	Immediate Reaction	Special Assessment	Construction Year	Total Length (m)
Steel Plate Girder	Lane Closed	Yes	1968	146

Description: A routine bridge inspection identified a fracture in the web and bottom flange of an interior girder. Traffic was immediately restricted above the affected girder. The girder was repaired by removing the crack tips and plate over the section. The repair was completed by the end of June and the traffic restriction was removed.

#25 USA – FHWA (3 SM)

Event Date	Trigger Category: Inspection
February 2011	Cracks in Tension Tie Discovered

Bridge Type	Immediate Reaction	Special Assessment	Construction Year	Total Length (m)
Tied Arch Truss Bridge	Special Inspection	Yes	1960	488

Description: The Bridge was under a fracture critical arm's length inspection when cracks were discovered in the tension tie. It was decided to manage the bridge with a special inspection and engineering analysis while the repairs were being made. During this monitoring period a crack was discovered and the bridge was closed until the repairs could be made over the next 6 months. These repairs included plating the members and some post tensioning. This work was completed on February 7, 2012.

#26 USA – WISCONSIN (1)

Event Date	Trigger Category: Bridge Inspection
September 2015	Excessive Pier Cap Deterioration

Bridge Type	Immediate Reaction	Special Assessment	Construction Year	Total Length
Prestressed Girder	No Immediate Reaction	No	1959	176

Description: Excessive deterioration was discovered during a routine visual inspection under a pier cap. The bridge was not closed or have traffic restriction. A 2d analysis was performed to ensure the pier cap had adequate load carrying capacity. The bridge will be rehabilitated in the near future.

#27 USA – WISCONSIN (2)

Event Date	Trigger Category: Bridge Impact
February 2016	Bridge Hit Severed Prestress Strands

Bridge Type	Immediate Reaction	Special Assessment	Construction Year	Total Length (m)
Prestressed Girder	Closed under highway	No	1966	52

Description: The Bridge was hit by a back hoe on a trailer and it damaged girders severing prestressing strands. deterioration was discovered during a routine visual inspection under a pier cap. Bridge inspectors closed the ramp pending further evaluation. The bridge was re-opened to legal traffic after an engineering analysis. The final repair was FRP and completed in the summer of 2016.

#28 USA – WISCONSIN (3)

Event Date	Trigger Category: Bridge Impact
February 2016	Truss Member Hit and Fractured

Bridge Type	Immediate Reaction	Special Assessment	Construction Year	Total Length (m)
Mixed Truss Bridge	Closed Bridge	Yes	1930	424

Description: The Bridge was hit by a back hoe on a trailer and it damaged the bottom chord at nine locations on two truss spans. The Bridge was closed until additional inspection and evaluation were completed. The bridge was opened under a 20 ton limit the next day. Members were fabricated and replaced the damage m

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