Antonia Menga
Terje Kanstad
Daniel Cantero

Norwegian University of Science and Technology

Corrosion induced failures of post-tensioned bridges

Report

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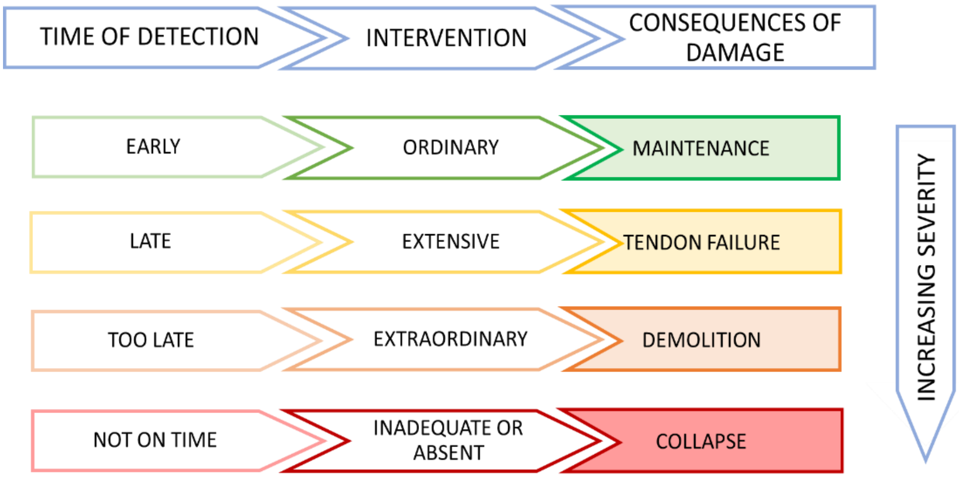
NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Structural Engineering



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The present research project was mainly conducted between September and November 2020, at the Department of Structural Engineering at NTNU in Trondheim, Norway. The study was supported by the 5-year research and development programme for bridges and ferry quays of steel and concrete "Better Bridge Maintenance", established by the Norwegian Public Road Administration (NPRA) in February 2017.

Abstract

The present report includes the results obtained from a literature survey about corrosion-induced failures of post-tensioned bridges and a few other cases of prestressed structures.

The structures have been briefly described with a focus on the prestressing system. After that, the failures have been characterized according to the severity of the observed damage, and attention has been given to the presence of warning signs. The major failure causes have been identified, with a subsequent in-depth analysis about the most frequent causes of corrosion.

Finally, comparisons among the different typologies of investigated structures have been made.

Indexing terms	**Stikkord**
Post-tensioned bridges	*Etterspente broer*
Corrosion-induced failures	*Korrosjon*
Literature survey	*Litteraturundersøkelse*

Table of contents

List of symbols

AASHTO	American Association of State Highway and Transportation Officials
ASBI	American Segmental Bridge Institute
BRUTUS	Bridge Management System of the NPRA
DE	Destructive evaluation
FHWA	Federal Highway Administration
FIP	International Federation for Pre-stressing
HDPE	High density polyethylene
LCPC	Laboratoire Central des ponts et chaussées
MCEER	Multidisciplinary Center for Earthquake Engineering Research
NDE	Non-destructive evaluation
NPRA	Norwegian Public Road Administration
NTNU	The Norwegian University of Science and Technology
PE	Polyethylene
RC	Reinforced concrete
UK	United Kingdom
USA	Unite States of America

1 Introduction

1.1 Background

When a bridge failure occurs, the loss of the structure constitutes only a part of the total effect. Its loss can result in much greater economic consequences than the value of the asset itself (Lee et al, 2013), e.g., loss of human lives and traffic disruption problems. Numerous investigations have been conducted to evaluate the health of bridges and the causes of their failure in different countries.

Harik et al (1990) reported that in 1988, in the United States there were 587 717 bridges, of which 40.8% were rated substandard by the Federal Highway Administration (FHWA). Moreover, between 1951 and 1988, 114 bridge failures occurred in the USA (excluding the ones that happened during construction phase). Most of these failures were due to accidents (e.g., cars or trucks colliding with the structure) and natural catastrophes like scour, earthquake, flood.

In 1970 the FIP (International Federation for Pre-stressing) Commission on Durability surveyed 200 000 prestressed structures. An extremely low proportion of cases causing concerns was reported, together with rare occurrences of corrosion where the consequences had been serious (West et al, 1999).

In the period 1977-1981, a study on 150 damaged and collapsed structures around the world was carried out by Hadiprono (1985). More than one third of the analysed structures were bridges, the degradation of which was mostly attributable to external events (like lateral impact forces, unexpected live loads) and construction deficiencies (e.g., falsework and concreting faults, lack of knowledge in long-term creep and shrinkage effects on concrete).

Between 1979 and 1992 the UK Standing Committee on Structural Safety published annual reports, which included reports on suspected deficiencies of grouting of post-tensioning tendons. Then, the Highway Agency in 1994 started a significant systematic series of inspections of their bridges. These activities gradually provided evidence of a growing problem with some post-tensioned structures (Clark, 2013).

Over 500 failures of bridge structures in the USA were studied by Wardana and Hadipriono (2003) between 1989 and 2000. The outcome of the investigation was that the most frequent reasons of failure were not due to design and construction fault, but due to flood and collisions, as already stated in Harik et al (1990).

Miller (1995) described the results of a durability survey promoted by the American Segmental Bridge Institute (ASBI) in North America (USA and Canada). The inspection of 96 bridges highlighted that segmental constructions performed well over time.

Between 1995 and 1998, a study on the durability of prestressed concrete bridges was carried out in Switzerland (Matt et al, 2000). Some cases of significant corrosion damages were identified. However, the study showed that prestressed concrete bridges generally behave very satisfactorily and fulfil the durability requirements, especially if they are properly maintained.

Another investigation was conducted by the FHWA in 2001. It reported that in the United States there were 691 000 bridges, of which nearly 30% were rated as deficient (Choudhury and Hasnat, 2015). Since 2008, the FHWA has been supporting a research project at the Multidisciplinary Center for Earthquake Engineering Research (MCEER) with the aim of establishing reasonable bridge damage/failure models (Lee et al, 2013).

In Germany, despite the design lifespan of more than 70 years, bridges showed major damage after a time period of 30 to 40 years (Venugopalan, 2008).

As it can be seen from the brief overview presented here, previous research investigated the overall health of bridges, highlighting that generally they tend to perform well over time. Nevertheless, there are many failures of bridges included in the previous surveys and their causes are quite various (accidents, natural catastrophes, external events, construction deficiencies, corrosion). Moreover, these causes proved to be strongly influenced by the characteristics of the bridge (like its location, environment, age, structural typology). Therefore, each country has tended to orient research accordingly to the characteristics and conditions relevant to their territory. This explains why, for example, UK has focused on post-tensioned structures.

In this scenario, in 2017 the Norwegian Public Road Administration (NPRA) promoted the 'Better Bridge Maintenance' research and development programme. The aim was to reduce the decay of national bridges by finding ways of assessing the state of the structures and identifying the most favourable maintenance methods.

According to the Bridge Management System (BRUTUS) of the NPRA, concrete bridges make up a majority of the 18 199 bridges on national and county roads in Norway, and a significant number of them is built with prestressing tendons. Many of the bridges are in or near coastal regions, with varying exposure to sea water, while all of them are subject to de-icing salts during the winter. In this chloride-contaminated environment, the risk of corrosion increases, depending on age, exposure, and detailing (Osmolska et al, 2019).

It is worth remembering that the technological methods of prestressing (pre-tensioning and post-tensioning) used worldwide can lead to different strand conditions. In the case of pre-tensioned bridges, the strands are placed in concrete without ducts, which means that conventional methods – non-destructive evaluation (NDE) and destructive evaluation (DE) – developed for ordinary reinforced concrete can be used to detect reinforcement corrosion (Osmolska et al, 2019). In contrast, strands in post-tensioned bridges are located inside ducts which affect the reliability and performance of NDE methods (Hurlebaus et al, 2017). In fact, NDE can be used to detect corrosion of strands only if they are enclosed in a non-metallic duct. Even if NDE methods can also be used to detect voids in the grout (where corrosion usually occurs) regardless of the duct type, the presence of voids does not always imply the presence of corrosion. This means that the only way to safely assess the presence and degree of corrosion in post-tensioning strands is through destructive testing (e.g., re-moving concrete and duct), which could compromise the capacity of the bridge.

Therefore, surveys are often limited to visual inspections which could overlook corrosion activity. In fact, there have been cases in which corrosion damage in post-tensioned elements has been found in situations where no external indications of the problem were apparent (West et al, 1999).

Nevertheless, it is largely acknowledged that much can be learned from damage information and past failures of bridges in terms of technical knowledge associated with bridge engineering (Lee et al, 2013, Choudhury and Hasnat, 2015).

Generally, post-tensioned concrete has performed very well indeed. However, in the late 1980s and early 1990s it became apparent that the steel tendons can suffer severe corrosion unless they are properly protected. There is normally adequate protection but there have been occasions when this had not been achieved (Tilly, 2002). For example, in 1992 in the UK, a moratorium on segmental bridges with internal post-tensioned tendons was placed after the collapse of two bridges of that kind in 1967 and in 1985 (Lau and Lasa, 2016). Furthermore, in 1989, a study was commissioned by the United States Department of Transportation, Federal Highway Administration to examine the performance of grouts for post-tensioned bridges, after the potential for corrosion of tendons in bridges in the USA had been recognized (Powers et al, 2002).

Unfortunately, it is not possible to obtain precise numbers on the incidence of corrosion in prestressed concrete structures, mainly because many cases are not reported and some occurrences of corrosion have not yet been detected (West et al, 1999).

Moreover, as described above, past surveys carried out in various countries mainly studied the overall health of the bridges. Even when the surveys focused on corrosion-induced damage, if more than general information was provided, research was limited in space (i.e., only bridges in a determined area were studied) or to a specific topic (e.g., grouting conditions).

This being the case, the lack of knowledge about corrosion-induced failures and serious damage in post-tensioning tendons is alarming, mainly because it is almost impossible to anticipate these kinds of failures.

1.2 Aim of the research

The 'Better Bridge Maintenance' project includes the collaboration between the NPRA and the Norwegian University of Science and Technology (NTNU). The main aim of this collaboration is to improve the understanding of the structural consequences of damage and/or corrosion in post-tensioned systems. In this regard, the following topics have been addressed:

a) increased knowledge of possible failure mechanisms (e.g., corrosion of the tendons due to poor grouting and/or corrosion of anchors);
b) assessment of the influence of failure of certain parts of the post-tensioned system on the load bearing capacity of the structure, by recalculation of critical cross sections;
c) overall assessment of the load bearing capacity for selected cases/bridges;
d) selection of relevant case studies with the aim of developing general guidelines for the assessment of structural consequences in case of damage of the post-tensioned system.

The present report is related to point d) in the above list. Therefore, the main aim of this report is to collect and investigate a number of representative post-tensioned structures (especially bridges), taking into account possible failure mechanisms induced by corrosion of the post-tensioned system. As a result, the intention is to increase the knowledge about the structural consequences of these failures beyond what can be acquired through merely visual inspections. For this purpose, the following problems have been addressed:

- Is there any way to improve visual inspections to assess the development of corrosion in post-tensioned structures? In other words, can the presence of warning signs be used to anticipate corrosion-induced failures?
- How does location (construction techniques used, climate conditions, proximity to the sea, to water in general or to sources of pollutants) affect the failure?
- For the different types of post-tensioned structures:
    - To what corrosion-induced problem are they most sensitive?
    - How severe is generally the damage when it is detected?

1.3 Methodology

To achieve the main aim of this report, a literature survey of corrosion-induced failures of post-tensioned bridges plus some cases of other types of prestressed structures was carried out. The survey consisted in the analysis of all the publicly available documents on the topic to the authors' knowledge, and all the failure cases with the above characteristics were included in this study. The questions specified above were thus answered and listed in the same order. These were addressed considering the following considerations:

- Attention was paid to the presence and description of warning signs in the studied failure cases, especially when they contributed to prevent the failure.
- The failure cases were included in the survey regardless of their geographical location.
- Failures, their causes, and the detected damage were investigated and correlated with the most common types of post-tensioned structures.

The failure cases identified during the literature review mostly involve post-tensioned bridges, but a few cases of pre-tensioned bridges and post-tensioned structures such as slabs or cylindrical containers were also included.

This was done to make it possible to evaluate whether considerations made for structures potentially easier to assess can be applied to post-tensioned bridges. The arguments can be listed as:

- Pre-tensioned bridges can be assessed through NDE methods.
- The assessment of simpler post-tensioned structures (i.e., when compared to bridges with short design working life, with smaller dimensions, and subject to smaller loads) such as slabs require less effort than the assessment of bridges.

Comparing different types of structures can indeed help understanding the behaviour of post-tensioned bridges. However, this analysis has not been included among the aims of the present research, because the number of structures different from post-tensioned bridges is too small to be of statistical importance.

To manage and analyse the considerable amount of data systematically, every failure case was given an identification number (denoted by the symbol ID-xx). The cases were listed as in Table A1 (reported in Appendix A), where characteristics about age, location, structure type, failure mechanism and failure causes were reported with additional notes. The information gathered in Table A1 was then summarized in Table B1 (reported in Appendix B). In Table B1, only the most important specifics were included, focusing on:

- type of structure and prestressing system;
- tendon and grouting description;
- characterization of corrosion products and causes;
- presence of warning signs;
- description of the failure mechanism and the associated damage.

Finally, keywords were assigned to every structure. The keywords were used to make graphical analyses of the case studies and are shown in the main body of the report.

1.4 Limitations

With regard to the analyses included in this report, the following limitations need to be highlighted:

- assessment of NDE methods is out of the scope of the present report, hence they have not been investigated;
- the review of failures presented herein cannot be considered exhaustive, because many cases have not been reported in the literature and/or have not yet been detected;
- the published information regarding some of the case studies is incomplete or lacks sufficient level of detail.

1.5 Outline of the report

This report consists of a main body of five sections and three appendices.

The main body is a compendium of the data collected in the literature survey and of the results of the analyses performed using them, in particular:

- Section 1 gives a background to the work, and presents its aims, methods and limitations.
- Section 2 presents the features of the selected case studies.
- Section 3 characterizes the failures.
- Section 4 describes the major failure causes and their correlation with the structure type.
- Section 5 provides the main conclusions drawn from this work and suggestions for future research.

The appendices contain the raw data and the analyses performed:

- Appendix A consists of a table listing the characteristics of each structure in detail.
- Appendix B includes two tables in which the key features of each structure are presented with brief summaries and keywords.
- Appendix C displays the most significant images of the studied structures.

2 Case descriptions

This report introduces 52 cases of prestressed structures in which the failure is attributable to corrosion. Every case was randomly associated with an identification number (denoted by the symbol ID-xx, see Appendices A and B) for ease of presentation.

The present section contains the general description of the case studies, where each subsection treats a separate aspect, as listed:

- Section 2.1 discusses the geographical location of the structures.
- Section 2.2 provides the description of the types of structure and prestressing system.
- Section 2.3 deals with the types of ducts and their filling.

A more detailed description of some particular cases is also provided throughout the entire Section 2.

2.1 Geographical location of the structures

The majority of the failures reported herein occurred in the USA (22 cases, 7 of these in Florida), in the UK (9 cases), in Italy (7 cases) and in France (6 cases). The other studied failures took place in Korea, India, Japan, Canada, Belgium, Germany and Australia.

Figure 2.1.1 shows also that 4 cases happened in Asia, 23 in North America, 1 in Oceania and 24 in Europe.

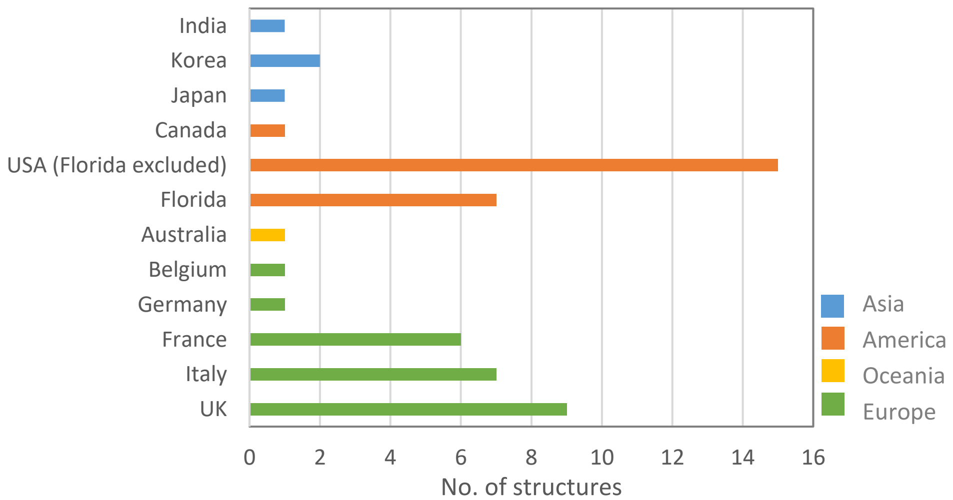

Figure 2.1.1. Geographical location of the case studies.

2.2 Type of structures

Of the aforementioned 52 cases, 47 were prestressed bridges and 5 other types of internally post-tensioned structures (i.e., one hyperbolic shell, 3 slabs and one cylindrical container).

As it can be seen in Figure 2.2.1, the majority (15 out of 47) of the analysed bridges consisted of a segmentally mounted (precast and cast in situ) deck. However, numerous cases of simply supported or continuous beam bridges were present, in particular 6 cases with I-section or T-section beams, and 14 cases including box section beams.

Furthermore, 6 cases in Figure 2.2.1 are described as 'innovative structure' due to their unique design, which has rarely or never been adopted in other structures. Among these, there are 4 bridges (i.e., Polcevera Bridge, Carpineto Viaduct, Sunshine Skyway Bridge and Melle Bridge), a hyperbolic shell structure and a cylindrical container. It has to be noted that, even though the design of the cylindrical container is of common use, this case has been included in the entry 'innovative structure' because it could be considered atypical in relation to the structures included in the present report.

In 7 cases it has not been possible to identify the type of structure due to lack of information in the literature.

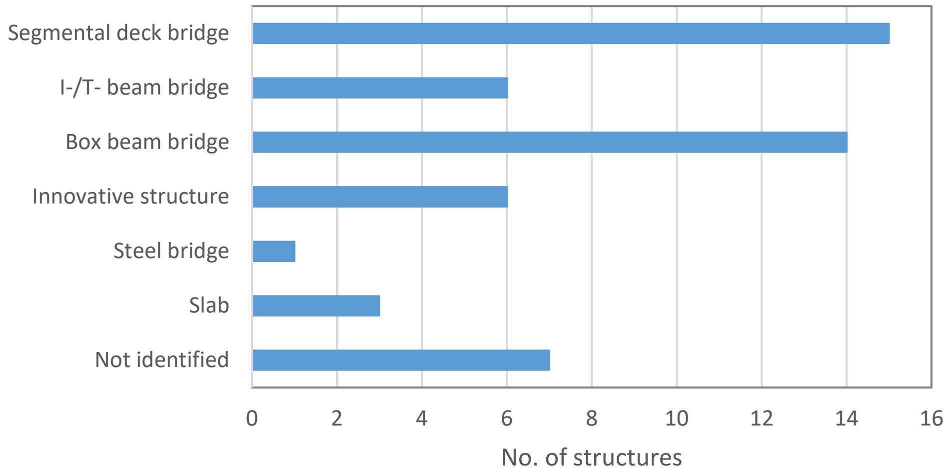

Figure 2.2.1. Types of studied structures.

The selected structures were also classified according to the type of prestressing system. There were:

- 44 post-tensioned structures, of which:
  - 5 internally post-tensioned structures different from bridges;
  - 18 internally post-tensioned bridges;
  - 21 externally post-tensioned bridges.
- 3 pre-tensioned beam bridges;
- 1 bridge with some pre-tensioned spans and some post-tensioned spans (ID-33);
- 3 cable-stayed bridges (ID-6, ID-8 and ID-10);
- 1 suspension bridge (ID-40).

Figure 2.2.2 shows the aforementioned classification considering all the investigated structures (i.e., not only bridges).

As it can be seen from the previous list and Figure 2.2.2, even though prestressed structures are the topic of this research, a cable-stayed and a suspension bridge have been included in the review despite not having a prestressed deck, but deemed relevant for this report because of the reported presence of corrosion in the cables. This has been done because the cables in those structures can be considered as externally post-tensioned tendons. In fact, the magnitude of stresses in the tendons, the kind of ducts in which they are encased and the exposure to external environment make these structures relevant.

For each structure, only the most important category was assigned. For example, Polcevera Bridge was a cable-stayed bridge with a post-tensioned deck, hence it could have been enlisted as a post-tensioned or a cable-stayed bridge. However, since the cables were the ones to fail, the entry 'cable-stayed' was selected.

F. G. Gardiner Expressway (ID-33) was the only bridge to present failures both in pre-tensioned and post-tensioned spans, so both the categories 'pre-tension' and 'post-tension' were indicated, considering the bridge twice. This is why the number of structures showed in Figure 2.2.2 is 53 instead of 52[1].

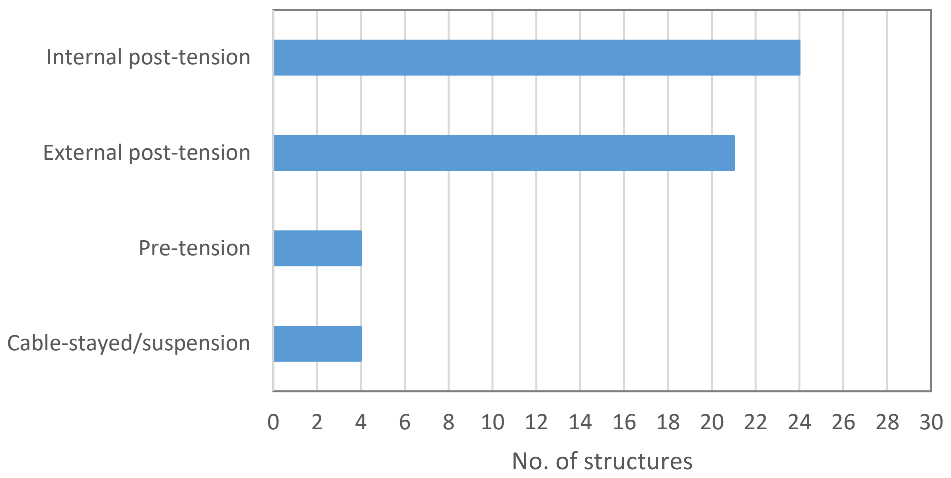

Figure 2.2.2. Type of prestressing system in the studied structures.

Detailed information about the type of tendons constituting the prestressing systems was found only in less than half of the studied cases (25 out of 52 cases). Most of them consisted of spirally wound seven-wire strands with diameter ranging between 12 and 20 mm. In some cases, the strands were made with 12, 18, 19 or 27 twisted wires, while only for ID-1 the strands were made of 12 straight wires each of 5 mm diameter.

After describing the types of structures and the types of prestressing system of the studied cases, a correlation between the two categories is shown in Figure 2.2.3.

Excluding the 'not identified' cases (for which too little or no information was provided in the literature), it is interesting to put the focus on post-tensioned structures. This analysis shows that:

- Internal post-tensioning system was equally adopted in different typologies of structures:
  - 5 segmental deck bridges;
  - 4 I-/T-beam bridges;
  - 5 box beam bridges;
  - 3 innovative structures;
  - 3 slabs.
- External post-tensioning system was mostly adopted in segmental deck bridges (10 out of 20 cases) and box beam bridges (9 out of 20 cases).

The majority (11 out of 15) of the segmental post-tensioned bridges studied in this work are made of precast segments. Precast are also the 4 post-tensioned I-/T-section beam bridges and 3 out of 14 post-tensioned box beam bridges. In particular:

- 6 out of 21 externally post-tensioned bridges consist of precast elements;
- 13 out of 19 internally post-tensioned bridges consist of precast elements.

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[1] In this report, considerations regarding the type of prestressing are always related to 53 structures, because bridge ID- 33 has been considered twice.

This information, together with the data presented in the above list (related to Figure 2.2.3), highlights the strict correlation between precasting and post-tensioning. In fact, it has been quite common to build big and/or complex structures such as bridges, with precast elements put together by post-tensioning systems.

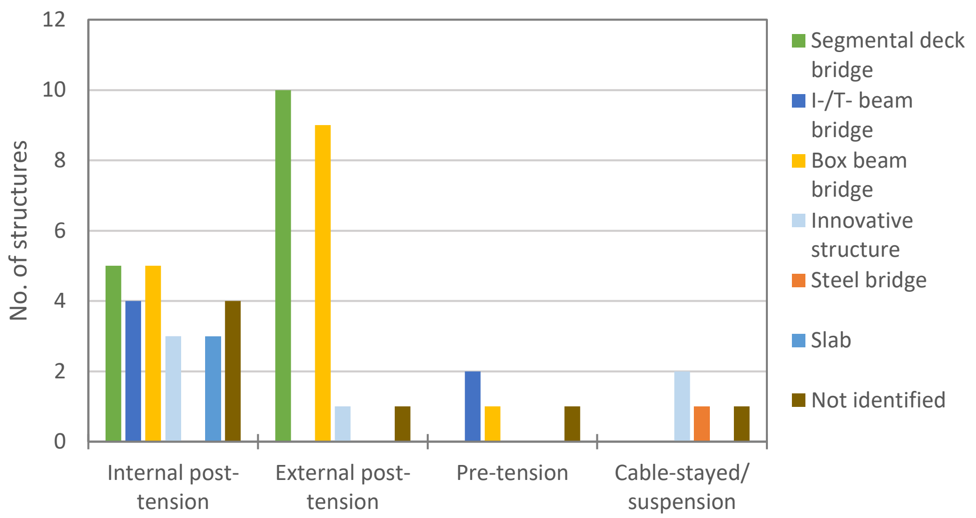

Figure 2.2.3. Types of studied structures divided by type of prestressing system.

In the following, some examples of the studied cases, listed by their identification number, have been reported. The examples are divided according to the type of structure and cover exclusively bridges. Some cases of segmental deck bridges, I-/T-beam bridges, box beam bridges and innovative structures have been included.

Note that the examples here proposed are not necessarily the most significant ones. They are the cases for which some clear pictures and a detailed description are provided in the literature.

Segmental bridges

ID-1 Ynys-y-Gwas Bridge, Wales, UK.

This bridge was built in 1953 and collapsed on 4th December 1985. It was a single span, simply supported segmental post-tensioned bridge, with a clear span of 18.3 m.

The deck consisted of nine precast I-section beams (Figure 2.2.4) with a web stiffer on one end. The beams were made of eight 2.45 m long segments (Figure 2.2.5). The segments were longitudinally post-tensioned by ten Freyssinet tendons, housed in smooth ducts.

The 25 mm transverse joints between segments were filled with mortar before post-tensioning. Cardboard tubes (Figure 2.2.6) enveloped the longitudinal tendons where they passed between the segments and the insertion of asbestos packing between the beams (Woodward et al, 1989).

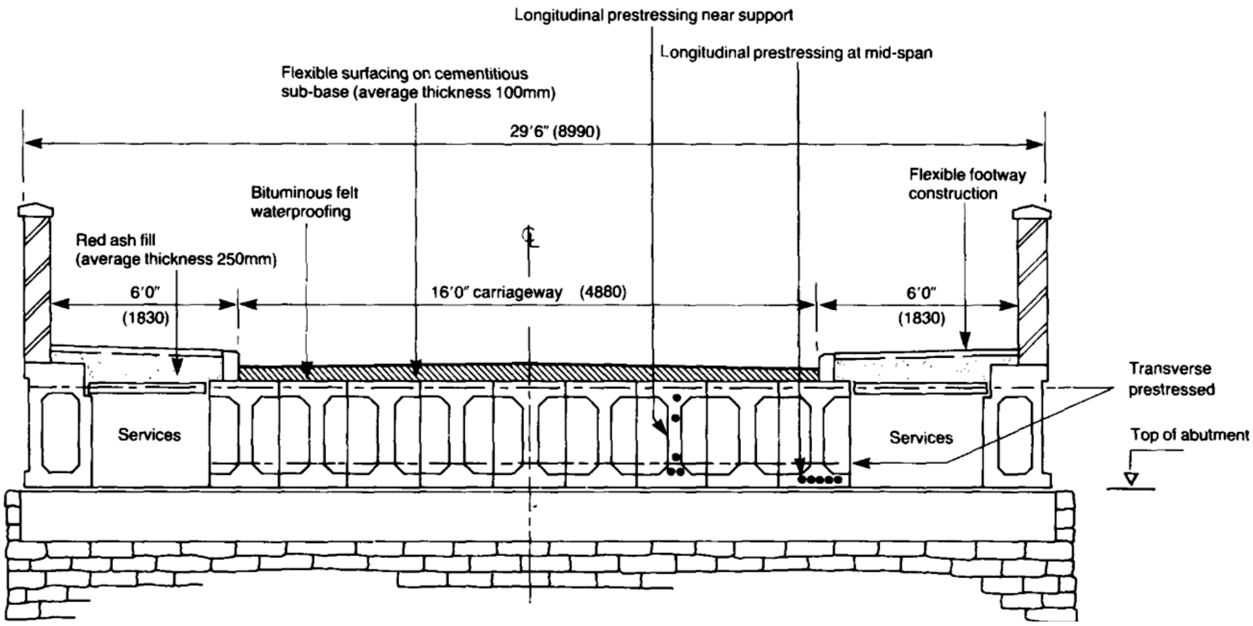

Figure 2.2.4. Cross section of Ynys-y-Gwas bridge (Woodward and Williams, 1988).

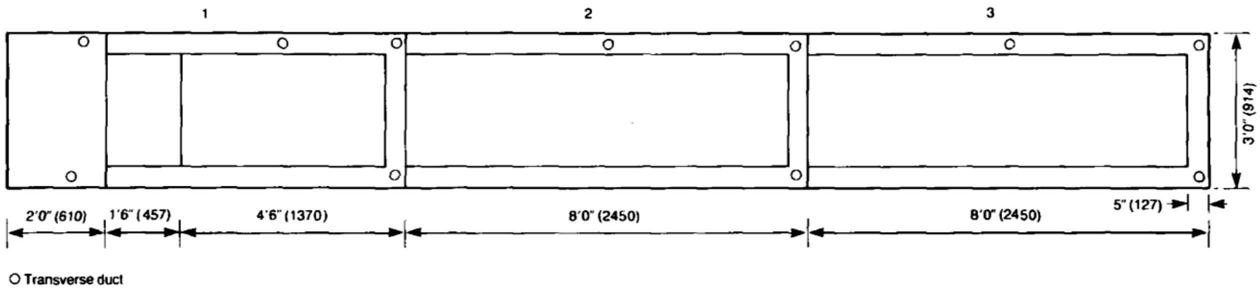

Figure 2.2.5. Longitudinal section of I-beam in Ynys-y-Gwas bridge (ID-1) (Woodward and Williams, 1988).

Figure 2.2.6. Cardboard tube across transverse joint in Ynys-y-Gwas bridge (ID-1) (Woodward and Williams, 1988).

ID-2 S. Stefano Viaduct, Sicily, Italy.

This bridge was built in 1954 and collapsed on 23rd April 1999. The superstructure consisted of four spans resting on three pillars and two abutments.

It was a simply supported girder deck made of seven trapezoidal box beams (Figure 2.2.7). The beams were post-tensioned with precast 1.5 m long segments. Six RC diaphragms and the thin concrete deck slab, cast in situ, transversally stiffened the box beams (Colajanni et al, 2016).

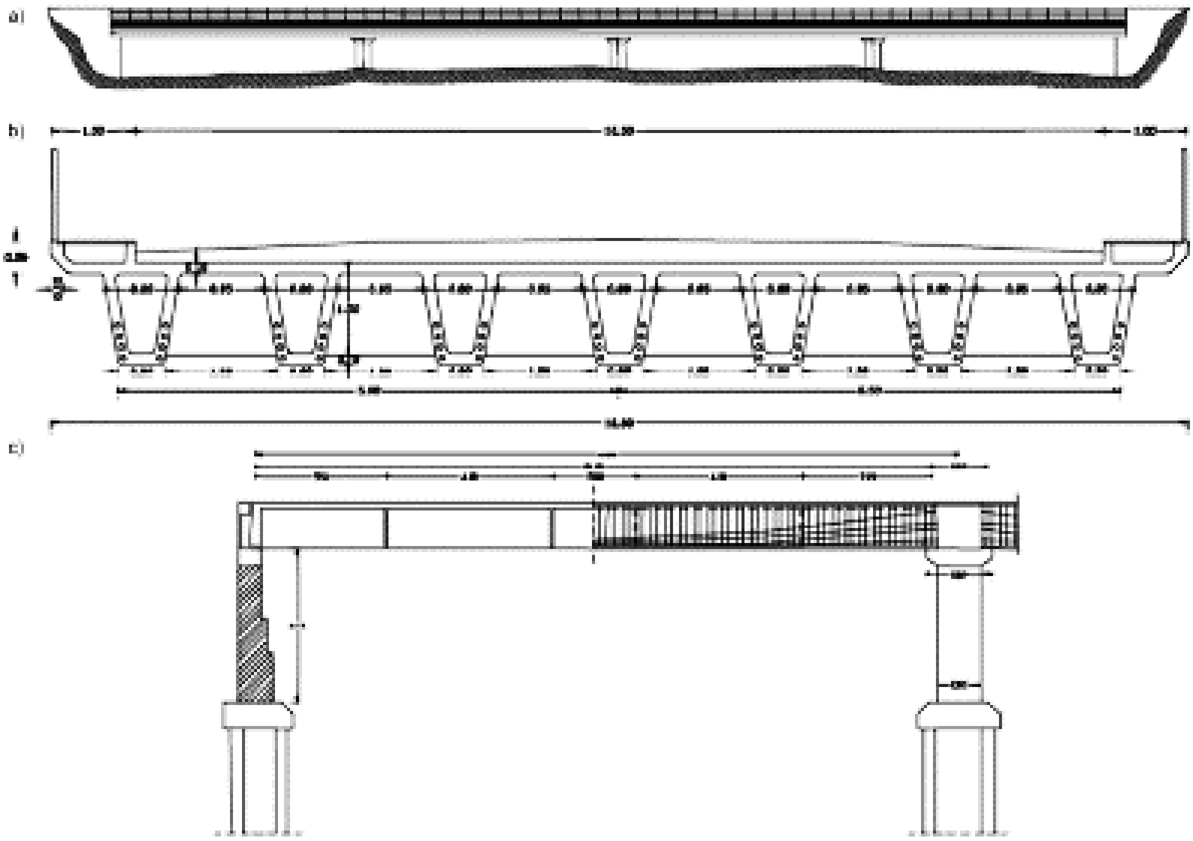

Figure 2.2.7. S. Stefano Viaduct (ID-2): a) front view; b) transversal cross section; c) longitudinal view and cross section (one span) (Colajanni et al, 2016).

ID-37 Hammersmith Flyover, London, UK.

This structure was built in 1962 and underwent maintenance in 2002. It is a 630 m long precast segmental bridge (Figure 2.2.8). The sixteen spans, in average 40 m long, that compose the bridge are post-tensioned both internally and externally (Cousin et al, 2017).

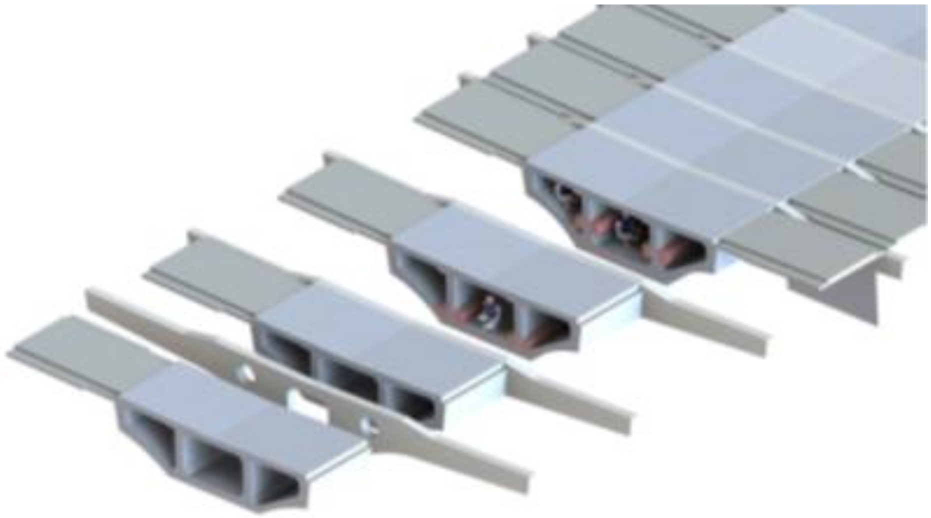

Figure 2.2.8. Simplified view of original construction of Hammersmith Flyover (ID-37) (Cousin et al, 2017).

I-/T- beam bridges

ID-30 I-94 Bridge over US 81, North Dakota, USA.

This structure was built in 1958 and was demolished in 1992. It was a precast, post-tensioned concrete girder bridge made of four spans.

The deck was supported by AASHTO Type II cross section beams (i.e., I-section beams, Figure 2.2.9) with three post-tensioning tendons (Dickson et al, 1993).

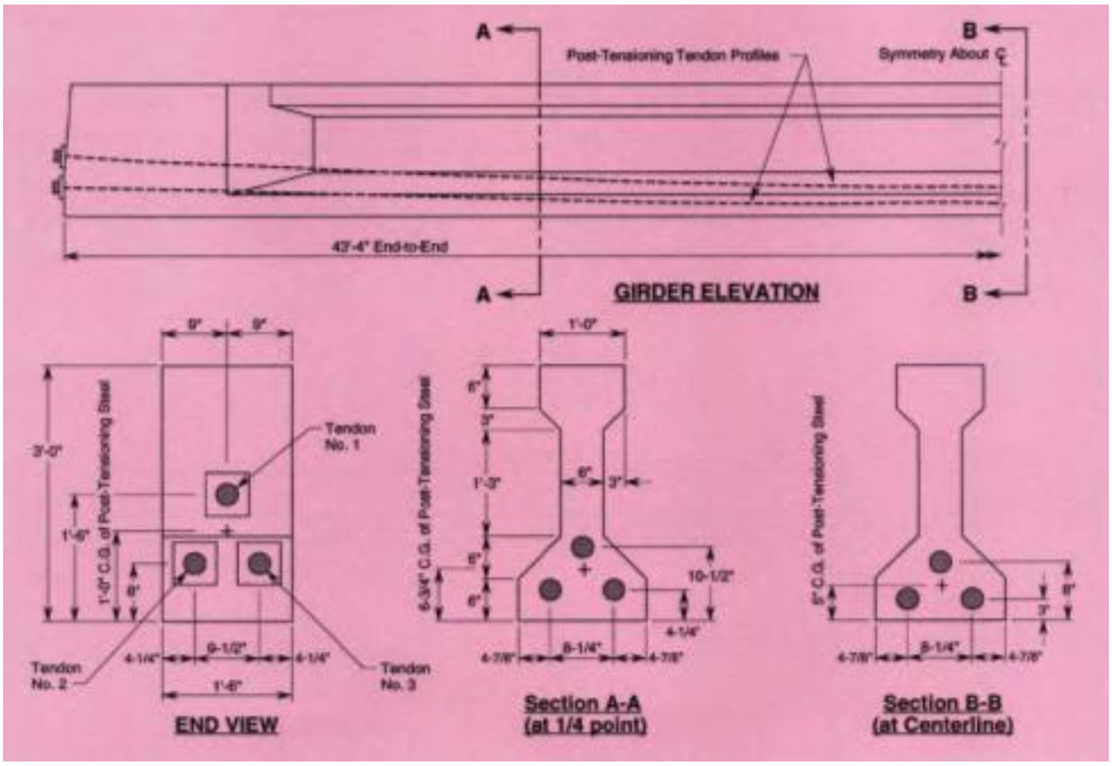

Figure 2.2.9. Location of post-tensioning tendons in I-94 Bridge over US 81 (ID-30) (Dickson et al, 1993).

Box beam bridges

ID-31 Walnut Street Bridge, Connecticut, USA.

This bridge was built in 1960 and was demolished in 1987. It was a 16.5 m long single span, simply supported bridge.

The deck was made of 13 precast, prestressed concrete box beams (AASHTO Type BI-36), post-tensioned together longitudinally and laterally at mid span and at each end (Figures 2.2.10-2.2.11). Longitudinal shear keys filled with grout connected the beams (Murray and Frantz, 1992).

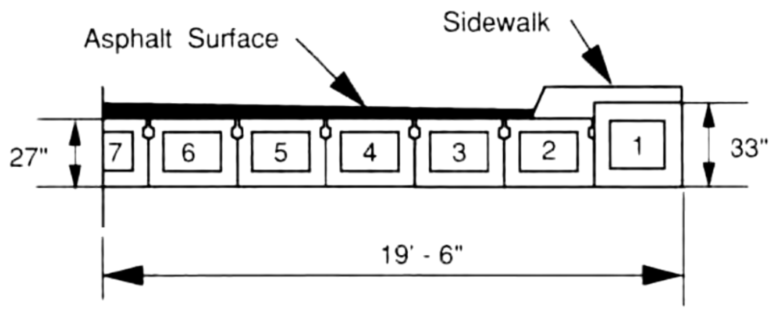

Figure 2.2.10. Walnut Street Bridge (ID-31) cross section, view of symmetric half from north end (Murray and Frantz, 1992).

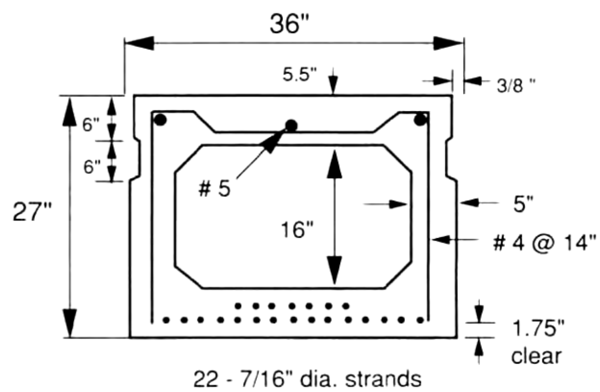

Figure 2.2.11. Walnut Street Bridge (ID-31)'s beam cross section (AASHTO Type B1-36) (Murray and Frantz, 1992).

ID-33 F. G. Gardiner Expressway, Toronto, Canada.

This bridge was built in 1963-1964 and it underwent maintenance in 1980. The 105 m long bridge includes 46 span of main roadway and 59 spans of approach ramps. The spans are made of precast prestressed concreate box beams simply supported on RC bents. The beams are covered by cast-in-place concrete topping and asphalt.

Most beams are pre-tensioned boxes (Figures 2.2.12) with spans ranging between 18-22 m. At two major road crossings the beams are post-tensioned boxes, spanning 27-30 m. The beams are laterally keyed by continuous mortar keys and are lightly transversally prestressed by two strands at mid span and at quarter points (Tork, 1985).

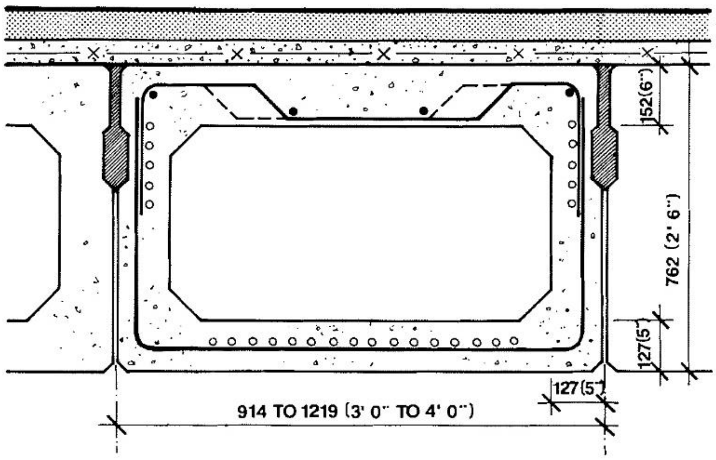

Figure 2.2.12. Typical pre-tensioned box beam cross section of F. G. Gardiner Expressway (ID-33) (Tork, 1985).

Innovative structures

ID-6 Polcevera Bridge (Morandi Bridge), Ligury, Italy.

It was built in 1967 and dramatically collapsed on 14th August 2018. It was a ten-span bridge, with three main spans supported by three cable stayed balanced systems (Figure 2.2.13).

Each balanced system (Figure 2.2.14) is made of (and listed in order of construction, Morgese et al, 2020):

- A pillar and two A-shaped antennas, forming the tower.
- The main deck (made of a five-sector box section), which was constructed in segments extending from adjacent pillars. Each part was supported at four locations by cable stays and by inclined pier trusses (buffer beams) extending from the pillar.
- Four transverse link girders connecting stays and pier trusses to the deck.
- Four cable stays.
- Two simply supported Gerber beam spans, connecting the balanced system to the adjacent parts of the bridge (Figure 2.2.14 (4)).

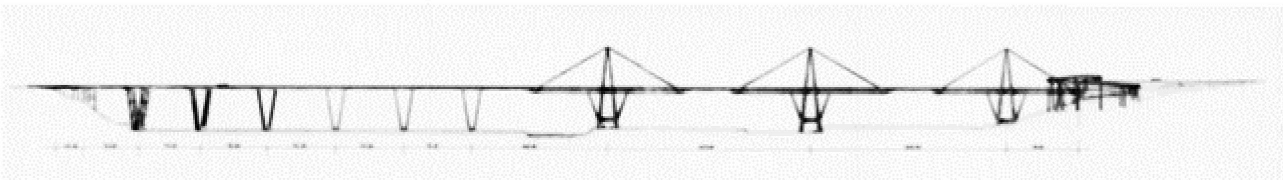

Figure 2.2.13. Elevation of Morandi proposal for Polcevera Bridge (ID-6) (Nuti et al, 2020).

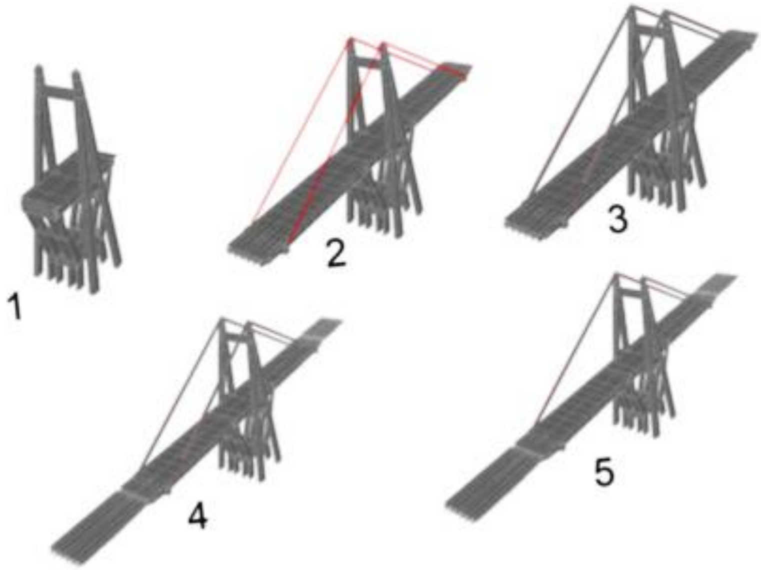

Figure 2.2.14. Polcevera Bridge (ID-6): illustration of the four construction stages, plus the case where the S-W stay is removed (Calvi et al, 2019).

ID-11 Sunshine Skyway Bridge, Florida, USA.

Built in 1982-1987, it suffered from tendon failure in 2000. It comprises three distinct types (Figure 2.2.15) of prestressed concrete structures (Sayers, 2007):

- The low level north and south trestle spans, made of two parallel two-lane structures.
  The superstructure consists of a 4 spans continuous reinforced concrete deck slab. The deck is supported on five precast prestressed concrete AASHTO type IV girders (Figure 2.2.16).
  The substructure consists of reinforced concrete wall type pillars founded on 51 cm square precast prestressed concrete piles. The pillars of the parallel roadways are connected across between the two structures by precast prestressed concrete frangible struts.
- High level north and south approaches (Figure 2.2.17), made of parallel two-lane structures.
  The superstructure consists of single cell precast post-tensioned, trapezoidal continuous concrete box girders.
  The girders are supported on precast, post-tensioned hollow elliptical column segments.
- Main span area (Figure 2.2.17) made of a single structure.
  The superstructure consists of a single cell, precast post-tensioned concrete girders. The girders are equipped with internal post-tensioning cables, shear keys along the edges and diaphragms over the support.
  The substructure consists of post-tensioned concrete pillars supported by 61 cm square precast prestressed concrete piles. The main pillars support 131.7 m high cable-stayed pylons, with a single plane of 42 stays at the centre of the roadway. The stays are bolted to the deck segments through anchorages that are embedded below the road level.

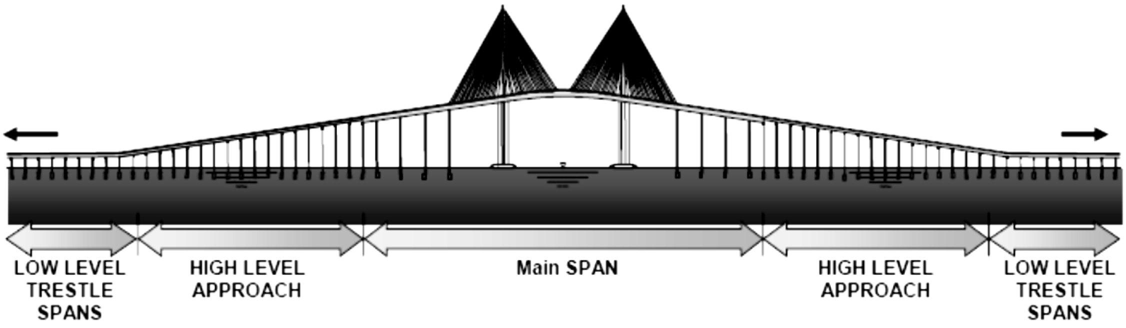

Figure 2.2.15. Sunshine Skyway Bridge (ID-11) geometry (Sayers, 2007).

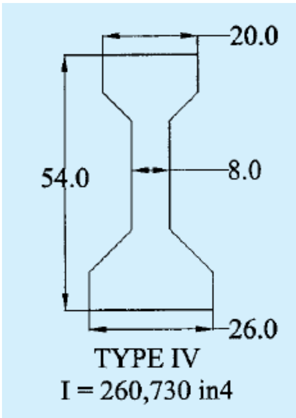

Figure 2.2.16. Sunshine Skyway Bridge (ID-11). Cross section of AASHTO Type IV girder (Kahn and Saber, 2000).

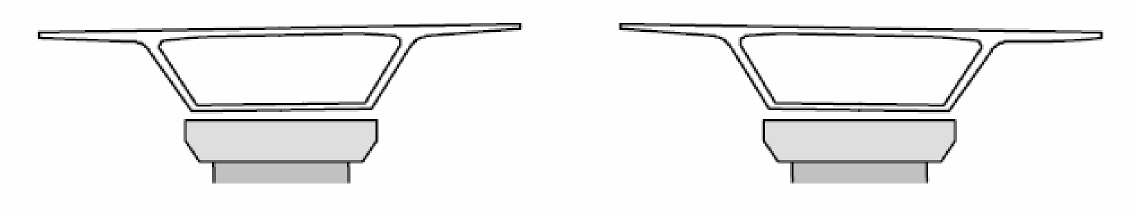

Figure 2.2.17. Sunshine Skyway Bridge (ID-11). Cross section of precast concrete sections for approach spans (Sayers, 2007).

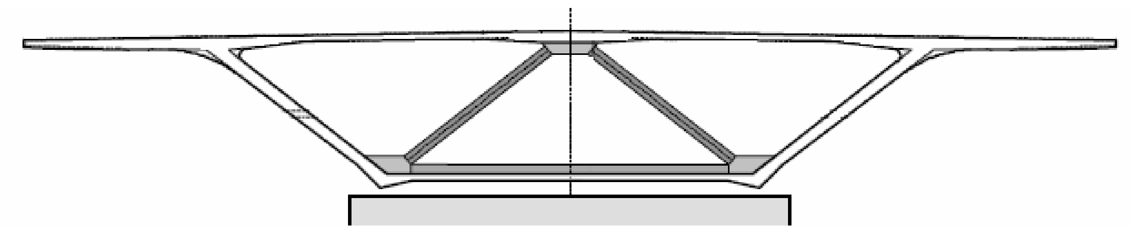

Figure 2.2.18. Sunshine Skyway Bridge (ID-11). Cross section of concrete sections for main span (Sayers, 2007).

2.3 Type of ducts and filling

While in pre-tensioning systems the tendons are bonded directly to the concrete, in post-tensioning systems, both internal and external, the tendons are enclosed in ducts generally filled with grout or grease.

Figures 2.3.1 and 2.3.5 report, respectively, the types of duct and filling for the studied structures. These figures clearly show that in most of the cases, the information included in the analysed papers were insufficient to determine the type of duct and/or filling.

Excluding the entry 'not identified':

- The majority (11 out of 28) of ducts in this study were made of plastic, polyethylene (PE) to be precise.
- There were some cases (7 out of 28) in which metal ducts were used.
- There were some cases (6 out of 28) in which the duct was absent for most of the length of the tendon or for its entire length.
  For example, in ID-1 the tendons were enclosed in cardboard ducts only at joint locations (Figure 2.2.6). On the other hand, in ID-3 the tendons were located in ducts formed using inflatable rubber tubes. The tubes were removed after casting and then the ducts were filled with cementitious grout. In this way, at the end of the prestressing process the tendons were embedded in bare concrete (Figure 2.3.2).
- There were few cases in which the duct was made of concrete.
  These cases are related to Polcevera Bridge (ID-6), Carpineto Viaduct (ID-8), both designed by R. Morandi and included in 'innovative structure', and to Hammersmith Flyover (ID-37).
  In the Morandi's cable-stayed bridges the main cables (Cables A in Figure 2.3.3) were protected by a concrete rectangular duct (Figure 2.3.4) made of precast blocks, post-tensioned by other secondary cables (Cables B in Figure 2.3.3). In Polcevera Bridge the cables were encased in metal ducts, before being inserted in concrete ducts. Hence, the type of duct of Polcevera Bridge is labelled as 'metal'.
  In Hammersmith Flyover the tendons were enclosed in cast in situ mortar boxes after stressing (Cousin et al, 2017).

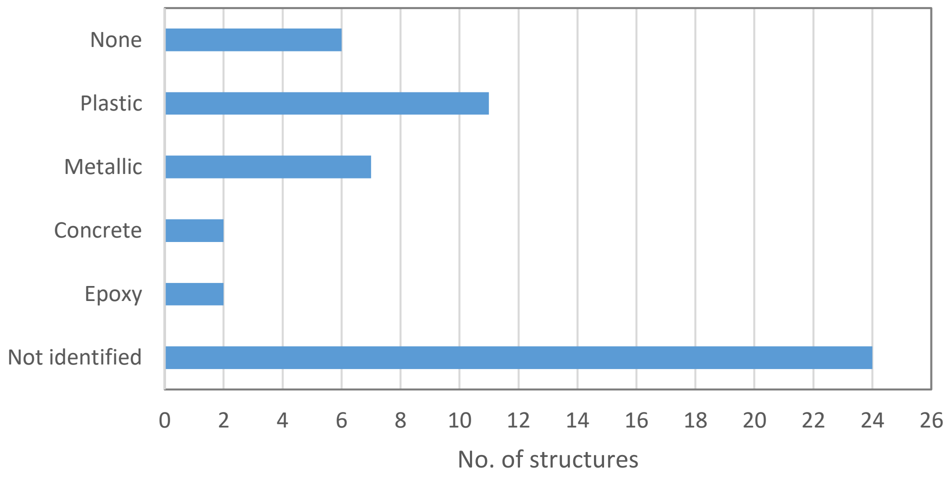

Figure 2.3.1. Type of ducts in the studied structures.

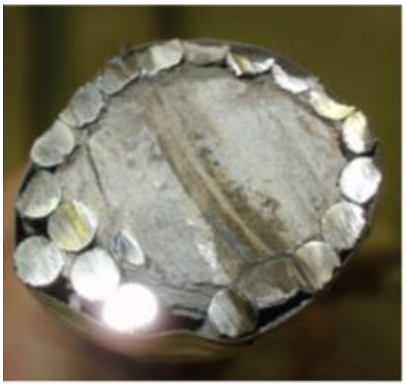

Figure 2.3.2. Sorell Bridge (ID-3). Cross sectional view of one of the most severely corroded tendons. The tape just visible around the outside was applied during recovery to keep the tendon together at the cross sectional cut. There is no tendon duct (Papè and Melchers, 2011).

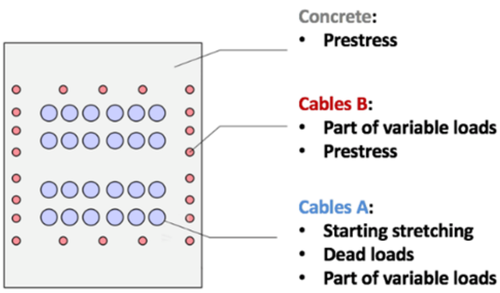

Figure 2.3.3. Polcevera Bridge (ID-6). Stays cross section (Domaneschi et al, 2020).

Figure 2.3.4. Carpineto Viaduct (ID-8). Stays overview (https://www.stradeeautostrade.it/ponti-e-viadotti/il-viadotto-strallato-carpineto-i-2/)

In Figure 2.3.5 the types of duct are correlated with the types of prestressing system.

As it could be expected, all the pre-tensioned structures did not have ducts.

Excluding the ‘not identified’ cases, ducts in internally post-tensioned structures were well distributed among the entries ‘metallic’, ‘plastic’ and ‘none’. On the other hand, the majority of the external tendons were enclosed in plastic ducts.

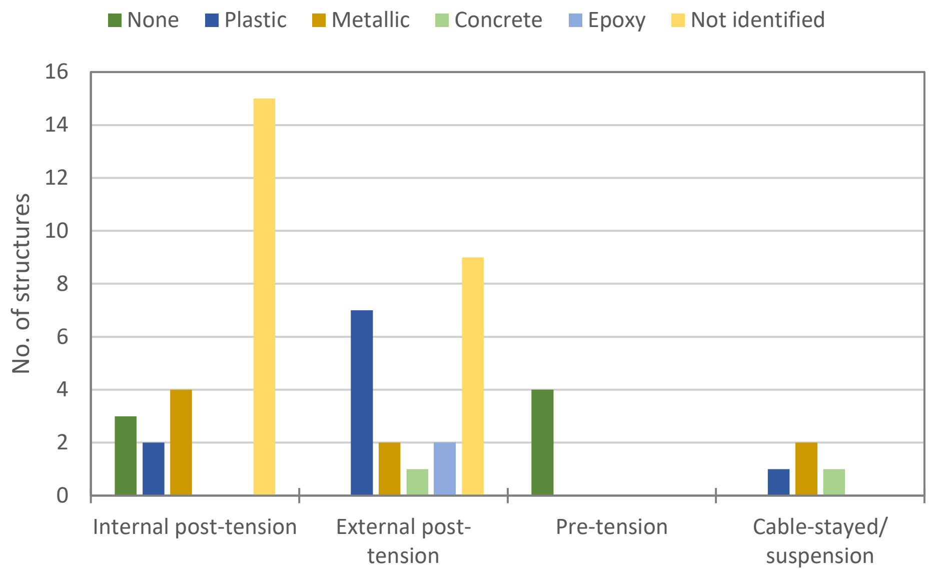

Figure 2.3.5. Type of ducts in the studied structures divided by type of prestressing system.

Figure 2.3.6 shows that, excluding the entry ‘not identified’:

- The majority (19 out of 32) of duct fillings in this study consisted of cementitious grout.
- In 7 out of 32 cases the duct showed no filling.
- In 5 out of 32 cases the duct was filled with grease.
- In 1 case the duct was filled with cotton soaked in oil.
  This last case refers to the only analysed suspension bridge (ID-40), whose cables were covered with slushing oil and three layers of waterproofed cotton. Finally, the cables were enclosed with a sheet-iron cover (Eiselstein and Caliguri, 1988).

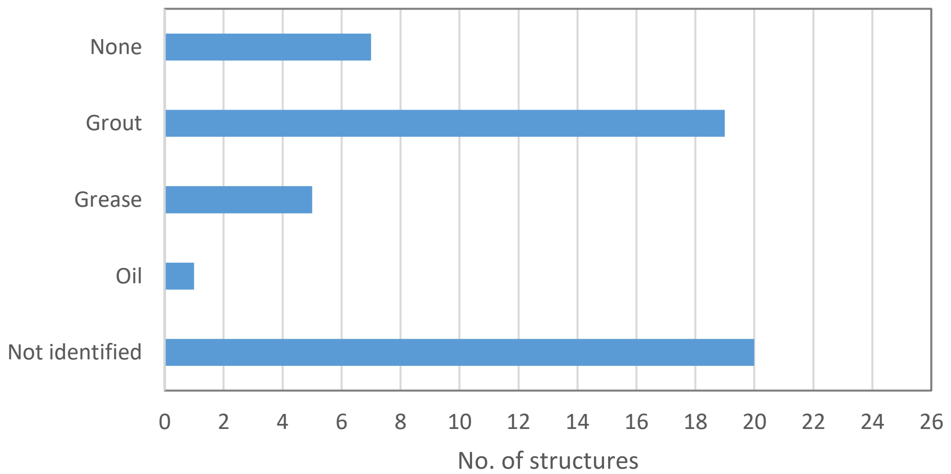

Figure 2.3.6. Type of duct filling in the studied structures.

In Figure 2.3.7 the type of duct filling is correlated with the type of prestressing system.

Since pre-tensioned structures did not have ducts, they did not have filling either.

Excluding the entry 'not identified', the data shows that:

- In relation to bridges with internal post-tensioning:
  - in 5 out of 9 cases the ducts were filled with cementitious grout;
  - in 2 cases the ducts were empty (ID-14 and ID-25).
- In relation to structures other than bridges with internal post-tensioning:
  - in 2 cases (i.e. ID-41 and ID-44) the ducts were filled with grease.
- In relation to bridges with external post-tensioning:
  - in the majority of cases (11 out of 16) the ducts were filled with cementitious grout;
  - in 3 cases the ducts were filled with grease;
  - in only 2 cases (i.e. ID-16 and ID-49) the tendons were epoxy coated and so they do not had filling.

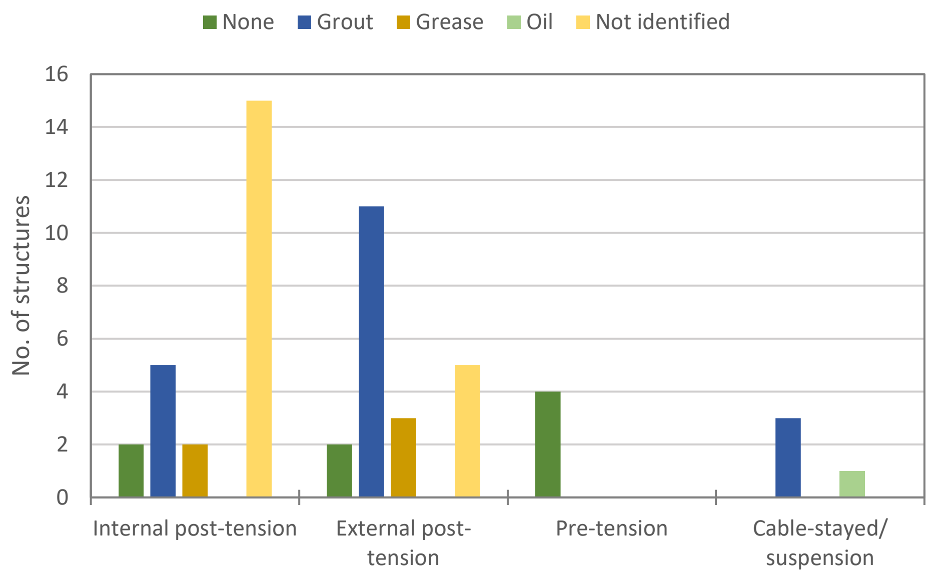

Figure 2.3.7. Type of duct filling in the studied structures divided by type of prestressing system.

3 Failures description

This section presents the characterization of the reported failures:

- Section 3.1 classifies the failures according to the increasing severity of the observed damage and consequent interventions. Moreover, the presence of warning signs is addressed in Section 3.1.1.
- Section 3.2 deals with the age of the structures at the time of their failure.
- Section 3.3. describes which parts of the structures were involved in the failure.

Finally, a comparison between post-tensioned bridges and other types of prestressed structures is provided in Section 3.4.

3.1 Level of damage

The term ‘failure’ is defined as “The state where the performance level of a structure or a structural element is inadequate” (fib, 2013). In this report, special attention has been given to the performance level related to the structure’s integrity and its load-carrying capacity. Therefore, the ‘failure’ has been strictly associated to the corresponding structural damage. In particular, it has been considered:

a) When and if the damage was detected:
   - Early.
     The damage was usually light (e.g., small crack width, light or no spalling of the concrete cover, light corrosion of tendons) and it was detected during planned inspections.
   - Late.
     The damage had severely damaged parts of the prestressing system.
   - Too late.
     The damage was so severe that no intervention could save the structure (e.g., very wide cracks, extensive concrete cover spalling, failed tendons).
   - Not on time.
     The damage was present, but it was not detected in time to save the structure.

b) The typology and suitability of the interventions carried out:
   - Ordinary.
     Ordinary maintenance activities proved to be sufficient in bringing the structure back to safety.
   - Extensive.
     Extensive operations on the prestressing system (i.e., tendon substitution) were necessary.
   - Extraordinary.
     Extraordinary operations like demolition were necessary.
   - Inadequate or absent.
     The interventions were inadequate compared to the extent of the damage or even absent.

c) The structural consequences of damage:
   - Maintenance.
     Moderate damage that could be repaired with ordinary maintenance activities.
   - Tendon failure.
     Damage including breakage of the tendons, potentially affecting the overall safety of the structure. Extensive operations like tendon substitution were necessary.
   - Demolition.
     Serious damage affecting the overall safety of the structure and requiring demolition (extraordinary intervention).
   - Collapse.
     Condition of total or partial collapse due to inadequate or absent interventions, often resulting from absence of warning signs.

Figure 3.3.1 shows how the damage was rated according to points a), b) and c) of the above list, in terms of increasing severity.

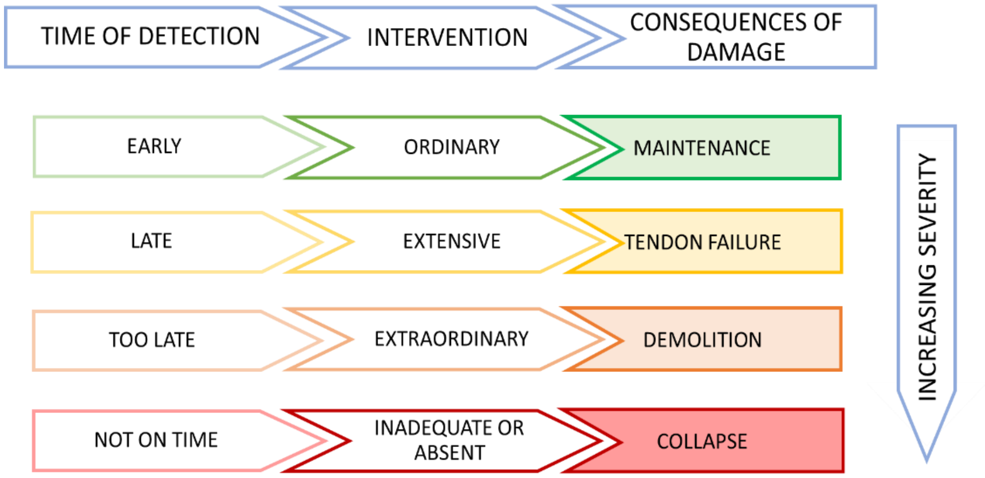

Figure 3.1.1. Illustration of typical relationships between how early the damage was detected, the typology and suitability of the interventions carried out, and the structural consequences in terms of increasing severity.

The structures studied in this research were classified according to the above mentioned consequences of damage, which represent the level of damage of the studied structures (Figure 3.1.2). The data show that:

- in 17 cases corrosion-induced damage was so light that maintenance operations were enough to take care of it;
- the majority (18 out of 52) of structures presented tendon failure;
- only a few structures (6 out of 52), all of them bridges, were demolished;
- 11 cases of collapsed structures were present.

These numbers suggest that (listed from the most to the least common):

- in 18 out of 52 cases the damage was detected late;
- in 17 out of 52 cases the damage was detected early;
- in 11 out of 52 cases the damage was not detected on time;
- in 6 out of 52 cases the damage was detected too late.

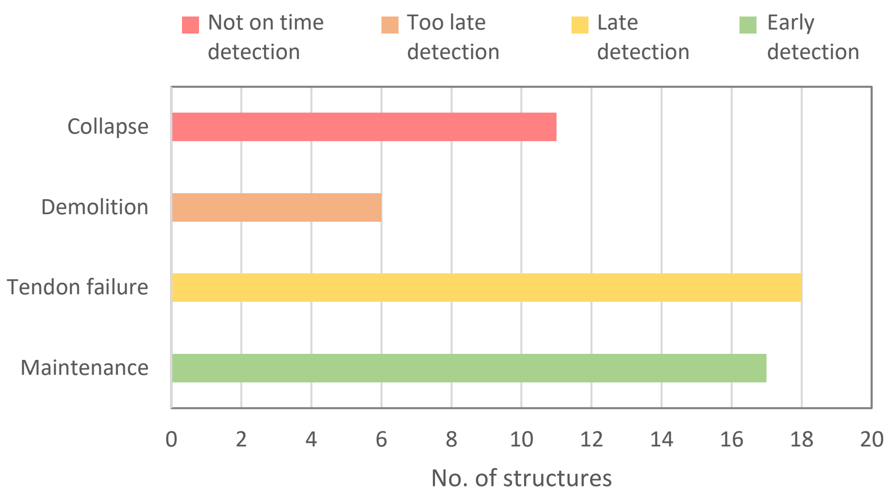

Figure 3.1.2. Level of damage of the studied structures.

Interesting considerations like failure mechanism, can be made correlating the level of damage with the type of prestressing system (Figure 3.1.3). In the following, they are reported for each type of prestressing system.

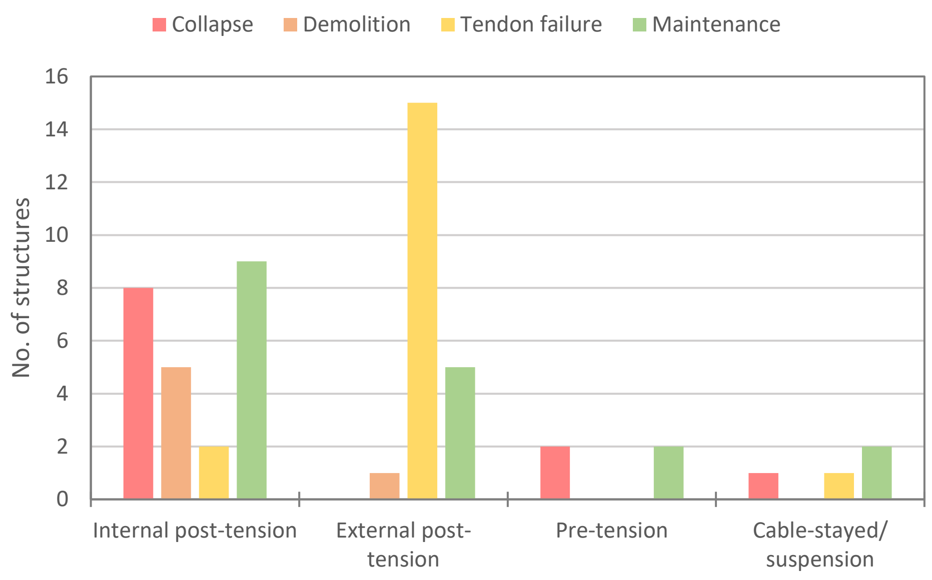

Figure 3.1.3. Level of damage in the studied structures divided by type of prestressing system.

Internally post-tensioned structures

This category comprises every level of damage:

- 8 cases of ‘collapse’;
- 5 cases of ‘demolition’ (all bridges);
- 2 cases of ‘tendon failure’;
- 9 cases of ‘maintenance’ (including ID-33, with both pre-tensioned and post-tensioned spans).

All the ‘collapse’ cases concerned bridges except for Berlin Congress Hall (ID-19).

ID-19 was a structure covered by a double curved roof (Figure 3.1.4) erected on only two bearings (Figure 3.1.5). The roof consisted of two prestressed parts (inner- and outer-roof, respectively) resting on a concrete ring beam. It suddenly collapsed (Figure 3.1.6) due to corrosion-induced fractures in the tendons. The collapse occurred without early indications (Helmerich and Zunkel, 2014).

Figure 3.1.4. Original structure of Berlin Congress Hall (ID-19) before sudden collapse (Helmerich and Zunkel, 2014).

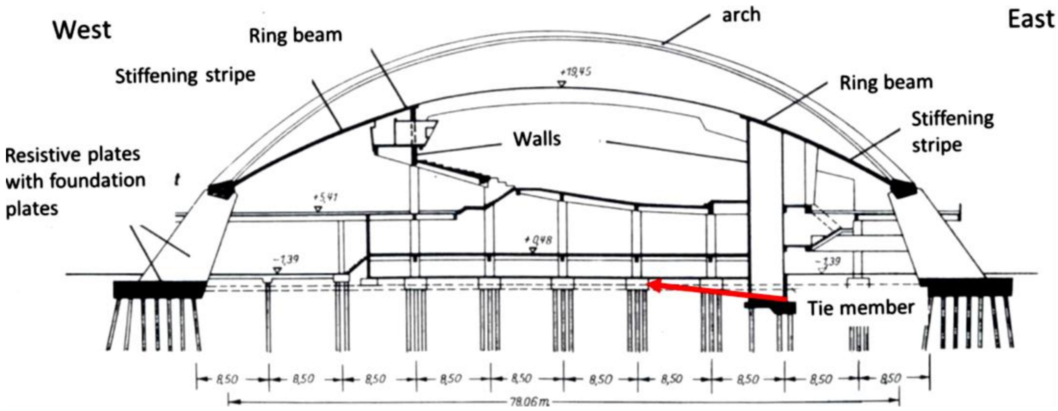

Figure 3.1.5. East–west section of the original Berlin Congress Hall (ID-19) (Helmerich and Zunkel, 2014).

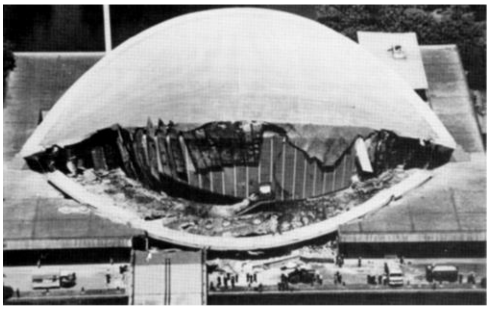

Figure 3.1.6. Berlin Congress Hall (ID-19). View from the South on the collapsed roof overhang in 1980 (Helmerich and Zunkel, 2014).

In the Petrulla Viaduct (ID-4) the collapse was determined by the breakage of the tendons, with subsequent expulsion of the anchorages (Figure 3.1.7) due to the release of stored elastic energy in the tendons. The breakage was followed by loss of prestress, hence loss of shear capacity, and consequent inward rotation of the lower flanges of the I-section beams. This mechanism ended by forming a plastic hinge (Figure 3.1.8) at mid span of one of the beams (Anania et al, 2018).

Figure 3.1.7. Petrulla Viaduct (ID-4). Expulsion of the anchorages. Global view of the expulsion at the end of the beam (Anania et al, 2018).

Figure 3.1.8. Collapse mechanism of Petrulla Viaduct (ID-4) (Anania et al, 2018).

Another example of collapse mechanism (Figure 3.1.9) is the one that took place in Fossano Bridge (ID-5). The collapse was triggered by a shear failure in one of the joints, due to absence of the equilibrating action of the prestressing system (Bazzucchi et al, 2018).

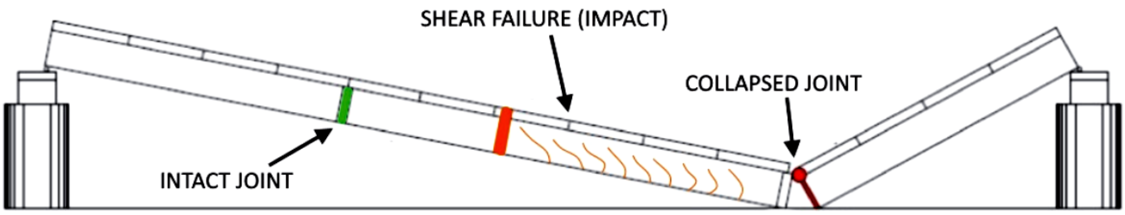

Figure 3.1.9. Collapse mechanism of Fossano Bridge (ID-5) (Bazzucchi et al, 2018).

Figure 3.1.3 shows that 'tendon failure' was mainly detected for cases with external post-tensioning. This could most probably be because external tendons are easier to inspect than internal tendons. For this reason, the two studied cases where tendon failure occurred in internal post-tensioned systems are particularly interesting.

The cases concerned two slabs (ID-43 and ID-44). Hence, they cannot be considered as 'common' (e.g., segmental, I-/T-section beams, box beams) bridges. Consequently, thoughts about these two cases should not be applied to 'common' internally post-tensioned bridges without careful consideration.

The two slabs (ID-43 and ID-44) were reinforced with mono-strand tendons. In slab ID-44 the tendons were encased in plastic ducts filled with grease. On the other hand, no description was provided for ducts in slab ID-43. In both cases, the failed tendons projected beyond the edge of the concrete slab, while some of the anchorage mortar plugs appeared to have shrunk away and were loose (Schupack and Suarez, 1982).

Among the cases with level of damage 'maintenance', is the San Francisco – Oakland Bay Bridge (ID-14). In this case rust coloured water was discovered being discharged from ungrouted tendon ducts during routine operations of tendon cleaning. Then, strands with moderate corrosion and indication of shallow pitting were observed (Figure 3.1.10a). Some of these strands failed to meet specified tensile strength and ductility requirement (Lau and Lasa, 2016). Cracking and/or moisture extrusion and signs of efflorescence from the concrete at cracks in the walls and/or anchor blocks (Figure 3.1.10b) were also visually observed (Reis, 2007).

a b

Figure 3.1.10. San Francisco – Oakland Bay Bridge (ID-14): a) close-up view of an anchorage head showing signs of corrosion from water collected at the anchorage; b) view of a crack at an anchor block showing efflorescence (Reis, 2007).

Externally post-tensioned bridges

Of the 21 cases included in this category:

- in only one case the bridge was demolished (ID-49);
- 15 consist of tendon failures;
- 5 are referred to level damage 'maintenance'.

The absence of the level of damage 'collapse' can be interpreted as a consequence of the relatively easy access and the possibility to inspect and replace external tendons, before they could compromise the overall safety of the bridge.

Pre-tensioned bridges

This typology considers:

- 2 cases of 'collapse' (ID-9 and ID-21);

- 2 cases of ‘maintenance’ (ID-32 and ID-33).

The collapse in Lowe’s Motor Speedway (ID-9) occurred while 107 people were passing over it (Poston and West, 2005), with the complete failure of one span (Figure 3.1.11). The collapse of Annone Viaduct (ID-21) was due to overloading, after the bridge suffered from numerous collisions and subsequent repairs over time (Di Prisco et al, 2018).

Both cases have been characterised by design or execution mistakes (see Section 4).

Figure 3.1.11. Collapsed span of Lowe’s Motor Speedway (ID-9) (Poston and West, 2005).

Cable stayed/suspension bridges

This category includes:
- the collapse of Polcevera Bridge (described in Section 2);
- one case of ‘tendon failure’;
- 2 cases of ‘maintenance’.

The collapse occurred with the rupture of the first cable-stay near the seaside, at the connection between the stay and the saddle top (Figure 3.1.12) of tower number 9. The occurrence yielded to the collapse of the deck on the west side of the pier, and then to the collapse of tower 9 balanced system with two buffer beams (Clemente, 2020).

The other three failures comprised in this category (i.e., 1 ‘tendon failure’ and 2 ‘maintenance’) also concern problems in the cables (see Section 3.3), but with a lower level of damage. Moreover, cable-stays are generally of simple accessibility for inspection (if compared to internal tendons), making maintenance activity relatively simple.

This may suggest that not proper inspection and/or maintenance was conducted on Polcevera Bridge (more details on the matter are provided in Section 3.1.1 and in Appendix A).

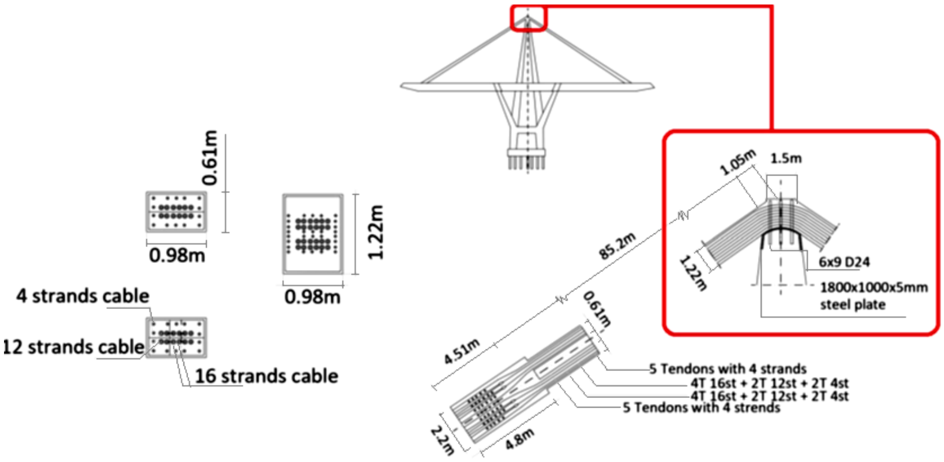

Figure 3.1.12. Polcevera Bridge (ID-6). View of the cable-stay system with the saddle detail (Morgese et al, 2020).

3.1.1 Presence of warning signs

Visual inspections can help limit and/or reduce the level of damage, to help prevent structural collapse. Specifically, visual inspections should focus on detection of warning signs (i.e., damage indicating the potential collapse of one or more elements of the structure).

However, as it can be seen in Figure 3.1.14, only in half the studied cases warning signs have been observed. In fact, there are 10 out of 52 cases in which information about them was not reported in the reference papers, plus other 16 cases in which warning signs were not detected at all.

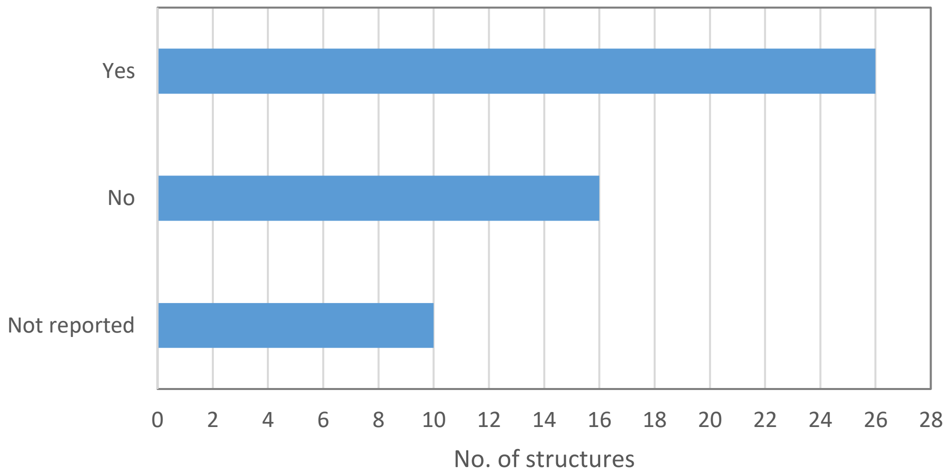

Figure 3.1.14. Presence of warning signs in the studied structures.

One of the aims proposed in Section 1.2 is to understand if the presence of warning signs can be used to anticipate corrosion-induced failures. For this purpose, it can be useful to correlate the typology of warning signs observed before or during failure occurrence with the type of prestressing system (Figure 3.1.15) and with the level of damage (Figure 3.1.16).

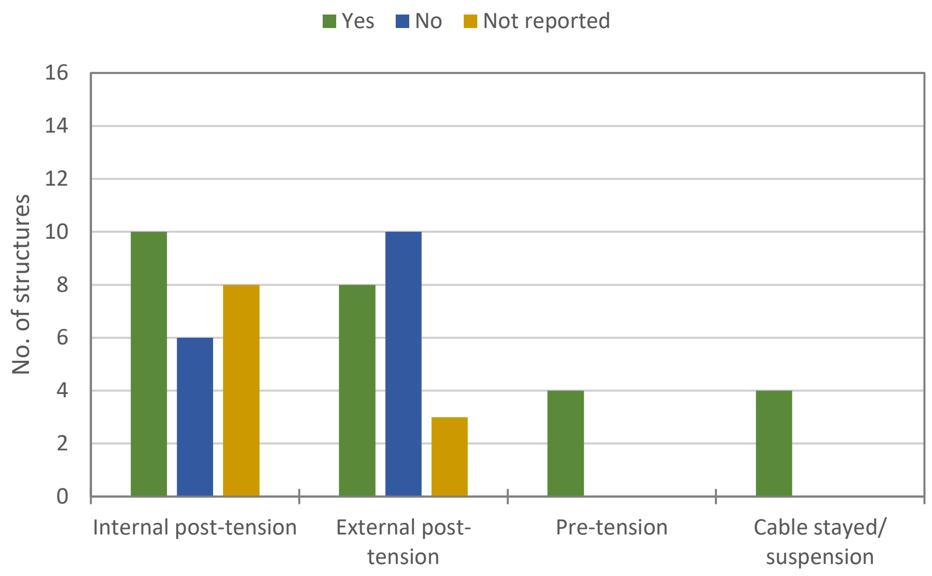

Figure 3.1.15. Presence of warning signs in the studied structures divided by type of prestressing system.

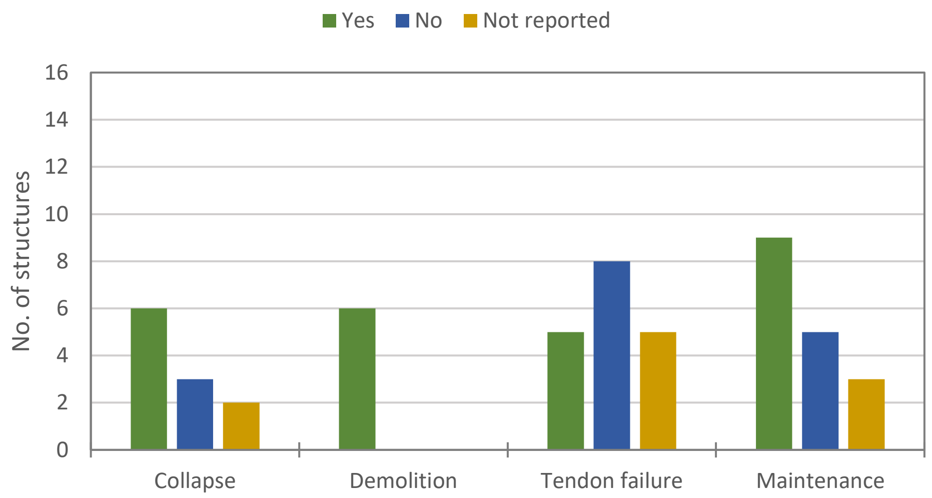

Figure 3.1.16. Presence of warning signs in the studied structures divided by level of damage.

Figure 3.1.15 shows that for internal post-tensioned structures there are more cases of observed than not observed warning signs. The opposite is true for external post-tension. Visual inspection of external tendons is easily performed, so the higher number of 'no' cases might mean that the damage remains hidden in the duct until failure, proving once more that NDE is not enough.

In the following, a description of the observed warning signs is provided for every level of damage (see Figure 3.1.16). Some meaningful examples and considerations are also reported.

Collapse

Many (6 out of 11) of the collapsed structures in this report presented warning signs before the collapse.

Poston and West (2005) estimated that the collapse of Lowe's Motor Speedway (ID-9) could have been avoided if observed warning signs had been taken into consideration. These signs included:

- longitudinal cracks (Figure 3.1.17) along the stem soffit at mid span directly under the grout plug location;
- corrosion staining around the grout plugs in several beams.

It was evident that the grout plugs, used in the process to give the strands their profile in the beams, clearly represented a weakness for the bridge.

Figure 3.1.17. Lowe's Motor Speedway (ID-9): longitudinal crack in double-T stem directly under the grout plug location (Poston and West, 2005).

Polcevera Bridge (ID-6) exhibited extensive strand corrosion (Figure 3.1.18), with oxidation of the metallic duct and some cables having loose strands already in 1992, 26 years before the collapse. In fact, the entire sets of stays of tower number 11 were replaced in 1993 with an external prestressing system. The same operation was planned for tower 9 in 2017, but the tower 9 balanced system collapsed in 2018 before the job was even started (Nuti, 2020).

This indicates that the collapse could have eventually been prevented, if the stays of tower number 9 had been replaced as planned. Moreover, if the stays' replacement of tower 11 had not occurred in 1993, probably the bridge would have collapsed earlier.

Therefore, for ID-6 warning signs and subsequent interventions proved to be useful in postponing the collapse for over 26 years.

Figure 3.1.18. Polcevera Bridge (ID-6). View of cables toward the support in 2011 (top) and 2013 (middle). Zoom of the cables in 2013 (bottom) where corrosion and partial pitting can be observed (Nuti et al, 2020).

In Annone Overpass (ID-21) high levels of corrosion as well as concrete spalling were observed along the beams (Figure 3.1.19). However, the presence of a shear crack at the Gerber joint (Figure 3.1.20) was well known from more than 10 years before the collapse (Di Prisco et al, 2018).

The shear crack was the one that induced the collapse of the bridge, because it allowed water and pollutants to penetrate inside the cross section of the beams and to corrode the tendons.

In case of ID-21, warning signs of a possible collapse had been evident for over 10 years, but insufficient measures were taken to prevent it.

Figure 3.1.19. Annone Overpass (ID-21). Damage observed on internal surfaces of the prefabricated beams in 2006 (Di Prisco et al, 2018).

Figure 3.1.20. Annone Overpass (ID-21). Critical Gerber joint view before the collapse (Di Prisco et al, 2018).

Demolition

As it can be seen from Figure 3.1.16, warning signs were observed in all the demolished structures. This was to be expected. In fact, a structure is usually demolished when the severity and extension of the detected damage threatens the overall safety of the structure and reparation measures are more expensive than the loss of the structure itself.

Sorell Bridge (ID-3) was demolished because of the appearance of cracking (Figure 3.1.21) along the web of 51 beams. The cracks followed the path of the post-tensioning tendons, leaving the tendons without concrete protection in some cases (Papè and Melchers, 2011).

The cracks raised concern especially because the tendons were encased directly in the concrete, without ducts. Hence, the tendons would have been directly exposed to the external environment (rich in chlorides since the bridge crossed a lagoon). Moreover, the damage was extended to several beams.

Figure 3.1.21. Typical longitudinal web cracking along a beam in Sorell Bridge (ID-3) (Papè and Melchers, 2011).

Bridges ID-29, ID-30 and ID-39 presented:

- extensive corrosion of the post-tensioning tendons at the anchorages;
- cracks at diaphragm and joint locations;
- deterioration of concrete (e.g., longitudinal cracks and spalling).

In Walnut Street Bridge (ID-31, see Section 2.2) stains were observed on the sides of the beams (Figure 3.1.22). The stains indicated that water had been seeping through the shear key joints between all beams. In addition, some of the beams were badly deteriorated with holes through the top flanges, crumbling concrete, and exposed strands (Murray and Frantz, 1992).

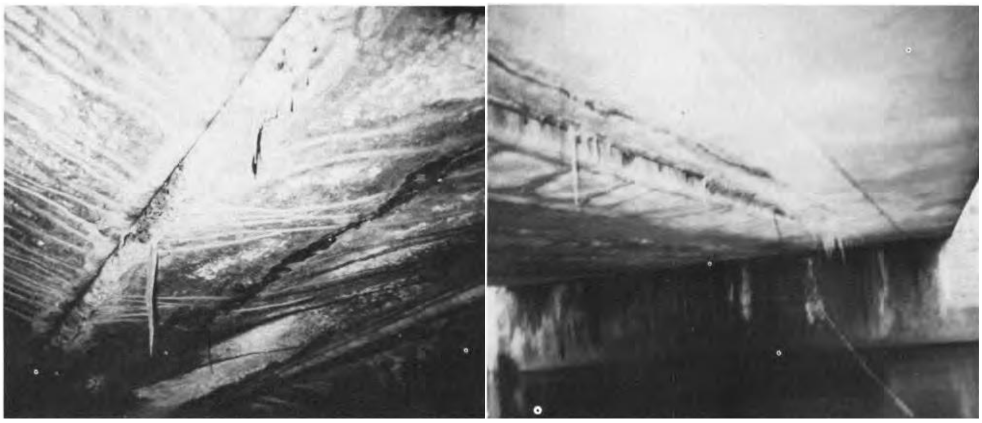

Figure 3.1.22. Walnut Street Bridge (ID-31). Stains on beams and ruptured strand hanging down into the river (Murray and Frantz, 1992).

Tendon failure

Typical warning signs for tendon failures were cracked ducts (e.g., ID-7, ID-10, ID-11).

In addition to these, Luling Bridge (ID-10) presented (Mehrabi, 2009):

- unplugged grout vents;
- extensive water leakage;
- cementitious grout efflorescence;
- rust at the deck level anchorage sockets.

The cases of tendon failure included in the literature survey showed that it is not common that a tendon fails alone. Conversely, when one tendon was found broken, other tendons in the same beam and/or also in adjacent beams, were also found broken. Therefore when a failed tendon is detected, it is wise to check the conditions of the tendons in the same beam and in the adjacent ones.

Maintenance

Maintenance activities were performed mostly after the visual inspections reported warning signs, such as:

- concrete cover spalling (e.g., ID-8 and ID-16)
- presence of efflorescence (Figure 3.1.23);
- small and large cracks (e.g., ID-13)
- rust stains on the web (Figure 3.1.24) or on beam soffits (e.g., ID-32 and ID-33).

In case of early detected failures, maintenance activities are effective in containing and/or reducing the damage. However, if maintenance is not conducted as planned (e.g., later than planned, see ID-6) the level of damage may rise.

On the other hand, in case of late detected failures, maintenance activities may not be sufficient to limit or reduce the damage. This is the case of demolished structures, for which interventions are technically insufficient and/or not economically rational.

Figure 3.1.23. Bridge in the Midwest, USA (ID-13). Presence of efflorescence, delamination, and spalling observed on post-tensioned box girders (Venugopalan, 2008).

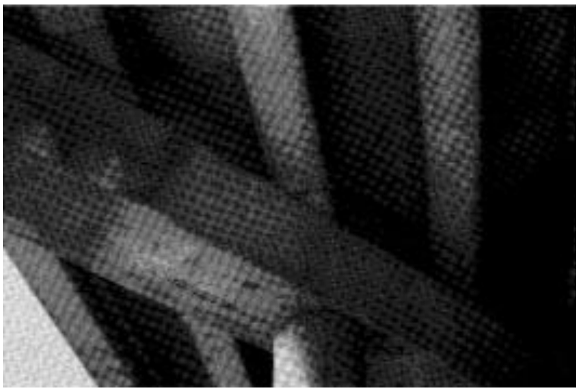

Figure 3.1.24. Harlem Avenue overpass, USA (ID-32). Corrosion of the bottom of the girder. (Gustaferro et al, 1983).

Drawing the conclusions for this section, it can be said that detection of warning signs can help limit and reduce the damage provided some conditions are fulfilled:

- the damage needs to be detected early enough for the repair measures to be effective;
- maintenance measures should be implemented as planned.

Nevertheless, in many cases failures such as broken tendons (5 cases) or the collapse of the structure (3 cases) occurred without warning signs being detected. In some other cases (i.e., 2 cases of collapsed structures and 5 cases of tendon failure) presence of warning signs was not reported in the literature. This last consideration highlights that the absence of warning signs does not guarantee the safety of the structure.

3.2 Age at failure

Figure 3.2.1 shows that the number of failures included in the present research decreases with the structure's age. In particular, it was found that:

- the majority of failures (14 cases) tend to occur when the structure is less than 10 years old;
- no failure has been reported for structures older than 60 years, except for Williamsburg Bridge (ID-40), which failed at 79 years.

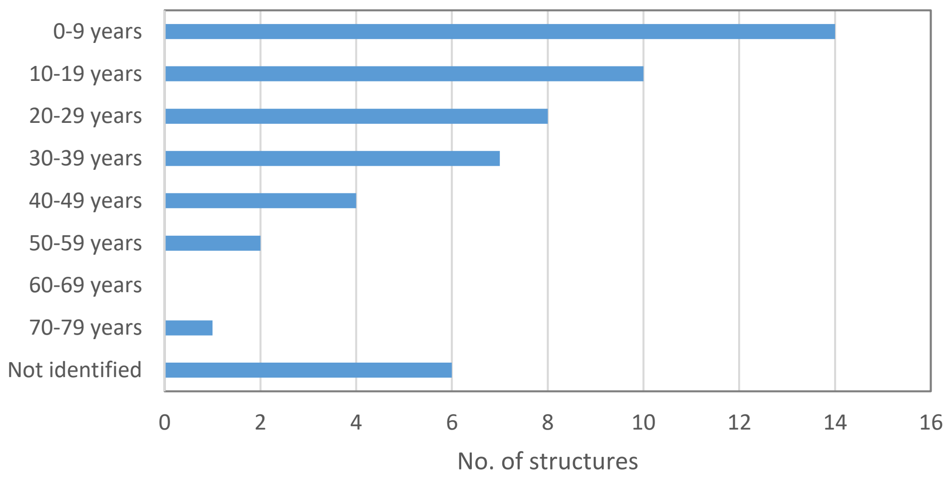

Figure 3.2.1. Age at failure of the studied structures.

The correlation of failure age with level of damage (Figure 3.2.2), excluding 'not identified' cases, shows interesting results:

- Demolitions took place at ages ranging between 10 and 50 years old, with a concentration of cases between 30 and 40 years.
- 8 out of 10 structures collapsed at an age comprised between 20 and 60 years, with peaks in numbers between 20 and 30 years and between 40 and 60.
- 15 out of 16 tendon failures occurred during the first 20 years of life of the investigated structures, with most of them (9 out of 16 cases) concentrating in the first 10 years.

- In 12 out of 13 cases, level of damage ‘maintenance’ was detected in the first 50 years after construction. The number of these cases decreases with age (e.g., there are 4 cases of age 0-9 years and 2 cases of age 40-49).

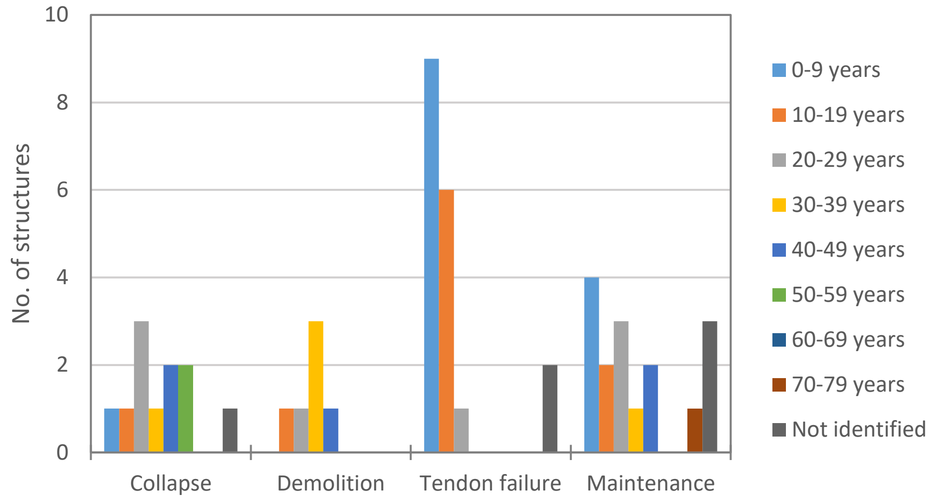

Figure 3.2.2. Age at failure of the studied structures divided by level of damage.

Considering the previous list (related to Figure 3.2.2), each level of damage was classified according to when the failure was detected in relation to the age of the structure:

- Short-term failures: ‘tendon failure’.
  Failures occurring during the first years of life of the structure (from 0 to 19 years).
- Long-term failures: ‘collapse’ and ‘demolition’.
  Failures mainly occurring 20 years after construction.
- Short- to long-term failures: ‘maintenance’.
  Failures occurring during the entire life span of the structure.

Even if they may appear similar, the previous classification differs from the one in Section 3.1 (i.e., the one including the entries ‘early’, ‘late’, ‘too late’, ‘not on time’).

In both cases the level of damage was classified according to when the failure was detected. However, in the list of Section 3.1 the time of detection is referred to the severity of damage and the possibility to limit or repair it. While, in the list above the time of detection is referred to the age of the structure at failure.

3.3 Failure location

Figure 3.3.1presents the failure locations in the studied structures.

Note that only locations where the most severe damage occurred (i.e., the one that induced failure) are reported in the figure, omitting other places with deterioration. For further information refer to Appendix A.

Failure of the investigated structures (52 cases) mostly occurred:

- in external tendons (16 out of 52 cases);
- in beams (8 out of 52 cases), specifically at the mid span and at deviation points;
- at joints location (6 out of 52 cases).

Excluding the entry ‘not identified’ (4 cases), failure locations can be collected in three macro categories (Figure 3.3.2). Considering only bridges (43 cases) the macro categories are:

- Superstructure (19 out of 43 cases).
  This category comprises the entries ‘superstructure’ (4 cases), ‘anchorages’ (1 case), ‘beams’ (8 cases), ‘joints’ (6 cases).
- Tendons (20 out of 43 cases).
  This category comprises the entries ‘cable-stays’ (3 cases), ‘external tendons’ (16 cases), ‘internal tendons’ (1 case).
- Miscellaneous (4 out of 43 cases).
  This category comprises the entries ‘pillars’ (2 cases), ‘samples’ (2 cases).

Considering only the structures different from bridges (5 cases), failure occurred:

- in the roof (3 out of 5 cases);
- at anchorage location (1 out of 5 cases);
- at internal tendons (1 out of 5 cases).

No distinction is made in Figures 3.3.1 ad 3.3.2 between bridges and other structures. This means that in Figure 3.3.1 the entries ‘anchorages’ and ‘internal tendons’ both include 1 bridge and 1 other structure. The same applies in Figure 3.3.2, where:

- the entry ‘superstructure’ includes 19 bridges and 1 other structure;
- the entry ‘tendons’ includes 20 bridges and 1 other structure;
- the entry ‘miscellaneous’ includes 4 bridges and 3 other structures.

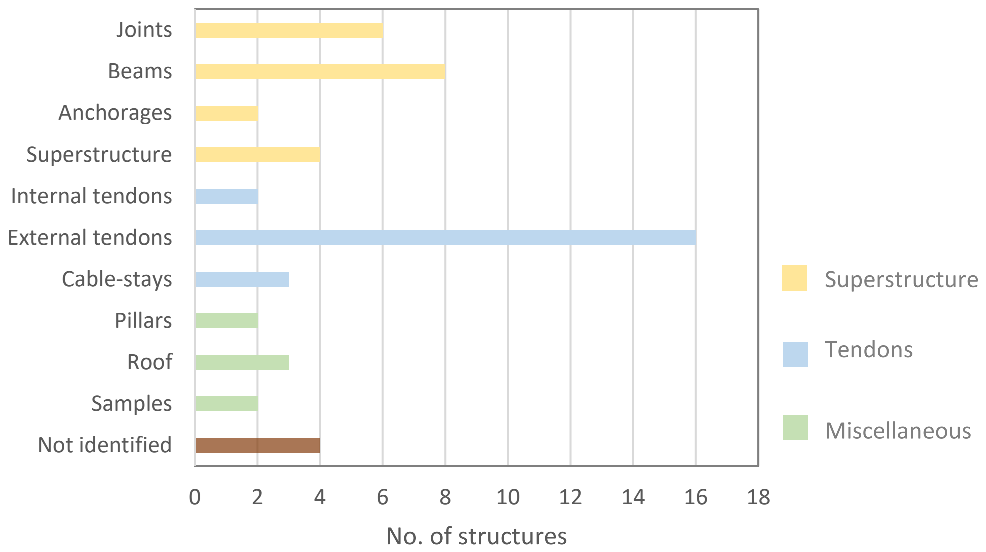

Figure 3.3.1. Failure location in the studied structures.

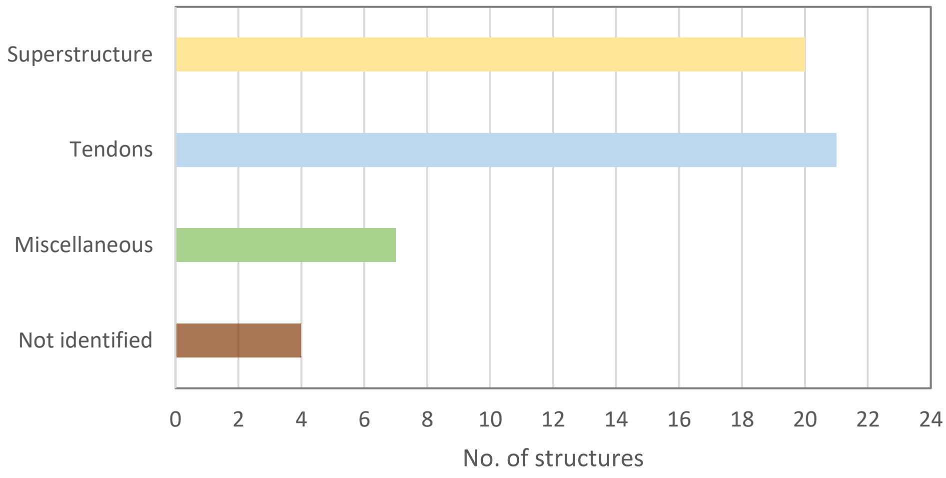

Figure 3.3.2. Failure location in the studied structures, representation by macro category.

Superstructure (bridges)

Failures involving the superstructure occurred at joints and deviation points. The damage consisted in:

- cracked diaphragms (Figure 2.2.6);
- deteriorated concrete;
- evidence of surface corrosion on all the anchorages and bearing plates (Figure 3.3.3);
- opening of joints (Figure 3.3.4);
- severe concrete cracking (Figure 3.3.5).

Figure 3.3.3. Corrosion of wires at anchorage plate in I-94 Bridge over US 81 (ID-30) (Dickson et al, 1993).

Figure 3.3.4. S. Stefano Viaduct (ID-2): a) collapse of the viaduct; b) slippage of cables; c) opening of joints; and d) rotation of the deck (Colajanni et al, 2016).

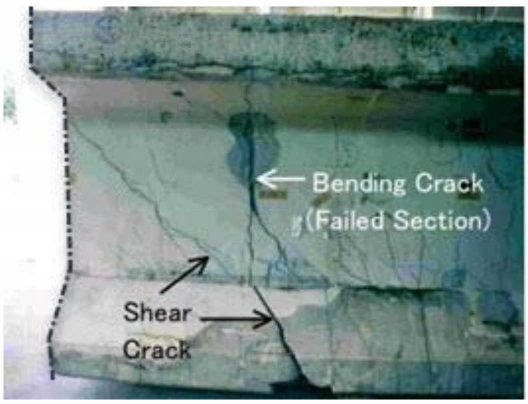

Figure 3.3.5. Kure-tsubo Bridge (ID-39). Cracks around failed section of beam S3 (Tanaka et al, 2001).

Tendons (bridges)

Failed tendons (either cables or prestressing tendons, externally or internally post-tensioned) usually appeared corroded, with longitudinal and transverse splits in the PE duct (Figure 3.3.6). There were also cases with completely ruptured tendons, lying on the bottom of the span (Figure 3.3.7) or tendon slippage from the ducts in the failed section of the structure (Figure 3.3.4).

Tendons generally presented evidence of strand corrosion damage in the form of localized pitting, wires breakdown or both (Figures 3.3.8 and 3.3.9).

Figure 3.3.6. Luling Bridge (ID-10). Corrosion of wires at PE split (Mehrabi, 2009).

Figure 3.3.7. Ringling Causeway Bridge (ID-15). Detensioned tendon discovered in July 2011 (Ahern et al, 2018).

Figure 3.3.8. Corroded tendon in a Florida Bridge (ID-20) (Lau and Lasa, 2016).

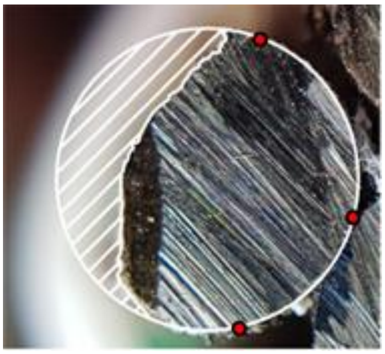

Figure 3.3.9. Measuring section loss due to corrosion in a Korean bridge (ID-45): identifying the corroded area. (Yoo et al, 2018).

Miscellaneous (bridges)

Stressed strand samples were exposed within the box sections and weight loss samples were placed outside the structure of bridges ID-34 and ID-35. The samples were meant to test how the environment within the box beams affected the structure, when compared with the environment outside.

In both bridges, spots of corrosion started to develop on both the categories of samples exposed in the boxes fairly soon after installation. The investigation's results highlighted that (Woodward and Milne, 2000):

- the environment within the box beams was more stable than outside;
- the corrosivity of the environment inside the box beams very low, less than that inside a bridge enclosure.

Failure occurred in the pillars of bridges ID-11 and ID-16.

Sunshine Skyway Bridge (ID-11, described in Section 2.2) suffered from severe tendon corrosion in the post-tensioned columns (Figure 3.3.10) of the northbound high level approaches. The vertical tendons that held the column segments together were internally bonded within the thick wall region in the lower part of the column and ran externally along the inner wall in the upper part. The tendons were housed in a 75 mm diameter smooth PE duct called the primary duct. The upper end of those tendons was anchored in the cap and formed a U-loop configuration in the footing of the column. In the thick wall region, the 75 mm primary duct was placed inside a 127 mm diameter corrugated PE secondary duct, which was cast inside the wall of the precast segment (Theryo et al, 2011). Failure occurred in the region of the column with external tendons, immediately below the column cap, where split PE ducts allowed the formation of corrosion in the tendons.

The case of Long Key Bridge (ID-16) shows that RC elements (the pillars) resulted to be more sensitive to corrosion-induced failure than prestressed elements (the superstructure), even if the reinforcement was epoxy coated.

It is known that prestressing steel is more sensitive to corrosion than reinforcing steel. Therefore, usually more measures are adopted to protect prestressing steel than reinforcing steel. This is why, prestressed elements appeared to be less sensitive to corrosion-induced damage than RC elements in ID-16.

Moreover, in ID-16, the pillars (i.e., the RC elements) were directly in contact with sea water, making it easier for corrosion to occur. For this reason, the reinforcement was epoxy coated, but this measure was not sufficient to protect the reinforcement. In fact, only a little scratch in the epoxy coating can compromise the safety of the structure. The scratch may represent an easy way for corrosion to penetrate underneath the layer of the coating, damaging the reinforcement without showing warning signs.

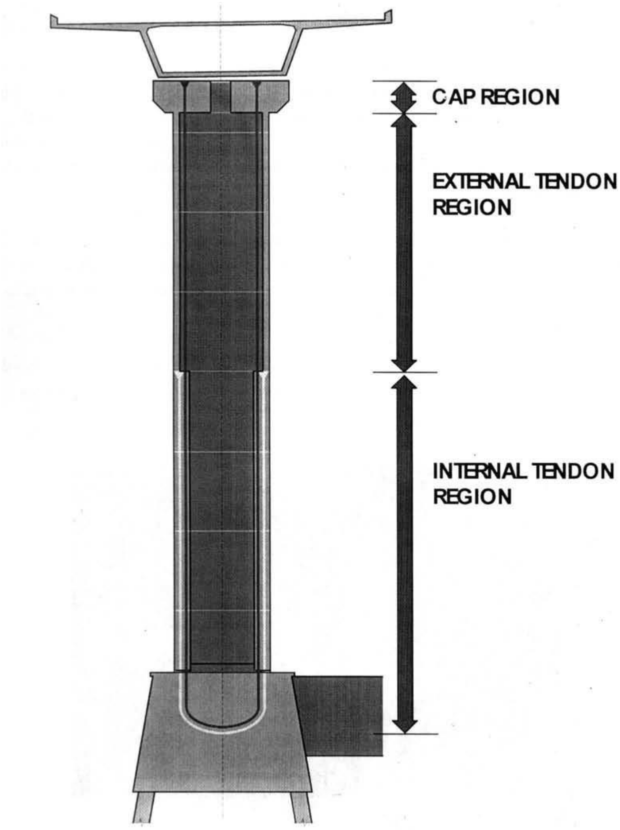

Figure 3.3.10. Sunshine Skyway Bridge (ID-11). Three distinct regions of columns (Theryo et al, 2011).

Other structures

Failure took place in the roof of ID-19, ID-43 and ID-44.

In Berlin Congress Hall (ID-19, described in Section 3.1) the roof failed next to the final groove of the ring beam (Helmerich and Zunkel, 2014). In that location, most of the tendons and the metallic ducts in which the tendons were encased appeared heavily corroded (Figure 3.3.11).

In structure ID-43 (described in Section 3.1) no particular corrosion-induced damage was found on the failed tendons projecting beyond the edge of the concrete slab. However, high chloride content was detected.

In structure ID-44 (similar to ID-43) the failure occurred at a short distance away from a vertical opening in the concrete slab. There, irregularly shaped patches of localised corrosion were observed on the wire surfaces (Schupack and Suarez, 1982).

Figure 3.3.11. Remaining bituminized roofing on a completely failed, non-grouted and heavily corroded tendon in Berlin Congress Hall (ID-19) (Helmerich and Zunkel, 2014).

In Figure 3.3.12 the various failure locations are subdivided according to the level of damage, yielding to the following considerations:

- Collapses mainly (8 out of 11 cases) occurred in the superstructure. In particular, 5 cases occurred at joint locations and 3 cases in the beams.
- In all the demolished bridges, failure involved the superstructure, with the exception of one case (ID-49) involving external tendons.
- The majority (12 out of 18 cases) of tendon failures concerned external tendons.
- The level of damage 'maintenance' was observed in all structural element types. The damages have been reported at the superstructure (6 cases), the tendons/cables (6 cases), the samples (2 cases) and the pillars (1 case).

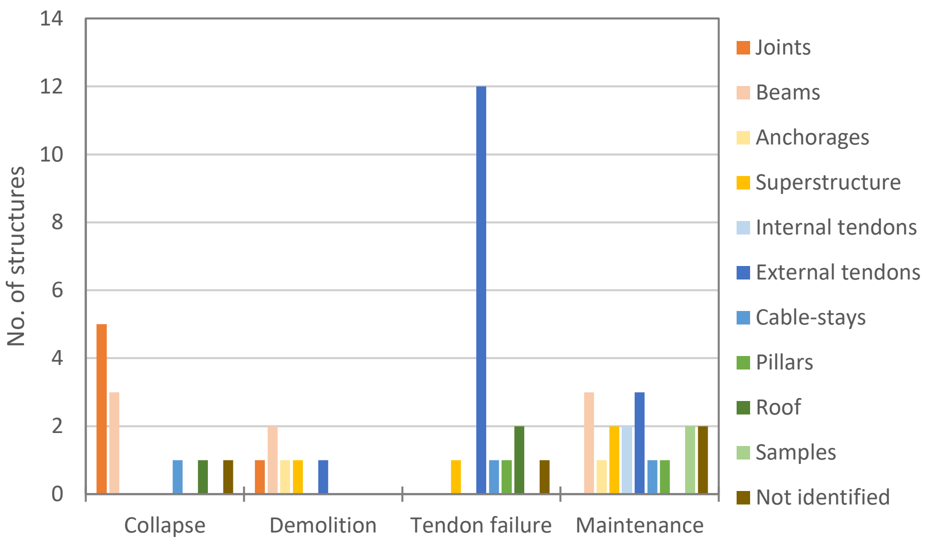

Figure 3.3.12. Failure location in the studied structures divided by level of damage.

Another interesting correlation is the one proposed in Figure 3.3.13. Here, failure locations are divided according to the type of prestressing system, yielding to the following considerations:

- Internally post-tensioned bridges mainly (13 out of 19 cases) suffered from damage in the superstructure. To be more specific, damage was observed:
    - at joint location in 5 cases;
    - in the beams in 5 cases;
    - at anchorage location in one case;
    - in different elements of the superstructure in 2 cases.

  Internally post-tensioned structures (i.e., excluding bridges) showed severe damage in the roof (e.g., ID-19, see Section 3.1) and in the tendons, in particular at anchorage location.
- Most (16 out of 21 cases) of the failures in externally post-tensioned bridges concerned external tendons.
- In all pre-tensioned bridges failures occurred in the superstructure.

  In 3 cases the damage affected the beams, more precisely:
    - at deviation points location (ID-9);
    - along the beam surface (ID-33);
    - at mid span (ID-32).

  In one case (ID-21) the damage occurred at a joint location (Figure 3.1.19).
- Cable stayed or suspension bridges mostly showed problems in the cables.

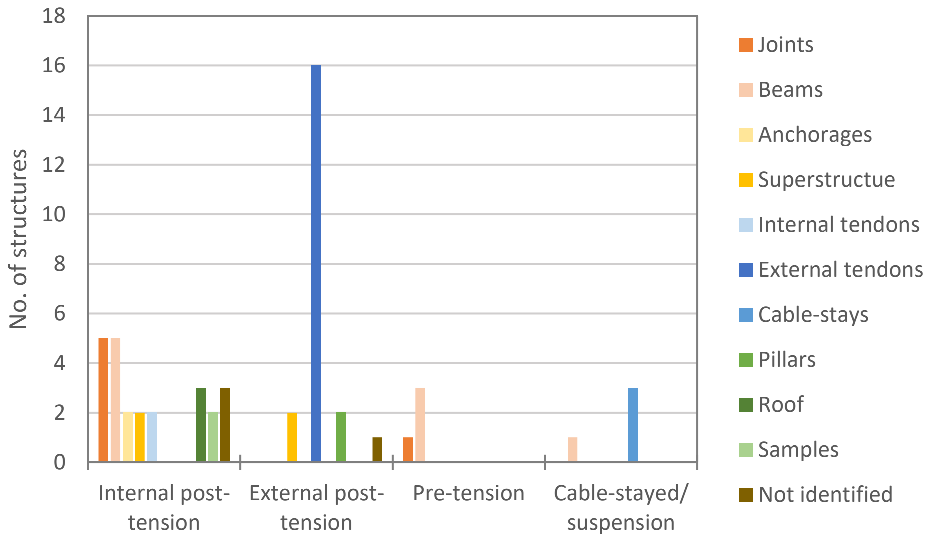

Figure 3.3.13. Failure location in the studied structures divided by type of prestressing system.

3.4 Comparison between the analysed structures

To conclude this brief overview on failures description, a synthesis of the main characteristics of the structures analysed in this report is presented in Table 3.4.1 and discussed afterwards.

It must be noted that the thoughts reported in this section are referred to the structures included in the literature survey (i.e., post-tensioned bridges, cable-stayed bridges, pre-tensioned bridges, post-tensioned structures other than bridges). Hence, the considerations here proposed do not have a general validity.

Table 3.4.1. Level of damage, presence of warning signs, age at failure and failure location in the case studies, divided by type of prestressing system. For each structure, the characteristics are reported in decreasing order, starting from the most frequently observed in the literature survey. The number of cases referred to each entry is written in brackets.

<table>
<tr><th colspan="2"></th><th>Level of damage</th><th>Presence of warning signs</th><th>Age at failure</th><th>Failure location</th></tr>
<tr><td rowspan="2">Internally post-tensioned structures
(24 cases)</td><td>Bridges
(19 cases)</td><td>(7) collapse
(7) maintenance
(5) demolition</td><td>(9) yes
(5) no
(5) not reported</td><td>(13) 0-39 years
(4) not identified
(2) 40-49 years</td><td>(5) joints
(5) beams
(3) not identified
(2) superstructure
(2) samples
(1) internal tendons
(1) anchorage</td></tr>
<tr><td>Other structures
(5 cases)</td><td>(2) tendon failure
(2) maintenance
(1) collapse</td><td>(3) not reported
(1) yes
(1) no</td><td>(5) 0-39 years</td><td>(3) roof
(1) internal tendons
(1) anchorage</td></tr>
<tr><td colspan="2">Externally post-tensioned bridges
(21 cases)</td><td>(15) tendon failure
(5) maintenance
(1) demolition</td><td>(10) no
(8) yes
(3) not reported</td><td>(14) 0-19 years
(2) 20-29 years
(2) 30-39 years
(1) 40-49 years
(2) not identified</td><td>(16) external tendons
(2) superstructure
(2) pillars
(1) not identified</td></tr>
<tr><td colspan="2">Pre-tensioned bridges
(4 cases)</td><td>(2) collapse
(2) maintenance</td><td>(4) yes</td><td>(3) 0-29 years
(1) 50-59 years</td><td>(3) beams
(1) joints</td></tr>
<tr><td colspan="2">Cable-stayed/suspension bridges
(4 cases)</td><td>(2) maintenance
(1) collapse
(1) tendon failure</td><td>(4) yes</td><td>(1) 10-19 years
(2) 40-59 years
(1) 70-79 years</td><td>(3) cable-stays
(1) beams</td></tr>
</table>

From Table 3.4.1 it can be noticed that:

- Internally post-tensioned bridges presented all levels of damage, mainly ‘collapse’, ‘maintenance’ and ‘demolition’. Warning signs were observed in half the cases:
  - cracking along the web of the beams, following the path of the post-tensioning tendons;
  - signs of water penetration;
  - cracking at diaphragms;
  - corrosion staining;
  - spalling of concrete.

  Failures occurred during the first 50 years of life of the structure in the majority of cases.
  Most of them involved the superstructure at various locations, like joints, beams, anchorages.
- Internally post-tensioned structures (i.e., except bridges) all failed during the first 40 years of life.
  The structures presented failure of tendons in 2 cases and damage of ‘maintenance’ level in the other 2.
  Damage was mostly located in the roof, specifically at tendon anchorages.
  In the majority of cases, the presence of warning signs was not reported in the literature papers.
- Externally post-tensioned bridges exhibited failure in external tendons in most cases (as expected), showing warning signs (i.e., cracks in the ducts) only in about one third of the cases.

Failures mostly occurred when the bridges were less than 20 years old, with many cases aged between 5 and 8 years (see Appendix B).

- Pre-tensioned bridges always presented warning signs, such as:
  - longitudinal cracks along the beams soffit;
  - corrosion staining;
  - concrete cover spalling;
  - leakage at expansion joints.

  Two bridges collapsed while other two showed damage of 'maintenance' level, mainly in the first 30 years after execution.
  Damage involved the superstructure in all the cases, in particular affecting joints, deviation points and the beams surface (e.g., concrete spalling).
- Cable-stayed/suspension bridges always presented warning signs involving the cables, like cracks in the ducts.
  Level of damage 'maintenance' was observed in half of the cases, accompanied by one case of 'collapse' and one of 'tendon failure'.
  Failures mostly occurred in the cables in various periods during the life span of the bridges.

This general outlook about the investigated structures highlights the presence of similarity between cable-stayed/suspension bridges and externally post-tensioned bridges, and between pre-tensioned bridges and internally post-tensioned bridges. The similarities are mainly related to where the corrosion-induced failure occurs:

- tendon system (e.g., tendons, ducts, tendon anchorages) for cable stayed/suspension and externally post-tensioned bridges;
- joints, tendon anchorages, deviation points for pre-tensioned and internally post-tensioned bridges.

This observation highlights once more the importance of correct design and execution, especially in these specific locations.

In fact, joints, tendon anchorages and deviation points are especially known to be vulnerable to corrosion attacks since they represent the place where the continuity of the element is broken. This is particularly true for pre-tensioned bridges, generally consisting of simply supported precast pre-stressed beams separated by joints. Conversely, in case of internally post-tensioned bridges the tendons and the ducts are continue throughout the joint between two adjacent segments. However, at joint locations we expect voids in the grout due to the grout composition, and corrosion of internal tendons is often associated with voids in the grout.

Internally post-tensioned structures different from bridges could be considered as small-scaled internally post-tensioned bridges. Even in this case, this is mostly because of similar failure location. In fact, the roof could be regarded as the superstructure, where failures mainly occur at anchorage points.

It is necessary to emphasize that these affinities do not mean that similar structures can be assessed in the same way. However, they can help guiding the assessment.

4 Failure causes

In the following section, the causes of the reported failures are analysed and discussed:

- Section 4.1 identifies the major causes that could have prompted the corrosion-induced failure for each case study.
- Section 4.2 provides an overview of the major corrosion causes, complemented by a discussion on the most relevant cases in Sections 4.2.1 and 4.2.2.

4.1 Major failure causes

In all the failures analysed herein, corrosion played an important role. In particular, the literature survey showed that failure mechanism had been enabled by the simultaneous presence of many factors, which very likely induced the onset of corrosion.

Figure 4.1.1 shows a list of the major failure causes and their frequency for the studied cases. Contrary to previous analyses (concerning e.g., type of structures, type of ducts, presence of warning signs), this figure includes up to three entries for each structure. This is because past investigations (e.g., Helmerich and Zunkel, 2014) highlighted how it is unlikely that failure can be caused by one of the insufficiencies alone. In fact, failures are usually the result of a combination of factors that arise over time.

Figure 4.1.1 shows that the principal reasons for failure involved:

- execution (23 cases);
- conceptual design mistakes (21 cases);
- problems in the grout (11 cases);
- presence of cracks (7 cases);
- use of inappropriate materials (6 cases);
- too low concrete cover (3 cases).

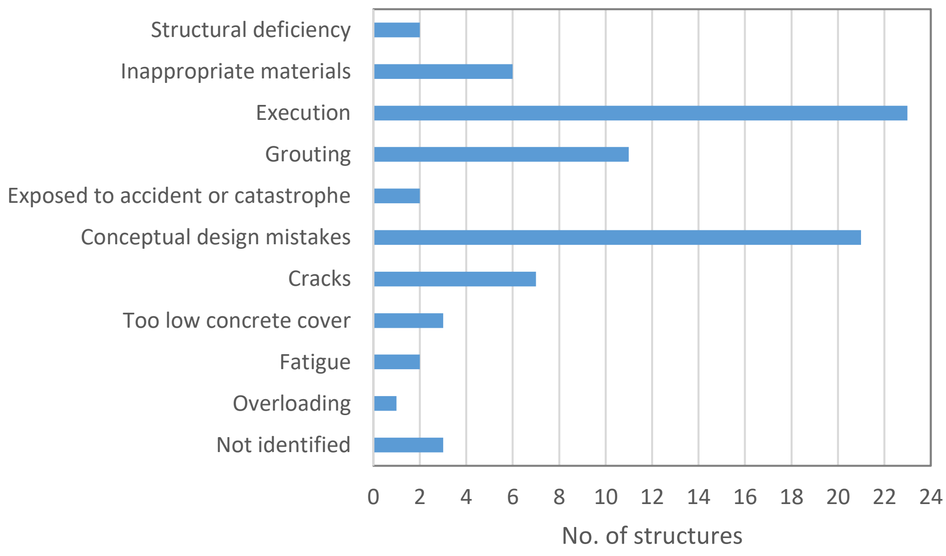

Figure 4.1.1. Major failure causes of the studied structures.

In order to better understand how the aforementioned causes affected failure, they are reported in Figure 4.1.2, classified according to the level of damage. The data in this new figure shows that:

- Collapses were mostly influenced by:
    - execution (8 cases);
    - conceptual design mistakes (6 cases);
    - use of inappropriate materials (3 cases);
    - too low concrete cover (2 cases).
- Demolished structures suffered from the same problems detected in collapsed ones, with:
    - 3 cases of execution;
    - 3 cases of conceptual design mistakes;
    - 1 case in which inappropriate materials have been used;
    - 1 case of too low concrete cover.
- Tendon failures were caused by:
    - grouting problems in the majority (10) of cases;
    - execution (6 cases);
    - conceptual design mistakes (4 cases);
    - use of inappropriate materials (2 cases);
    - presence of cracks (2 cases);
- Damage of 'maintenance' level was caused mainly by:
    - conceptual design mistakes (8 cases);
    - execution (5 cases);
    - presence of cracks (4 cases).

The list above demonstrates the importance of accurate design and careful execution in preventing failure. Moreover, it highlights that tendon failures were caused mostly by grouting problems (see Section 4.2.2). Conversely, damage of other levels was caused mainly by execution and conceptual design mistakes.

This information is valuable because, as already discussed in Section 3, tendon failure occurred in almost all the externally post-tensioned bridges included in the survey. This means that those bridges were extremely sensitive to corrosion due to grouting problems, more than to execution or conceptual design mistakes.

Figure 4.1.2 also shows that cracks have some importance in cases where monitoring and inspections could be performed (i.e., tendon failures, when interpreted as failure of external tendons, and damage of 'maintenance' level). Moreover, cracks were caused by different factors like for instance, shrinkage, thermal effects, and not only due to design and execution mistakes (see Appendix A). This seems to confirm that corrosion was induced not only by issues in the planning and construction phases, but also by events during the structure's nominal life (as it is proved by the existence of the entry 'exposed to accident or catastrophe' as well).

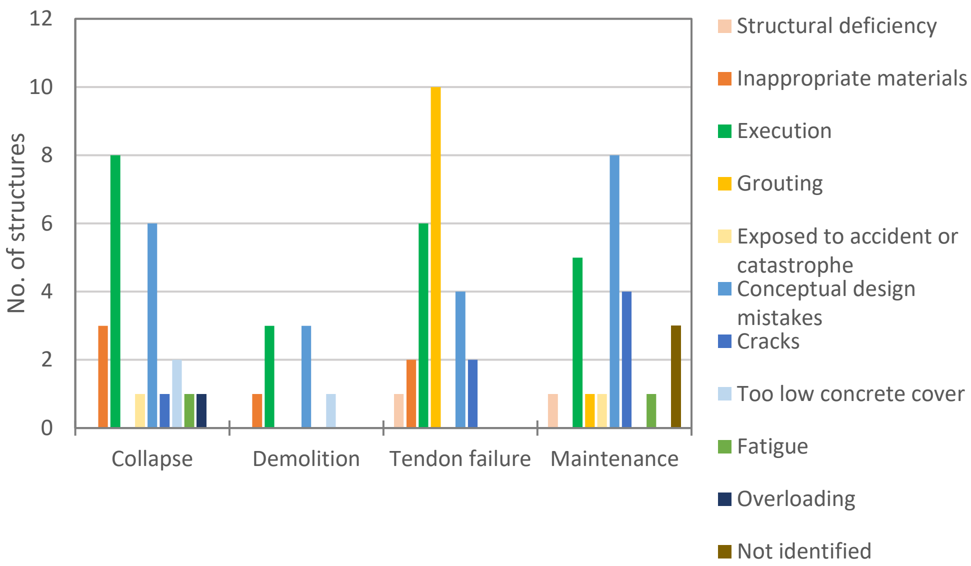

Figure 4.1.2. Major failure causes of the studied structures divided by level of damage.

4.2 Major corrosion causes

To cause the chemical reaction called corrosion the presence of determinate elements (namely water, oxygen, and chlorides – this last is not required in case of carbonation-induced corrosion) is needed. In this report the words ‘corrosion causes’ are used to indicate the sources of the aforementioned elements. Both corrosion causes and failure causes (see Section 4.1) contributed to the onset of corrosion in the studied cases. Specifically, failure causes created the conditions and corrosion causes provided the elements for corrosion to occur.

Figure 4.2.1 describes the major corrosion causes detected in the survey. In this case for the sake of clarity only one corrosion cause (i.e., the one that seemed to be the most relevant in enabling corrosion) is associated to each structure.

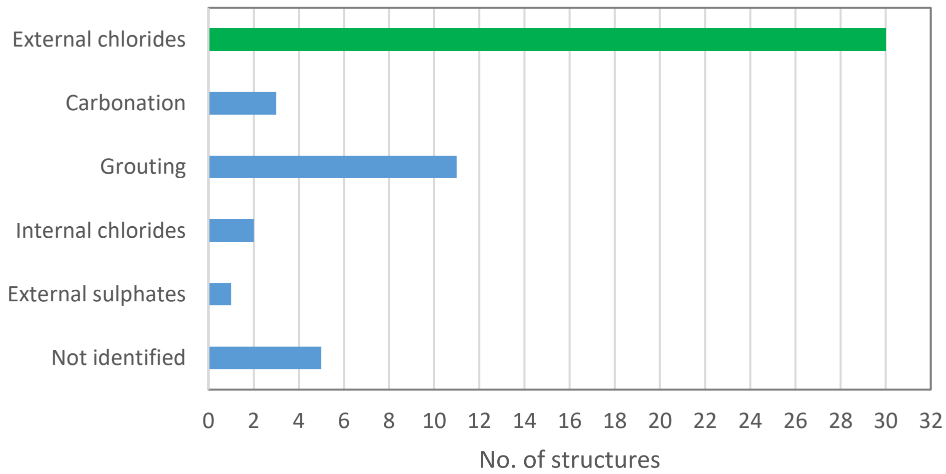

Figure 4.2.1. Major corrosion causes of the studied structures.

The most frequent (30 out of 52 cases) corrosion cause was the presence of external chlorides (in green in Figure 4.2.1). It must be noted that the second most frequent cause 'grouting' was observed in 'only' 11 cases. Moreover, the other corrosion causes (i.e., 'internal chlorides', 'external sulphates' and 'carbonation') occurred just in 6 other cases. Therefore, it can be said that the majority of structures included in this report underwent corrosion-induced failure due to external chlorides penetration and problems in the grout.

External chlorides can come from:

- de-icing road salts, which is one of the major sources of chlorides in cold climates (hence very common in Norway);
- sea water, which might be in the liquid or air-form state.

Therefore, in Figure 4.2.2 the major corrosion causes are reported specifying the entry 'external chlorides' according to their source (in green):

- 18 out of 30 cases of road salt penetration;
- 9 out of 30 cases of air-form sea water (contained in the atmosphere around the structure) penetration;
- 3 out of 30 cases of liquid sea water penetration.

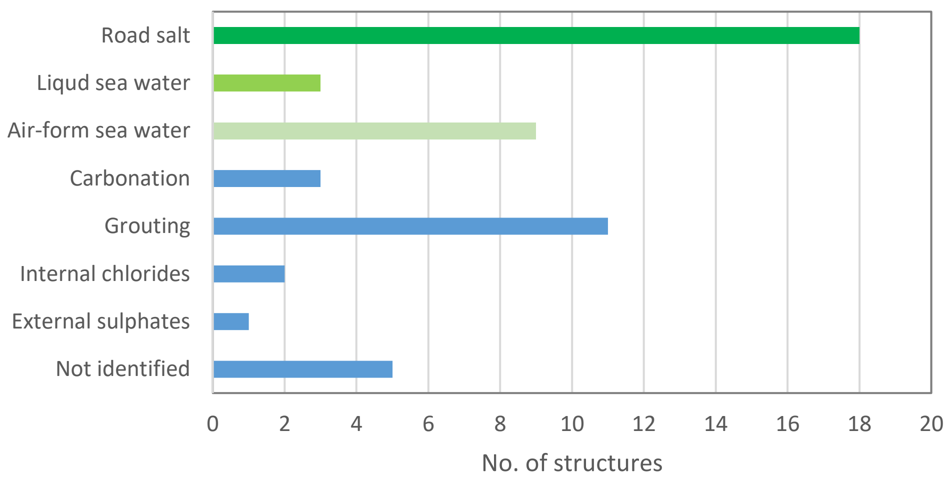

Figure 4.2.2. Major corrosion causes of the studied structures, with detailed 'external chlorides' from Figure 4.2.1.

In Figure 4.2.3 the major corrosion causes are shown according to the level of damage. Excluding the cases where the corrosion cause was not identified, it can be noticed that:

- Corrosion originated in collapsed structures mainly due to external chlorides. They were due to air-form sea water dispersed in the atmosphere surrounding the structure (4 cases), or in road salt (3 cases). The chlorides could have penetrated inside the concrete mainly through cracks or at joint location.
- In almost all (5 out of 6 cases) the demolished structures corrosion was due to the presence of external chlorides, specifically road salt.
- In tendon failures corrosion originated because of the characteristics of the grout in most cases (10). In 6 other cases the major corrosion cause was the presence of external chlorides. They were due to de-icing salts in 3 cases, to air-form sea water in 2 cases and to liquid sea water in one case.
- External chlorides were the most frequent cause (12 out of 17 cases) of level of damage 'maintenance'. Chlorides originated from:
    - road salt (7 cases);
    - liquid sea water (2 cases);

- air-form sea water dispersed in the atmosphere surrounding the structure (3 cases).

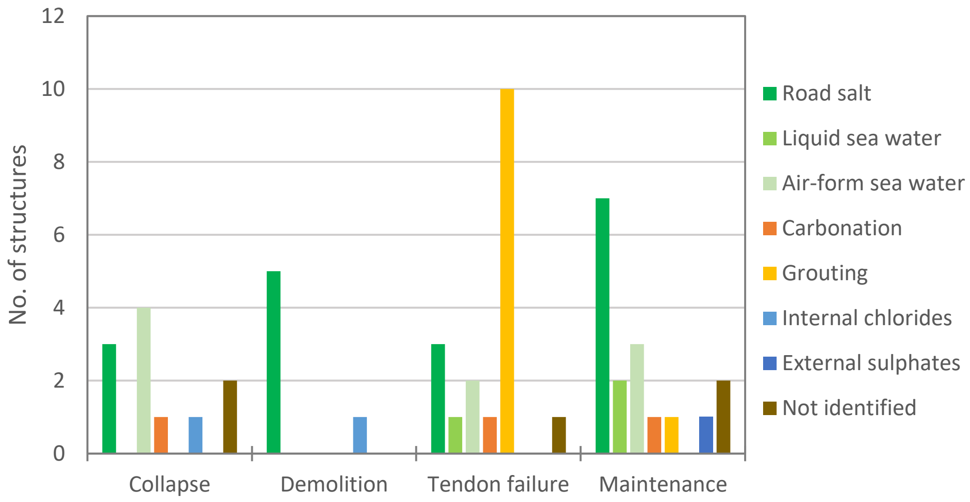

Figure 4.2.3. Major corrosion causes of the studied structures divided by level of damage.

The overview presented above about major corrosion causes, and the one presented in Section 4.1 about major failure causes highlight that:

- In structures that collapsed, were demolished or manifested a damage of level 'maintenance', corrosion was mainly generated by external chlorides.
  The chlorides were mainly contained in de-icing salts or in the surrounding environment in the air-form state. From these sources, they penetrated inside the concrete through locations debilitated from execution and conceptual design mistakes.
- In structures that exhibited failure of tendons, corrosion was mostly enabled by problems within the grout.

The two scenarios exposed in the previous list are discussed with additional detail in the following sections.

4.2.1 External chlorides

In places with cold climates, it is common practice to spread salt on the roads to prevent them from icing. However, chlorides contained in de-icing salts could penetrate inside the structure through pores in the concrete or worse, through openings at joints, anchorages or tendon deviation points not properly designed or constructed. Moreover, the present research displayed that other sources of external chlorides are sea water in the liquid and air-form state (see Figure 4.2.3).

The majority of Norwegian bridges are located in coastal regions, and climate in Norway is notoriously cold. Taking this into consideration, the simultaneous presence of both road salt and external chlorides coming from the sea aerosol raises great concern. Even more since chlorides generally induce pitting corrosion. In fact, pitting corrosion creates localized holes and cavities in steel tendons, it is more destructive than uniform corrosion, and results in reduced capacity, especially under repeated loads. It is also more difficult to detect, since its occurrence is local, subjecting the tendons to high levels of stress concentration (Morgese et al, 2020). Therefore, a more detailed analysis on corrosion induced by road salt and external chlorides is needed.

In this regard, Tables 4.2.1.1, 4.2.1.2 and 4.2.1.3 provide a summary of the analyses presented in this report on cases with external chlorides as major corrosion cause. In the specific, the tables address the cases with road salt, liquid sea water and air-form sea water as major corrosion cause, respectively.

For each analysis (e.g., geographical location, level of damage, etc.), the characteristics of the structures are reported in decreasing order, starting from the most frequently observed in the literature survey. In addition, for the sake of clarity, the number of cases referred to each characteristic is written in brackets.

The data provided in Tables 4.2.1.1, 4.2.1.2 and 4.2.1.3 confirm the previous considerations. Hence, regarding failures caused by external chlorides it is possible to say that:

- They mainly occurred in places with relatively cold climate (e.g., UK, USA – Florida excluded).
- They principally involved segmental and I-/T- or box beam bridges, mostly prestressed with internal tendons: in 16 out of 19 internally post-tensioned structures and in 3 out of 4 pre-tensioned bridges failure was caused by external chlorides.
- They took place during the entire life span of the structures. Specifically:
  - when chlorides came from de-icing salts, failures concentrated in the first 40 years of the structure;
  - when chlorides came from liquid sea water, failures concentrated in the first 20 years of the structure;
  - when chlorides came from air-form sea water, failures occurred with peaks between 20 and 30 years and 50 and 60 years.
- They were anticipated by different warning signs, such as:
  - mild general or severe localized corrosion;
  - prestress and/or tendons cross section reduction;
  - presence of cracks and efflorescence;
  - concrete spalling and/or delamination.

  Failures occurred at those locations where chlorides had easy access to the concrete and to the tendons, principally due to execution and conceptual design mistakes.
- They were localized in the superstructure of internally prestressed bridges. Specifically:
  - at anchorages;
  - at joints or at tendon deviators locations.

Table 4.2.1.1. Overview of case studies with external chlorides coming from road salt as major corrosion cause.

Geographical location	Level of damage	Type of structure	Type of prestressing system	Presence of warning signs	Age at failure	Failure location
(7) UK (6) USA (1) Italy (1) France (1) Canada (1) Japan (1) Korea	(7) maintenance (5) demolition (3) tendon failure (3) collapse	(5) segmental bridge (4) I-/T-beam bridge (5) box beam bridge (2) roof (2) not identified	(11) internal post-tension (4) external post-tension (2) pre-tension (1) cable-stayed/ suspension	(13) yes (3) no (2) not reported	(5) 10-19 years (5) 30-39 years (3) 0-9 years (2) 20-29 years (1) 40-49 years (1) 70-79 years	(5) beams (4) super-structure (3) joints (3) external tendons (2) anchorages (1) roof

Table 4.2.1.2. Overview of case studies with <u>external chlorides coming from liquid sea water</u> as major corrosion cause.

Geographical location	Level of damage	Type of structure	Type of prestressing system	Presence of warning signs	Age at failure	Failure location
(2) Florida (1) USA	(2) maintenance (1) tendon failure	(2) segmental bridge (1) innovative structure	(2) external post-tension (1) internal post-tension	(3) yes	(2) 0-9 years (1) 10-19 years	(2) pillars (1) internal tendons

Table 4.2.1.3. Overview of case studies with <u>external chlorides coming from air-form sea water</u> as major corrosion cause.

Geographical location	Level of damage	Type of structure	Type of prestressing system	Presence of warning signs	Age at failure	Failure location
(3) Italy (2) UK (2) France (1) USA (1) Belgium	(4) collapse (3) maintenance (2) tendon failure	(3) box beam bridge (2) segmental bridge (2) innovative structure (1) steel bridge (1) not identified	(4) internal post-tension (2) external post-tension (2) cable-stayed/ suspension (1) pre-tension	(4) yes (4) no (1) not reported	(2) 50-59 years (2) 20-29 years (1) 0-9 years (1) 10-19 years (1) 30-39 years (1) 40-49 years (1) not identified	(3) beams (2) cables (2) samples (2) external tendons

In internally post-tensioned bridges, the major conceptual design mistakes concerned the inadequacy of:

- the drainage system;
- the joints (e.g., their design, their waterproofing cover);
- the bridge's height (which caused the occurrence of various vehicle impacts against the bridge's deck);
- the reinforcement;
- the distance among the ducts employed (Figure 4.2.1.1);
- the position of the ducts' vents or of the anchorages (e.g., at the extrados of the deck, allowing water infiltrations inside the ducts).

On the other hand, execution mistakes induced:

- the malposition of the cables (leading to insufficient concrete cover);
- inadequate waterproofing of the joints;
- incorrect grouting operations, which resulted in presence of voids in the ducts (Figure 4.2.1.2) and/or vents not fully sealed.

Figure 4.2.1.1. No gap among the tendons in Petrulla Viaduct (ID-4) (Anania et al, 2018).

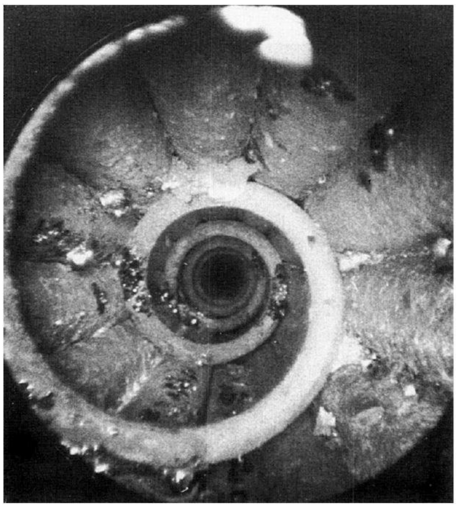

Figure 4.2.1. Void in centre of longitudinal tendon in Ynis-y-Gwas bridge (ID-01). Elical coil was used to space the wires apart (Woodward and Williams, 1988).

The consequences of design and execution mistakes were:

- tendons that were not adequately protected by the grout-duct system;
- ducts not adequately protected by concrete in sensitive locations like joints, anchorages, and tendon deviators.

In fact, voids in the duct meant that tendons were surrounded by air instead of grout. Hence, once chlorides penetrated inside the duct, they reacted with the air and triggered corrosion of the tendons. Since air is lighter than grout, voids tended to be situated at higher locations inside the duct. For this reason, the strands generally corroded more severely along the top and sides (Papè and Melchers, 2011). Moreover, bridge ID-13 demonstrated that actively corroding tendons would continue to corrode even if the voids had been subsequently filled with grout (Venugopalan, 2008).

However, it must be noted that chlorides need time to penetrate the concrete. This is why corrosion-induced failures associated to external chlorides penetration generally occur after the structure is at least 10 years old (see Tables 4.2.1.1, 4.2.1.2 and 4.2.1.3). On the other hand, failures occur due to a combination of causes (see Section 4.1). Hence, short-time failures (especially structures younger than 10 years old) with external chlorides as major corrosion cause, may be due to the combination of other failure causes. For example, in ID-14 the ducts remained ungrouted for up to 17 months (execution mistake), allowing liquid sea water to penetrate inside the ducts and corrode the tendons in relatively short time.

In pre-tensioned bridges, the technology to apply prestress forces does not involve the grout-duct system. The absence of this system:

- reduces possible mistakes related to grouting operations;
- makes NDE possible because there is no duct interfering with the evaluation.

However, the present research highlighted that, as with internally post-tensioned bridges, attention needs to be paid to joints, anchorage regions, and other locations sensitive to mistakein both phases of design and execution in pre-tensioned bridges as well (see Appendix A). In this research only a reduced number of pre-tensioned cases were explored, so for further detail on durability of pre-tension structures please refer to other studies, for instance that by (Osmolska et al, 2019).

4.2.2 Grouting

As already mentioned in the previous section, the integrity of grout is fundamental in protecting post-tensioned tendons from corrosion. Furthermore, Figure 4.2.3 showed that problems in the grout, such as bleeding and segregation, are the major corrosion cause for tendon failures.

Table 4.2.2.1 reports failures caused by problems in the grout. The data supports that the problems in grout:

- Occurred in Florida, France, USA (in particular the Midwest), Italy and Korea, which are places characterised by hot and humid summers, when temperatures range between 24 and 30°C (Climi e viaggi).
- Always involved external tendons enclosed in ducts (generally made of PE) filled with cementitious grout.
- Occurred at a young age (mostly before the bridges were 9 years old), without warning signs in most cases.

Table 4.2.2.1. Overview of case studies with grouting as major corrosion cause.

Geographical location	Level of damage	Type of structure	Type of prestressing system	Presence of warning signs	Age at failure	Failure location
(4) Florida (3) France (2) USA-Midwest (1) Italy (1) Korea	(10) tendon failure (1) maintenance	(6) segmental bridge (5) box beam bridge	(11) external post-tension	(8) no (2) yes (1) not reported	(6) 0-9 years (3) 10-19 years (1) 20-29 years (1) not identified	(11) external tendons

Corrosion, mostly in the form of pitting, took place in segments of the tendon that exhibited visible segregation of the grout or had partial or full depth voids (Ahern et al, 2018). In these locations the grout remained unhardened with a white, soft, and chalky appearance (Figures 4.2.2.1 and 4.2.2.2). The whitish grout had high pH, and contained only trace levels of chlorides, but high sulphate levels, even if the corrosion process occurred without infiltration of external chlorides or sulphates into the ducts. It is important to highlight that no corrosion attacks were found in the areas where the tendons were embedded in a regular hardened cement grout (Carsana and Bertolini, 2015).

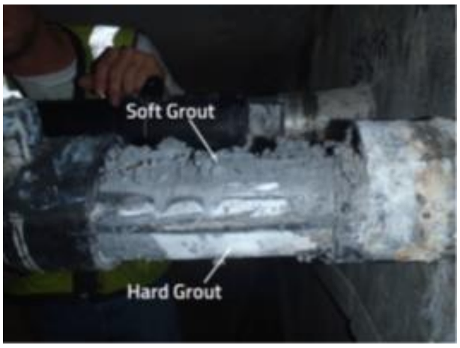

Figure 4.2.2.1. Segregation of the grout material observed near the high points of the tendon profile in Ringling Causeway Bridge (ID-15) (Ahern et al, 2018).

Figure 4.2.2.2. Example of whitish segregated grout embedding corroding strands in an Italian bridge (ID-18) (Bertolini and Carsana, 2011).

The typical grout used through the 1990's was made of cement, water and an expansion agent, and in some cases a gelling agent that made the grout thixotropic (i.e., a property of certain gels and emulsions of becoming fluid when agitated and then setting again when left at rest).

When corrosion of tendons coincided with the presence of voids, the corrosion cause was generally identified as external chlorides penetration through inadequately protected anchorages, grout and vents. However, in some cases the observed corrosion was due to excessive accumulation of bleed water (Ahern et al, 2018).

Therefore, in 1989 the Federal Highway Administration (United States) commissioned a study to evaluate the performance of grouts for post-tensioned bridge structures.

The study demonstrated that conventional grout was susceptible to develop significant levels of bleed-water under normal handling conditions. It was also shown that, although the bleed-water eventually dissipated, significant corrosion developed on the strand at the grout-water interface. Moreover, one particular commonly used grout, containing an aluminium based expanding admixture, experienced the highest amounts of bleed-water development and subsequent corrosion (Powers et al, 2002).

In France controls on grouting began in 1995, after anomalies were detected in ducts grouted with a cement mixed with admixtures in the external prestressing tendons of a box girder bridge under construction in 1994.

Laboratory testing in tilted transparent tubes showed a phenomenon of exudation combined with a settlement of the grout. The exudation phenomenon (i.e., the discharge of a liquid or viscous gel-like material through a pore, crack or opening in the surface of concrete) was amplified by the presence of a superplasticizer. At the end of the test, in the higher part of the tube, a layer of whitish paste topped by a yellowish liquid was produced. The liquid was itself topped by a space filled with air. Mineralogical analyses carried out at the 'Laboratoire Central des ponts et chaussées' (LCPC) on the various products reported that (Godart, 2001):

- The whitish paste, which hardened quickly in contact with the air, was primarily made up of ettringite (40%), portlandite (20%) and calcite (20%). Calcite was coming mainly from the carbonation of the portlandite. The remainder of the paste presented an enrichment in admixtures and sulphates.
- The yellowish liquid presented a composition close to the interstitial solution of a cement paste with a very strong alkalinity (pH of 13.8). This admixture could present in some cases an incompatibility with the cement, causing an instability of the grout during the dormant phase of the set.
- The air was saturated with water (100% of relative humidity).

Under these conditions, combined with the effect of variations in temperature, a pure water condensation could occur. The water would condense either on the interior wall of the duct, or on the parts of the prestressing wires exposed to this air saturated with water, triggering the onset of corrosion.

In Florida, concerns about grouting practices rose again in 2000, with the failure of external tendons (Figure 4.2.2.3) at the Mid-Bay Bridge (ID-7).

The post-tensioning industry in the United States responded with the adoption of more rigorous grout specifications (low permeability and little to no bleed) and execution programmes to ensure high-quality grouting operations. Thanks to the measures adopted, the number of tendon failures due to corrosion dropped. However from 2011 other bridges, constructed with the new measures adopted in 2000 (e.g., ID-15, Figure 4.2.2.4), reported tendon failures due to grout segregation.

Figure 4.2.2.3. Broken wire in one of the strands of Mid-Bay Bridge (ID-7) (Venugopalan and Powers, 2003).

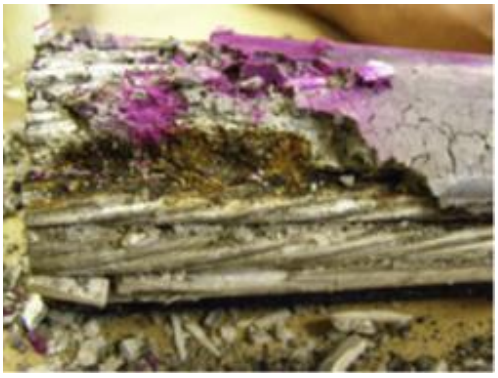

Figure 4.2.2.4. Corrosion of a strand embedded in deficient grout in Ringling Causeway Bridge (ID-15). Pink colour shows the pH indicator (phenolphthalein) sprayed on the grout surface (Lau and Lasa, 2016).

In line with the French studies, the soft grout material exhibited double the amount of free moisture compared to the hard grout (47% and 25%, respectively). The high amount of moisture suggested that the grout had high water to cement ratio and was aqueous in nature. The soft grout material exhibited elevated sulphur and chloride concentrations that were two and three times the concentrations recorded in the hard grout, respectively. On the other hand, the pH values were relatively the same as in the hard grout, with high alkalinity. Corrosion products were primarily composed of iron oxides and contained exceptionally high sulphur concentrations, but no trace of chlorides (Ahern et al, 2018).

Research on the topic continued in Italy since 2011 (Bertolini and Carsana, 2011).

In the specific, these investigations showed that:

- sometimes the segregated grout had a light grey colour with small black spots and was hardened;
- although weak, this type of grout was located in intermediate position between the conventional grey hardened paste and the whitish paste (Figure 4.2.2.5).

The Italian investigation continued with the microstructural analysis of broken wires taken from tendons failed under service and removed afterwards.

The analysis showed that the failure was ductile and no cracks were observed, which could be attributed to hydrogen induced stress corrosion cracking. It was verified that corrosion attacks only took place in the presence of the segregated grout, which was usually found only in the upper part of the cables, near their ends. Finally, it was confirmed that the whitish grout was a product of segregation. In fact, the material had a high concentration of the chemical compounds that were in solution in the initial stage of hydration of cement paste, namely, sulphates (due to the presence of gypsum as setting regulator) and alkalis (released in the early stage of hydration of clinker).

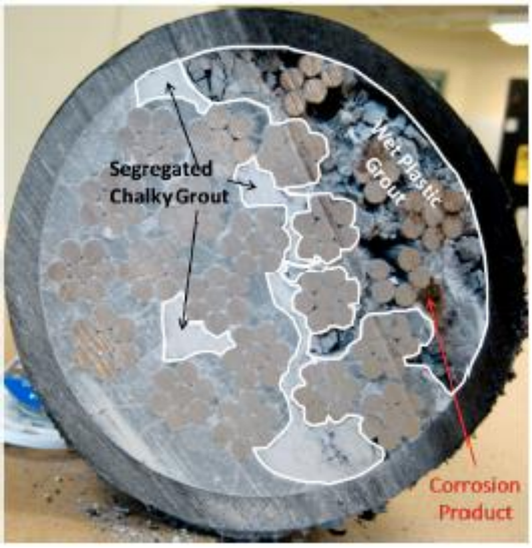

Figure 4.2.2.5. Grout segregation appearance (Lau et al, 2016).

To conclude, in case of grouting problems, the usual causes of steel corrosion (chlorides and/or carbonation) in concrete could not be responsible for the corrosion attacks in the prestressing tendons because:

- high pH excludes the possibility of carbonation-induced corrosion;
- low levels of chlorides exclude the possibility of pitting corrosion;
- plastic ducts exclude the possibility of water and air infiltration (in the absence of cracks, design or execution defects).

Therefore, the exudation phenomenon combined with grout settlement observed in LCPC testing seemed to be the most probable corrosion cause.

Moreover, the places where these failures occurred (i.e., Florida, France, Italy, Korea) suggest that external temperature should be quite high (approximately between 24 and 30° C) to cause corrosion. Hence, places with cold climate like Norway might be less vulnerable to corrosion occurring due to grouting problems.

5 Summary, conclusions, and recommendations for future research

This section presents the summary and the conclusions of the present study, and proposed suggestions for future research.

5.1 Summary

The aim of this report was to expand the current knowledge about corrosion of post-tensioned tendons in bridges. To this aim, an extensive literature survey about corrosion-induced failures in 52 prestressed structures has been conducted.

The results of this study have been summarized in the following, subdivided according to the topics:

- case studies (see Section2);
- failures (see Section 3);
- presence of warning signs (see Section 3.1.1);
- failure causes (see Section 4).

Case studies

The structures included in the present research have been described in Section 2. In that section, the focus has been on the structures geographical location, their type and the type of prestressing system. Moreover, in case of post-tensioned structures, the type of ducts and their filling have been examined. The analyses showed that:

- The failures reported herein occurred in:
  - the USA (22 cases, 7 of which in Florida);
  - the UK (9 cases);
  - Italy (7 cases);
  - France (6 cases);
  - Korea (2 cases).

  The other studied failures (one case for each country) took place in India, Japan, Canada, Belgium, Germany, and Australia.
- Of the total 52 case studies, 47 were related to prestressed bridges and 5 to other types of internally post-tensioned structures (i.e. one hyperbolic shell, 3 slabs and one cylindrical container).
  The analysed 47 case studies about bridges comprised:
  - 15 cases of segmental bridges;
  - 6 cases of I-section or T-section beam bridges;
  - 14 cases of box section beam bridges;
  - 6 cases of 'innovative structures', i.e. structures with unique design, which has rarely or never been adopted in other structures.

  In 7 cases it has not been possible to identify the type of structure due to lack of information in the literature papers.
- According to the type of prestressing system, this work included:
  - 44 post-tensioned structures, in particular:
    - 5 internally post-tensioned structures different from bridges;
    - 19 internally post-tensioned bridges;
    - 21 externally post-tensioned bridges;
  - 3 pre-tensioned beam bridges;
  - 1 bridge with some pre-tensioned spans and some post-tensioned spans;
  - 2 cable-stayed bridges;

- 1 suspension bridge;
- In 24 out of 52 cases it was not possible to identify the type of duct. Therefore, only the remaining 28 cases have been classified:
  - 11 ducts were made of plastic, polyethylene (PE) to be precise.
  - 7 ducts were made of metal.
  - In 6 cases the duct was absent for most of the length of the tendon or for its entire length.
  - In 2 cases the duct was made of precast concrete blocks, post-tensioned by other cables.
  - In 2 cases failure involved RC elements of the prestressed structure. In these cases, the reinforcement was epoxy coated.
- In 20 out of 52 cases it was not possible to identify the type of duct filling. The remaining 32 cases have been classified as showed in the following list:
  - in 19 cases the ducts were filled with cementitious grout;
  - in 7 cases the ducts presented no filling;
  - in 5 cases the ducts were filled with grease;
  - in one case the duct was filled with cotton soaked in oil.
- Many external tendons were enclosed in plastic ducts. However, in almost half the cases with external tendons it was not possible to identify the type of duct.
  Regarding the ducts filling of the external post-tensioning systems analysed in the present study:
  - half the cases presented ducts filled with cementitious grout;
  - in 3 cases the ducts were filled with grease;
  - in 2 cases the ducts did not have filling.
- Ducts in internally post-tensioned structures were either absent, made of plastic or of metal. Even so, in the majority of cases with internal post-tensioning system the type of duct was not identified.
  Ducts in the internally post-tensioned structures analysed in this work were filled according to the following list:
  - More than half the internal post-tensioned tendons were grouted with cementitious grout.
  - In few cases the ducts were empty.
  - In 2 cases the ducts were filled with grease. It must be noted that these cases are referred to post-tensioned slabs.

Failures

The reported failures have been characterized in Section 3.

The failures have been classified according to the increasing severity of the observed damage and consequent interventions. From lowest to highest, the consequences of damage (i.e., the level of damage) were:

- Maintenance. Light damage (concrete cracking, concrete cover spalling) that could be taken care of by ordinary maintenance activities.
- Tendon failure. The damage included breakage of the tendons, potentially affecting the overall safety of the structure. Extensive operations like tendon substitution were necessary.
- Demolition. Serious damage affecting the overall safety of the structure and requiring demolition (extraordinary intervention).
- Collapse. Condition of total or partial collapse due to inadequate or absent interventions, often resulting from absence of warning signs.

Additionally, some importance has been given to when the damage was observed. In this regard, the time of damage detection was related to:

- The level of damage: how serious was the damage when it was detected?
  From the less to the most serious, the categories are: ‘early’, ‘late’, ‘too late’, ‘not on time’.
- The age of the structure: how old was the structure when the most severe damage was detected on it?

In this case the categories are: ‘short-term failures’, ‘long-term failures’ and ‘short- to long-term failures’.

The analyses showed that:

- According to the level of damage, the failures included in this report have been classified as follows:
  - 17 out of 52 structures with level of damage ‘maintenance’;
  - 18 out of 52 structures with level of damage ‘tendon failure’;
  - 6 out of 52 structures (all bridges) with level of damage ‘demolition’;
  - 11 out of 52 structures with level of damage ‘collapse’.
- Of the study cases:
  - 17 out of 52 cases are early detected failures;
  - 18 out of 52 cases are failures detected late;
  - 6 out of 52 cases are failures detected too late
  - 11 out of 52 cases are failures not detected on time.
- In internally post-tensioned structures all levels of damage were observed.
  The majority of externally post-tensioned bridges exhibited tendon failures.
  Half of the pre-tensioned bridges collapsed.
  Damage of level ‘maintenance’ was most common in cable-stayed bridges.
- The number of failures included in the present report decreased with the structure’s age.
- The correlation of age at failure with level of damage showed that:
  - 8 out of 10 structures collapsed at an age comprised between 20 and 60 years, with peaks in numbers between 20 and 30 years and between 40 and 60.
  - Demolitions took place at ages ranging between 10 and 50 years old, with a concentration of cases between 30 and 40 years.
  - 15 out of 16 tendon failures occurred during the first 20 years of life of the investigated structures, with most of them (9 out of 16 cases) concentrating in the first 10 years.
  - In 12 out of 13 cases, level of damage ‘maintenance’ was detected in the first 50 years after construction. The number of these cases decreases with age (e.g., there are 4 cases of age 0-9 years and 2 cases of age 40-49).

Finally, the locations of the structure where failure occurred have been investigated. The analyses showed that:

- Failure of the investigated structures (52 cases) mostly occurred:
  - in external tendons (16 out of 52 cases);
  - in beams (8 out of 52 cases), specifically at the mid span and at deviation points;
  - at joints location (6 out of 52 cases).
- Considering only bridges (47 cases) and excluding the cases labelled as ‘not identified’ (4 cases), the failure locations can be collected in three macro categories:
  - Bridge superstructure (19 out of 43 cases).
    This category comprises the entries ‘superstructure’ (4 cases), ‘anchorages’ (1 case), ‘beams’ (8 cases), ‘joints’ (6 cases).
  - Tendons (20 out of 43 cases).
    This category comprises the entries ‘cable-stays’ (3 cases), ‘external tendons’ (16 cases), ‘internal tendons’ (1 case).
  - Miscellaneous (4 out of 43 cases).
    This category comprises the entries ‘pillars’ (2 cases), ‘samples’ (2 cases).
- Failures involving the superstructure occurred at joints and tendon deviation points. The damage consisted in:
  - cracked diaphragms;
  - deteriorated concrete;
  - evidence of surface corrosion on all the anchorages and bearing plates;
  - severe concrete cracking.

- Considering only the structures different from bridges (5 cases), failure occurred:
    - in the roof (3 out of 5 cases);
    - at anchorage location (1 out of 5 cases);
    - at internal tendons (1 out of 5 cases).
- The various failure locations have been subdivided according to the level of damage, yielding to the following list:
    - Collapses mainly (8 out of 11 cases) occurred in the superstructure. In particular, 5 cases occurred at joint locations and 3 cases in the beams.
    - In all the demolished bridges, failure involved the superstructure, with the exception of one case involving external tendons.
    - The majority (12 out of 18 cases) of tendon failures concerned external tendons.
    - The level of damage 'maintenance' was observed in all structural element types. The damage involved the superstructure (6 cases), the tendons/cables (6 cases), the samples (2 cases) and the pillars (1 case).
- The various failure locations have been divided according to the type of prestressing system, yielding to the following considerations:
    - Internally post-tensioned bridges mainly (13 out of 20 cases) suffered from damage in the superstructure. Specifically, damage was observed:
        - at joint location in 5 cases;
        - in the beams in 5 cases;
        - at anchorage location in one case;
        - in different elements of the superstructure in 2 cases.
    - Internally post-tensioned structures (excluding bridges) showed severe damage in the roof and in the tendons, in particular at anchorage location.
    - Most (16 out of 20 cases) of the failures in externally post-tensioned bridges concerned external tendons.
    - In all pre-tensioned bridges failures occurred in the superstructure.
      In 3 cases the damage involved the beams, precisely:
        - at deviation points location;
        - along the beam surface;
        - at mid span.

      In one case the damage occurred at joint location.
    - Cable stayed or suspension bridges mostly showed problems in the cables.

Presence of warning signs

One of the aims proposed in Section 1.2 was to understand if the presence of warning signs could be used to anticipate corrosion-induced failures. Hence, the levels of damage have been correlated with the typology of warning signs observed before or during failure occurrence. The analyses showed that:

- Only in half the studied cases warning signs have been observed.
  In fact, there were 10 out of 52 cases in which information about them has not been reported in the reference papers.
  In addition, in other 16 cases warning signs were not present at all.
- Many (6 out of 11) of the collapsed structures reported in this work presented warning signs before the collapse. The most common were:
    - strand corrosion with oxidation of the metallic duct;
    - tendons with loose strands;
    - longitudinal and shear cracks;
    - corrosion staining;
    - concrete spalling.

- Warning signs were observed in all the demolished structures:
  - cracking along the web of the beams following the path of the post-tensioning tendons;
  - extensive corrosion of the post-tensioning tendons at the anchorages;
  - cracks at diaphragm and joint locations;
  - concrete cracks and spalling.
- Typical warning signs for tendon failures were:
  - cracks in the ducts;
  - unplugged air vents;
  - extensive water leakage;
  - cementitious grout efflorescence;
  - presence of rust.
- In damage of level ‘maintenance’ typical observed warning signs were:
  - concrete cover spalling;
  - presence of efflorescence;
  - presence of small and large cracks in the concrete;
  - rust stains on the web or on beam soffits.
- Detection of warning signs can help limiting and reducing the damage. However, to do so some conditions need to be fulfilled, namely:
  - the damage needs to be detected early enough so that maintenance measures are effective;
  - maintenance measures should be implemented as planned.

  Nevertheless, in many cases failures such as broken tendons (5 cases) or the collapse of the structure (3 cases) occurred without warning signs being detected. In some other cases (i.e., 2 cases of collapsed structures and 5 cases of tendon failure) presence of warning signs was not reported in the literature.
  This last consideration highlights that the absence of warning signs does not guarantee the safety of the structure.

Failure causes

In Section 4 corrosion and failure causes have been analysed and discussed.

The difference between failure causes and corrosion causes is that the first ones created the conditions (e.g., cracks in the concrete), while the second ones provided the elements (i.e., water, chlorides, air) for corrosion to occur.

The analyses showed that:

- The principal failure causes were:
  - execution (23 cases);
  - conceptual design mistakes (21 cases);
  - problems in the grout (11 cases);
  - presence of cracks (7 cases);
  - use of inappropriate materials (6 cases);
  - too low concrete cover (3 cases).
- The most frequent (30 out of 52 cases) corrosion cause was the presence of external chlorides.
  The second most frequent cause ‘grouting’ was observed in ‘only’ 11 cases.
  The other corrosion causes (‘internal chlorides’, ‘external sulphates’ and ‘carbonation’) occurred just in 6 other cases.
  Therefore, it can be said that the majority of the structures included in this work underwent corrosion-induced failure due to external chlorides penetration and problems in the grout.
- External chlorides can come from:
  - de-icing road salts, one of the major sources of chlorides in cold climate;

- sea water, in liquid or air-form state.

- In structures that collapsed, have been demolished or manifested a damage of level ‘maintenance’, corrosion was mainly generated by external chlorides.
  The chlorides were mainly contained in de-icing salts or in the surrounding environment in the air-form state. From these sources, they penetrated inside the concrete through locations debilitated from execution and conceptual design mistakes.
  It must be noted that chlorides need time to penetrate the concrete. This is why corrosion-induced failures associated to external chlorides penetration generally occur after the structure is at least 10 years old. On the other hand, failures generally occur due to a combination of causes. Hence, short-time failures (especially structures younger than 10 years old) with external chlorides as major corrosion cause, may be due to the combination of other failure causes.
- In structures that exhibited failure of tendons, corrosion was mostly triggered by problems within the grout. In these cases, the grout underwent the process of exudation (i.e., the discharge of a liquid or viscous gel-like material through a pore, crack or opening in the surface of concrete), bleeding and segregation due to variation in temperature. Under these conditions, combined with the effect of variations in temperature, a pure water condensation could occur. The water would condense either on the interior wall of the duct, or on the parts of the prestressing wires exposed to this air saturated with water, triggering the onset of corrosion.
  At the end of the process the grout remained unhardened, with a whitish and soft appearance. High pH, low levels of chlorides and high levels of sulphates were detected inside the whitish grout.
  In case of grouting problems, the usual causes of steel corrosion (chlorides and/or carbonation) in concrete could not be responsible for the corrosion attacks in the prestressing tendons:
  - high pH excluded the possibility of carbonation-induced corrosion;
  - low levels of chlorides excluded the possibility of pitting corrosion;
  - plastic ducts excluded the possibility of water and air infiltration (in the absence of cracks, design or execution defects).

  Therefore, the exudation phenomenon combined with grout settlement seemed to be the most probable corrosion cause.

5.2 Conclusions

As already discussed in Section 1.2, the work presented in this report is strictly related to the ‘Better Bridge Maintenance’ project. To be more specific, through a selection of relevant case studies, this report aims to contribute to the development of general guidelines for the assessment of structural consequences in case of damage of post-tensioned systems.

For this reason, this last section discusses if the observations presented in the previous topics can be generalised. In particular, the questions raised in Section 1.2 are now answered:

- Detection of warning signs can help limit and reduce the damage provided some conditions are fulfilled:
  - the damage needs to be detected early enough for the repair measures to be effective;
  - maintenance measures should be implemented as planned.

  Nevertheless, the absence of warning signs does not guarantee the safety of the structure.
- Since all the cases with chalky grout problems were observed in places with high-temperature climates (e.g., Florida, Italy), it is the authors’ opinion that grouting-induced failures are more probable in locations where temperatures of 30 °C are commonly reached. On the other hand, the analyses confirmed that in cold climates the structures are more sensitive to the penetration of external chlorides (mainly coming from de-icing salts).
- Various types of structures have been analysed in this report, showing that:

- Internally post-tensioned bridges can show all levels of damage, and that they appear in the superstructure at various locations (joints, anchorages, and other structural details). Warning signs are not always present. On the contrary, failure may occur without showing any warning signs.
- Internally post-tensioned slabs show damage mainly at tendon anchorages.
- In externally post-tensioned bridges, failure usually involves external tendons. In cable-stayed/suspension bridges, failure can be due to the exposure of the external tendons/cables, which carry the main load globally. On the other hand, frequent inspections and easy access mean warning signs are usually observed earlier in external tendons than in internal tendons.
- In pre-tensioned bridges, damage mostly involves the superstructure, in particular affecting joints, tendon deviation points, and anchorages.

5.3 Recommendations for further work

According to the aim of the 'Better Bridge Maintenance' project, more research is needed to improve the understanding of corrosion-induced failure in post-tensioned systems relevant for Norwegian conditions. In addition to the specific aims of the project (see Section 1.2, points a), b) and c)), the work exposed in this report leads to the following suggestions:

- The absence of warning signs does not guarantee the safety of the structure. Therefore, an accurate programme of inspection and maintenance activities throughout all the life span of the structure is necessary.
  In this regard, it is suggested to develop a classification system for the bridges related to their robustness against unforeseen failures (i.e., how probable is an unforeseen failure without any warning signs?).
- This report showed that pre-tensioned bridges and internally post-tensioned bridges share some similarities related to where the corrosion-induced failure occurs (e.g., joints, tendon anchorages, and deviation points). This observation highlights once more the importance of correct design and execution, especially in these specific locations. In fact, joints, tendon anchorages and deviation points are known to be vulnerable to corrosion attacks since they represent the place where the continuity of the element is broken. This is particularly true for pre-tensioned bridges, generally consisting of simply supported precast pre-stressed beams separated by joints. On the other hand, in case of internally post-tensioned bridges the tendons and the ducts are continue throughout the joint between two adjacent segments. However, at joint locations we expect voids in the grout due to the grout composition, and corrosion of internal tendons is often associated with voids in the grout.
- Study and development of new NDE methods that could be applied even to internally post-tensioned structures are highly recommended.

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Appendix A

The present appendix includes a list of the collected case studies in the literary survey.

The cases, associated with an identification number (ID-xx), are presented in Table A1. For each case study, the table provides essential information about age, geographical location, structure description and failure characterization. Moreover, references and additional notes about e.g. presence of warning signs are included.

Table A1. Case studies.

<table>
<tr><td colspan="3">ID-1 Ynys-y-Gwas Bridge. 1953 (built) - 4.12.1985 (collapsed)</td></tr>
<tr><td colspan="2"><u>Location</u>: West Glamorgan, Wales</td><td><u>Reference</u>: Woodward et al. (1989), Woodward et al. (1991), Woodward and Williams (1988)</td></tr>
<tr><td><u>Description</u></td><td><u>Failure characterization</u></td><td><u>Notes</u></td></tr>
<tr><td>• Single span simply supported segmental post-tensioned deck (clear span of 18.3 m).
• 8 precast I-section beams with a web stiffer on one end.
• Beams made up of eight 2.41 m long segments.
• The segments are longitudinally post- tensioned together by 10 Freyssinet tendons.
Each tendon consists of 12 ϕ5 straight wires and was housed in a smooth duct.
• 25 mm transverse joints between segments filled with mortar before post-tensioning.
• Cardboard tubes around the longitudinal tendons where they passed between the segments and the insertion of asbestos packing between the beams.
• Designed for zero tension.
• Shear capacity was marginally deficient, while bending capacity was well below current requirements (maybe also contemporary ones).</td><td>• Failure caused by corrosion.
• No evidence of damage before failure. Absence of visual evidence of corrosion (cracking or spalling), thanks to partially grouted ducts that left space for expansion of corrosion products (of high density).
• The I-beams collapsed as a single unit (good transverse distribution of loads).
• Chlorides as primary cause of corrosion. They originated after construction, penetrating from the deck through the longitudinal joints between the beams.
• De-icing salts main source of chlorides.
• Hypothesis of sea sand used in the mortar: it explains the wide variation in chloride concentration in the joints and was largely used in the area. On the other hand, there was no evidence of chlorides in the grout, but only few samples of grout have been analysed.
• Experimental result (single beam). No fractured wires imply the overall response of the beam is not affected until collapse is imminent. Fractured wires imply loss of prestress with small deflections of the beam without change of load. However, in presence of transversal load distribution, warning deflections could be minimal and hence not useful.</td><td>• All the tendons examined were corroded where they crossed the joints. In other places they were corroded very little.
• Poor detailing of the joints, which could have opened under live loads. Yet there was no evidence of fatigue.
• “Overloading a structure to check if it has reserves of strength may open cracks or cause deterioration that would not otherwise have occurred”. Load testing is unlikely to give any indication of damage, because if corrosion is localized to the joints, the behaviour of a corroded beam is identical to that of a non-corroded one until failure is imminent.
• Most longitudinal ducts were well grouted, with few exceptions. Evidence of grout leakage at the longitudinal joints during construction.
• Corrosion products: black (magnetite, produced in restricted supply of oxygen) and reddish-brown oxides of iron. Magnetite is denser than common rust, so it does not produce the same expansive forces.</td></tr>
<tr><td colspan="3">ID-2 S. Stefano Viaduct. 1954 (designed by Morandi) - 1956 (built) - 23.04.1999 (collapsed)</td></tr>
<tr><td colspan="2"><u>Location</u>: Messina, Sicily, Italy</td><td><u>Reference</u>: Calvi et al. (2019), Colajanni et al. (2016)</td></tr>
<tr><td><u>Description</u></td><td><u>Failure characterization</u></td><td><u>Notes</u></td></tr>
<tr><td>• Post- tensioned box-section deck (see ID-6).
• 4 spans resting on 3 piers and 2 abutments + 2 sidewalks cantilever of 1 m.
• Simply supported girder deck by 7 post-tensioned box beams with precast segments of 1.5 m length, having a trapezoidal cross section.
• 6 RC diaphragms and thin concrete desk slab, cast in situ, transversally stiffened the box beams.
• Cables: 6 constituted by 18 ϕ5 wires; 2 constituted by 12 ϕ5 wires.</td><td>• No signs of imminent collapse.
• One of the 4 span of the viaduct, with no vehicles and/or pedestrians, collapsed in a cross section near the middle of the span between two joints.
• The tendons showed a slippage from the ducts.
• Substantial reduction in the cables cross section, just in correspondence of the parts where the sealing protection was absent/insufficient (on some points of the wires the reduction was 100%).
• Back analysis methodology results.
The collapse mechanism appears to be a progressive failure, begun from the beam on the seashore side.</td><td>• The holes of 40 mm diameter for prestressing tendons were made in situ by a concrete hammer drill.
• Inadequate protection of prestressing reinforcement.
• Numerous areas of corrosion in the transversal rebars.
• Prestressing reinforcement was visible from the outside of the concrete (small concrete cover thickness: 10 mm).
• Complete lack of grout sealing for a significant length of the tendons.</td></tr>
<tr><td colspan="3">ID-3 Sorell Bridge. 1957 (built) - 2002 (demolished)</td></tr>
<tr><td colspan="2"><u>Location</u>: Tasmania, Australia</td><td><u>Reference</u>: Papé and Melchers (2011)</td></tr>
<tr><td><u>Description</u></td><td><u>Failure characterization</u></td><td><u>Notes</u></td></tr>
<tr><td>• 34 spans, each comprising 14 precast simply supported T-beams (13 m long). The beams were post-tensioned with 2 parabolically-draped tendons.
• 18 high-tensile steel wires ϕ5 per tendon, located in ducts formed using inflatable rubber tubes, removed after grouting. Hence, the tendons were enclosed in bare concrete.
• The tendons were stressed using the Freyssinet method.
• Transversally, the beams were connected together by post-tensioning through transverse diaphragms between the webs (and the flanges).
• Minimum concrete cover of rebars and tendons: 25 mm.</td><td>• 1976: during construction calcium chloride had been added to aid early setting of the concrete.
• 1978: corrosion detected on the pillars and cross heads.
• 1993: cracking along the web on one of the interior beams following the path of the post-tensioning tendons.
• 2000: 51 beams showed the same crack pattern (in some cases it was observed that the prestressing strands were unprotected by concrete cover.
• 2005: 3 beams for laboratory investigation.
Beam in good condition: failed in bending at about mid-span, at 100% of its capacity; 10 strands failed; presence of vertical regularly spaced cracks on the web.
Beam with the most severe cracking: failed in shear at the 4th diaphragm, at 51% of its capacity; 17 strands failed + severe strand corrosion (more than 75% cross section loss); presence of large diagonal cracks following the path of the strand.
Beam with moderate cracking: failed in shear at 70% of its capacity; 33 strands failed; crack pattern similar to the most damaged beam.</td><td>• The longitudinal reinforcement did not comply with the design requirements.
However, since the main load carrying elements are the tendons, it is unlikely to have had an effect on the ultimate load behaviour.
• Rust staining was visible on the exterior concrete surfaces of all the beams tested, mainly due to shear ligatures and lower longitudinal bars. Little or no rust was observed adjacent to the longitudinal web cracking.
• Strand corrosion: general and pitting corrosion; minimal rust staining despite substantial section loss.
The strands had corroded more severely along the top and sides, with irregular semi-circular, concave corrosion profiles.
• Conventional reinforcement corrosion: generally in good condition; observed some areas of spalling and cracking of the concrete.
• Some of the corrosion products were indicative of the involvement of bacterial activity in the corrosion process.</td></tr>
<tr><td colspan="3">ID-4 Petrulla Viaduct. Mid ‘80s (built) - 07.07.2014 (collapsed)</td></tr>
<tr><td colspan="2"><u>Location</u>: Licata, Sicily, Italy</td><td><u>Reference</u>: Anania et al. (2018), Bazzucchi et al. (2018)</td></tr>
<tr><td><u>Description</u></td><td><u>Failure characterization</u></td><td><u>Notes</u></td></tr>
<tr><td>• 13 simply supported beams.
• Deck made of 4 precast and prestressed concrete I-beams.
• 5 transverse beams constituted the girder that supported the pavement slab.
• Each beam was prestressed by means of 5 tendons made by 12 strands of 0.6 in.
• The tendons were positioned in a corrugated metal duct of 70 mm diameter.
• Mainly devoted to vehicular traffic (transport of raw materials for agriculture).</td><td>• Collapse mechanism: forming of a plastic hinge in the mid-span of a bridge beam.
• Collapse determined by the breakage of the tendons (the wires inside them appear completely rusted – up to 61% cross section loss - or dissolved).
Subsequent expulsion of the ducts’ anchorages at the head beam due to the release of elastic energy.
Loss of prestress, hence, increase in shear stress and consequent inward rotation of the lower flanges + expulsion for tensile action of the mild reinforcement: sudden flexural failure.
• Initial faults during tendons design, such as, inadequate grout composition (clear mortar and not Portland cement) and filling +inadequate distance among the ducts employed.
• Chloride induced corrosion.
• Diffused oxidation in the prestressing cables, severe corrosion of the metallic sheathing, accelerated by the large absence of the protective grout inside the cables.</td><td>• A warning sign of the imminent collapse could have been noticed by a severe and characteristic crack pattern present in all the bridge spans adjacent to the collapsed one.
• The anchor region for tendons 4-5 (the ones who broke) is on the extrados of the deck beam. This facilitated periodic water infiltrations.
• Inadequate waterproofing cover of the joints.
• Error in positioning of the prestressing cables, yielding to insufficient concrete cover.
• Inadequate workability and fluidity of the concrete.</td></tr>
</table>

Table A1. Case studies.

ID-5 Fossano Bridge. 1992-1993 (built) - 18.04.2017 (collapsed)

Location: Cuneo, Piedmont, Italy

Reference: Bazzucchi et al. (2018), https://torino.repubblica.it/cronaca/2017/04/18/news/crolla_il_ponte_della_tangenziale_di_fossano_schiacciata_un_auto_dei_carabinieri-163288432/, https://www.ingenio-web.it/16537-crolla-il-ponte-in-calcestruzzo-di-fossano-tangenziali-tangenti-e-altre-storie

Description	Failure characterization	Notes
• A simply supported structure, 30.80 m long and 8.90 m wide, constituted by a multiple-box post-tensioned beam and by an in-situ casted slab. • The section was realized by connecting two concrete precast U-elements by a shear-key casted in situ. • The connection between the segments was realized by an in-situ casted concrete joint 0.5 m wide. • Post-tensioning system constituted in 8 parabolic cables, each of them made by 19 0.8'' strands.	• The collapsed structure evidenced an intact joint and a collapsed one, together with an evident shear failure where the bridge impacted the ground. • Visual inspections consented to affirm that the collapse mechanism was triggered by a shear failure in one of the joint due to the absence of the equilibrating action of the prestressing. • Visual inspections immediately also demonstrated that the cables did not have sufficient grout protection in the collapsed joint area. • Causes of collapse are still unknown. • Hypothesis of corrosion of the tendons in the joint due to water and de-icing salts. • Failure probably due to constructive defects.	• 2010: huge flood. The guard rail fell towards the joint; landslide occurred near the bridge, causing the closure of part of it. • The morning of the collapse there has been an inspection of the bridge, with a positive response.

ID-6 Polcevera Bridge. 1967 (designed by Morandi) - 14.08.2018 (collapsed)

Location: Genoa, Ligury, Italy

Reference: Bazzucchi et al. (2018), Calvi et al. (2019), Clemente (2020), Domaneschi et al. (2020), Invernizzi et al. (2019), Morgese et al. (2019), Nuti et al. (2020), Relazione della Commissione Ispettiva Mit (2018)

Description	Failure characterization	Notes
• Construction phases: 1) pylons; 2) deck constructed in segments extending from pylons (temporary external post-tensioned cables); 3) permanent cables 24 for dead loads; 4) permanent cables 28 for live loads + compression of the stay cover; 5) simply supported transfer Gerber beams. • Elements of one balanced system of the bridge: pylons; antenna or towers (two A-shaped structures); main deck (with a five-sector box section, supported at 4 locations and with no connection with the antenna); 4 transverse link girders (connecting stays and pier trusses to the deck); 4 cable stays (angle 30°); 2 simply supported Gerber beam spans (connecting the balanced system to the adjacent parts of the bridge). • The deck would not have been able to resist even its own weight without the restraining action provided by the cables. • Cable-stays each with a total of 464 strands (323 located first, related to dead loads).	• Many of the parts of the tower broke with planar surfaces, highlighting insufficient rebars content and insufficient plasticity reserve. • Hypothesis: the collapse occurred due to a combination of fatigue and corrosion of the cables. • Pitting corrosion was discovered in the cables following post-collapse inspection. • Deficiency of grout in the tendon ducts was considered the main culprit for instigating pitting corrosion in the steel tendons. • Dynamics of failure (confirmed by a video): rupture of the first cable-stay near the seaside, at the connection between the stay and the saddle top of Tower 9. Subsequent collapse of the deck on the west side of the pylon, yielding to the collapse of Tower 9 balanced system and two buffer beams. • Causes of the cable-stay failure under investigation. • If sections other than the stay cables were responsible for the collapse, large deformations and displacements would have warned the authorities of the impending failure. • The abundance of the steel capacity has possibly played a role in avoiding premature problems. • Presence of tensile concrete stress + absence of bond (absence of grouting) + deterioration of the steel tendons. It yielded to increased deformability and a consequent different distribution of shear and bending moments.	• 1981: evident corrosion of superficial reinforcing bars with some concrete cover failures + external steel plate and support corrosion; Morandi highlighted the inefficiency of the drainage system • 1982-1986: restoration of concrete surfaces and creation of passages for inspection in the deck caissons. • 1986-1993: retrofitting of I-prestressed beam lower bulb; substitution of corroded supports and creation of other passages; retrofitting of part of the connection between external vertical wall and slab in the caisson beams. • 1991-1992: most of the ducts of Towers 9 and 11 did not have grouts and strands showed extensive corrosion, with some cables having loose strands. • 1993: inspection through the insertion of an endoscopy inside the stays of Tower 11. Observed severe oxidation of the metallic protective membrane and of the strands. Some of the strands appeared slacked or sheared. The entire sets of strays were replaced with an external prestressing system. • 2009: deck joint retrofitting; substitution of prestressing cables in 3 simply supported deck beams. • 2015: level of corrosion detected 10-20%. • 2017: dynamic tests of the balanced systems highlighted a lack of symmetric response in the mode shapes. • 2019: 22% of strands with 50-0% corrosion; 78% of strands with 30-50%. • Environment rich in chloride and sulphuric dioxide.

ID-7 Mid-Bay Bridge. 1992-1993 (built) - beginning of 2000 (inspection)

Location: Destin, Florida, USA

Reference: Venugopalan and Powers (2003)

Description	Failure characterization	Notes
• 141 span structure; two-lane undivided highway with shoulders on both sides. • Segmental precast concrete box girders held together by 6 post-tensioning tendons (3 on each side). The tendons span 8-9 segments and terminate at a metal trumpet type anchorage assembly. • Each tendon is comprised of 19 spirally wound 5/8 in. diameter seven wire strands with a grouted 4 in. diameter polyethylene duct.	• Failure of individual wires was primarily due to corrosion and subsequent elevated tensile stress that resulted from the reduced cross section. • Visual inspection of the tendon ends highlighted the presence of acid corrosion products, meaning active corrosion was ongoing. • Cracking of the polyethylene ducts is extensive, but it has not been a primary cause of tendon corrosion problems. However, if left unrepaired, the cracks will contribute in the long-term to further tendon corrosion.	• Beginning of 2000: replacing of 11 tendons after disclosing of a box girder. • Tendon corrosion associated with grout voids and bleed water is more likely to occur along the inclines rather than horizontal runs. First, since the latter location are at a lower elevation and as such exhibit fewer void and. Second, because the incline from which mortar was not pumped should be particularly likely to contain both voids and bleed water.

ID-8 Carpineto Viaduct. 1971-1974 (designed by Morandi) - 2018 (inspection)

Location: Potenza, Basilicata, Italy

Reference: http://www.lecronachelucane.it/2018/08/17/il-ponte-morandi-in-basilicata-il-viadotto-strallato-carpineto-i/, https://www.stradeeautostrade.it/ponti-e-viadotti/il-viadotto-strallato-carpineto-i-2/

Description	Failure characterization	Notes
• Similar to ID-6. • Cables with 240 parallel tendons 0.5 in., protected by a concrete rectangular duct made of precast blocks. • The ducts are post-tensioned by other 80 0.5 in. tendons.		• 2013: adding of an external prestress system. • August 2018: visual investigation. Concrete cover spalling. Inspection through the insertion of an endoscopy inside all the cables highlighted the presence of mild general corrosion and a more severe one on some tendons. Prestress in tendons reduced up to 20%.

ID-9 Lowe's Motor Speedway. 1995 (built) - May 2000 (collapsed)

Location: Concord, North Carolina, USA

Reference: Poston and West (2005), Sly (2001)

Description	Failure characterization	Notes
• Simply supported, 4 spans, pre-tensioned, pre-cast double T beam bridge. The beams are located side by side and connected longitudinally by weald shear connectors along the flange. • Some strands are straight, and some are harped to a low point at mid span, where a single hold-down is used. • 22 special ½ inch diameter strands were used for the prestressing.	• One span of the north bridge collapsed with 107 people over it. • Rusted half-inch steel cables protruding from the broken concrete spans. • 3-foot cracks underneath three remaining spans. • Severe corrosion in the form of pitting and loss of cross sectional area in all the beams (even in those that did not collapse), limited to the centre span region at the position of the hold-down. • It was possible that the grout used to fill the deep pocket left by the mandrel during fabrication, experienced	• No evidence of water seepage in the concrete surrounding the cables. • Calcium chloride in the grout used as concrete filler. • A mandrel was used to depress the strands from above. After casting and hardening of the concrete the mandrel was removed. The resulting cavity was then filled with grout. • The hold down was executed from the top and not from the bottom, facilitating water infiltration.

Table A1. Case studies.

	excessive shrinkage thereby allowing more rapid ingress of moisture and oxygen. • High levels of chlorides were detected in the grout.	• Warning signs: longitudinal cracks along the stem soffit at mid span directly under the grout plug location + corrosion staining around the grout plugs in several beams.
ID-10 Luling Bridge. 1984 (built)		
Location: New Orleans, Louisiana, USA	Reference: Elliott and Heimsfield (2003), Mehrabi (2009)	
Description	Failure characterization	Notes
• Superstructure with 3 cable-stayed spans (151 m, 372 m, 155 m). • The cables were hung from two 122 m high steel towers. • Wire used for the cables: 6.35 mm diameter, cold down, stress relieved. • The cables are encased using a high-density polyethylene sheathing, injected with a Portland cement grout • The pylons are a modified A-shape, and the deck is composed of twin steel trapezoidal box girders all made of weathering steel. • The stay-cables are arranged in two planes and are grouped by pairs or fours.	• Damage observed in the anchorage zones: corrosion of sockets and button heads; missing or broken seals at the joint between the transition pipe and PE pipe; open grout vents. • Inspection in the cables free length: longitudinal and transverse split in the PE pipe; exposure and degradation/corrosion of grout filler and steel wires; budges and holes in the PE pipe; tape damage; voids in the grout; concrete delamination.	• 1985: some cracking of the sheathing was noticed; hence the original black polyethylene pipes were replaced with white PVF tape. • 1990: all cables were wrapped with UV protection tape after existing splits and cracks were filled with epoxy. • 1995 the first evidence of damage of the cable wrapping tape was detected. Subsequent inspections showed the existence of: exposed and rusted stay-cable wires, unplugged grout ports and extensive water leakage, cementitious grout efflorescence and rust at the deck level anchorage sockets. • 2002: comprehensive evaluation of the stay-cable array and cables substitution.
ID-11 Sunshine Skyway Bridge. 1982-1987 (built) - 2000 (tendon substitution)		
Location: Florida, USA	Reference: Chandra and Szecsei (1988), Illig and White (2010), Sayers (2007), Theryo et al. (2011)	
Description	Failure characterization	Notes
• 3 distinct types of prestressed concrete structures. • Low level north and south approaches: two parallel two-lane structures. The superstructure consists of a 4-spans continuous reinforced concrete deck slab supported on 5 precast prestressed concrete AASHTO type IV girders. The substructure consists of reinforced concrete wall type pillars founded on 51 cm square precast prestressed concrete piles. The pillars of the parallel roadways are connected across between the two structures by precast prestressed concrete frangible struts. • High level north and south approaches: parallel two-lane structures. Single cell precast post-tensioned, trapezoidal continuous concrete box girders, supported on precast, post-tensioned hollow elliptical column segments. The vertical tendons that hold the column segments together are internally bonded within the thicker wall region and run externally along the inner wall in the upper part. The tendons are housed in a 75 mm diameter smooth polyethylene duct called the primary duct. The upper end of these tendons is anchored in the cap and forma U-loop configuration in the footing. In the thick wall region, the 75 mm primary duct was placed inside a 127 mm diameter corrugated polyethylene secondary duct, which was cast inside the wall of the precast segment. • Main span area: a single structure with a single cell, precast, post-tensioned, concrete superstructure. The superstructure has internal post-tensioning cables + shear keys along the edges + diaphragms over the support. The substructure consists of post-tensioned concrete piers supported by 61 cm square precast prestressed concrete piles. The main piers support 131.7 m high cable-stayed pylons, with a single plane of 42 stays at the centre of the roadway. • Each stay is formed using bundles of high-tension steel cables that have been spun together. These are then sheathed using steel tubing to provide protection from corrosion. • The stays are bolted to the desk segments through anchorages that are embedded below the road level. • A thin coating of protective paint is all that stands between the steel and the aggressive environment.	• Shear cracking was observed during routine inspections of the bridge in the concrete girders of the low level spans. • Inclined shear cracking was much more prevalent in the exterior girders. • Cracks were observed in numerous pillar caps. In some cases, these cracks were very large and exhibited visible signs of water penetration and damage. • The reduction in shear capacity was due to the excessive strand debonding at the ends of the girders. • August 2000: severe tendon corrosion in column 133NB (northbound). 11 out of 17 strands in the SE tendon leg had failed in the external region, immediately below the column cap. The NE tendon leg exhibited minor surface as well as pitting corrosion, but no strand failures were observed. Both tendon legs had split polyethylene duct in the corroded region. • September 2000: water with high chloride concentrations was found at the bottom of 28 columns. • Deficiencies detected in the critical columns: water in the column interior; segment joint leaks adjacent to the tendons; possible active corrosion; ungrouted tendons; severe splitting in the polyethylene ducts; possible grout deficiencies based on construction records. • Gout voids detected in the trumpet areas. • None of the external tendons had lost tension force. • Strand failure only in column 133NB. • At locations where the duct were uncracked no strand corrosion was observed.	• A high level of corrosion has taken place in the cables. In many instances, failure of individual cable strands has begun to occur, but repairs could be carried out reasonably easily. • Inspections were also carried out on the internal post-tensioned cables within the concrete deck, but in general the damage of these areas was far less due to the added protection from the concrete. • Signs of fatigue were beginning to show in other areas of the structure: cracks in the lower areas of the bridge. • The primary ducts at the base of the columns were not concentric within the secondary ducts. This condition eliminated the grout protection over a portion of the tendon.
ID-12 Varina Enon Bridge. 1990 (built) - 2007 (tendon failure)		
Location: Virginia, USA	Reference: Brodsky (2020), Lau and Lasa (2016), Sprinkel et al. (2010), Venugopalan (2008)	
Description	Failure characterization	Notes
• External tendons. • Two parallel 28 spans bridges. • Precast box girder cable-stayed bridge. • External longitudinal post-tensioning consists of 8 tendons located in the hollow interior of the 7 20-ft long precast segments. • The joints between the segments are epoxied and the spans are completed with 6 in. cast-in-place closure joints on either side of the pier segment. • The tendons are grouted in ducts that run through the deviator blocks.	• The primary causes of tendon corrosion are compromised alkalinity of the grout and the presence of voids. • Past routine investigations identified voids in the cables that were then filled with grout, but 3 years later, one of the tendons was completely severed due to severe corrosion.	• The bridge did not exhibit any sign of distress before the collapse. • The Niles Channel, Mid Bay, Seven Mile, Sunshine Skyway bridges exhibited corrosion of external grouted post-tensioned tendons. Corrosion in the tendons is largely attributed to void formation in the tendon due to bleed water formation in the neat grout commonly used at the time.
ID-13 Post-tensioned bridge in the Midwest. 25 years old		
Location: Watson (Oklaoma, Lousiana, Texas), USA	Reference: Venugopalan (2008)	
Description	Failure characterization	Notes
• 25-spans cast-in-place box girder bridge. • six lane divided highway with shoulders on both sides. • 3 boxes adjacent to each other. • each tendon is made up of several spirally wound, ½-5/8 in. diameter, seven-wire strands inside a grouted 4 in. diameter galvanized metal duct.	• Visual inspection: cracks on the riding deck; active cracks on webs and diaphragms; corrosion-induced damage on the underside of the riding surface; voids along the tendons. • Moderate to high corrosion rate in the tendons. • Signs of problems throughout the structure: efflorescence; cracks (small and large); several spalled areas on the underside of the top slab.	• It was not clear if the visual signs were the result of tendon corrosion or were contributing to tendon corrosion. • Actively corroding tendons would continue to corrode even if the voids are subsequently completely filled with grout.

Table A1. Case studies.

	• Numerous small and some large voids in the grout surrounding the tendons in different parts of the structure.	
ID-14 San Francisco – Oakland Bay Bridge. 2006 (failure)		
Location: San Francisco, California, USA	Reference: Lau and Lasa (2016), Reis (2007)	
Description	Failure characterization	Notes
• 14 spans twin precast segmental box girder bridges.	• 2006: runoff water from the deck entered the duct through unsealed grout tubes. • Rust coloured water was discovered being discharged from ungrouted tendon ducts during routine tendon duct cleaning operation. • Strands with moderate corrosion and indication of shallow pitting were observed. Some of the strands failed to meet specified tensile strength and ductility requirements. • Transverse cracks and fractures in some wires in strands touching a duct hardpoint may have been associated with environmentally assisted cracking. • Visual observations of cracking and/or moisture extrusion and signs of effervescence from the concrete at cracks in the walls.	• Internal ducts were left ungrouted for up to 15 months during construction. • The level of observed corrosion was proportional to the amount of water observed in the ducts. • It is suspected that the main source of water was rainwater entering through improperly sealed grout tubes on the surface of the deck. • In some cases, tendons at the project site had remained ungrouted with post-tensioning steel in place and stressed for periods up to 17 months.
ID-15 Ringling Causeway Bridge. 2003 (built) - 2011 (tendon failure)		
Location: Sarasota Bay, Florida, USA	Reference: Ahern et al. (2018), Lau and Lasa (2016)	
Description	Failure characterization	Notes
• 1 km long, 11-spans, post-tensioned, segmental bridge with internal tendons and external tendons. • 3 cell box girders. • A total of 132 external tendons with 12 tendons in each cross section along the length of the bridge. • Each tendon contains 22 strands encased in a HDPE duct. • 15 mm diameter seven-wire strands. • After stressing, the tendons were pressure-grouted with cementitious grout. • The external tendons are draped with a linear transition between the high points and the low points of the tendon path. • Concrete deviators are installed at the high and low points.	• 2011: corrosion failures of two longitudinal external post-tensioned tendons, completely ruptured and lying on the bottom of the span. • Both tendons failed near the high-point deviator. • 13 tendons, in addition to the broken ones, had evidence of strand corrosion damage in the form of localized pitting, wire breaks or both. • Corrosion damage was limited to high points deviators. • Much more than 10% of the external post-tensioned tendons had to be replaced because of corrosion. • Corrosion was the direct result of the segregation of the cementitious grout material.	• The corrosion of the strand occurred at locations with deficient grout. • In the most severe manifestation of the deficient grout, the grout remained unhardened. • The observed tendon corrosion typically occurred in tendons that either exhibited visible segregation of the grout or had partial or full depth grout voids. • Corrosion was limited to the segments of the strands embedded in the soft grout material. • No damage in the hardened grout material parts. • The chloride and sulphur ions travelled with the bleed water and settled near the high points.
ID-16 Long Key Bridge. 1979-1983 (built) - 1986 (corrosion was observed)		
Location: Florida Keys, USA	Reference: Moreton (1998), Sagüés et al. (1994)	
Description	Failure characterization	Notes
• The first trapezoidal section, precast, concrete segmental, box girder bridge constructed in USA using span-by-span erection. • External post-tensioning, and multiple shear key dry joints between the segments. • 101 spans of 36 m and 2 end spans of 34.5 m • The superstructure is supported by precast concrete V-piers resting on laminated neoprene bearings atop water-level footings. Each footing rests on two 1.1 m diameter drilled shafts. • All reinforced steel is epoxy coated.	• Corrosion related spall. • Corrosion is locally confirmed to the splash zones containing the bases of the V-shaped piers, the bearing areas of these bases, and the footers above water level. • In every other respect, the superstructure has suffered no corrosion at all. • Cracks, spalls or other signs of corrosion damage were visually inspected.	• 1986: spalling of concrete attributed to corrosion, and since then it has increased in frequency. • 1991: metalized zinc cathodic protection was first applied to a few selected areas and has proved to be somewhat effective in arresting the attack. • The corrosion attack is the result of high chloride penetration in the splash zone and progressive corrosion under the epoxy coating of the reinforcing steel.
ID-17 Niles Channel Bridge. 1983 (built) - 1999 (tendon failure)		
Location: Florida, USA	Reference: Freyermuth et al. (2001), Powers et al. (2002)	
Description	Failure characterization	Notes
• Low-level span-by-span precast segmental bridge. • It contains a total of 234 external tendons. • External tendons arranged in a configuration such that the centre lengths of the tendons are draped downward from the anchorages through deviation blocks along the length of the spans. • The anchorages utilize ductile cast iron anchors and forged steel wedge plats.	• The failed tendon was at an expansion joint. • Corrosion was mainly at or near the anchorages. • Corrosion was always associated with grout voids, grout bleed-water and soft, chalky grout in the affected areas. • Corrosion took place in the transition zone between grout and air space, while the metal completely embedded in grout remained in the passive condition.	• The grout contained only trace levels of chlorides. • Lowered pH could develop at the interface between the grout and the void area by reaction with CO2 leaking in from the external atmosphere. • Chloride concentration increases may occur there by penetration into the void area by salty runoff from the bridge surface.
ID-18 Italian bridge. Tendon failure 2 years after construction		
Location: Italy	Reference: Bertolini and Carsana (2011), Carsana and Bartolini (2015)	
Description	Failure characterization	Notes
• Segmental box girder post-tensioned bridge. • External tendons consisting of 27 strands, embedded in high density polyethylene ducts, injected with a cementitious grout. • Spans of the bridge ranged about 50-125 m. • The ducts were injected with a grout mixed at the construction site with w/c 0.32 and the addition of a commercial admixture specific for grouts.	• Severe corrosion attacks in areas where the grout was segregating; mainly in the highest parts of external prestressing tendons, where a whitish unhardened paste was found. Such paste was characterized by an alkaline pH and a high content of sulphate ions. • Deep localized attacks that resembled the form of pitting attacks. • About 24% of the expected wires were missing. • No corrosion attacks were found in the areas where the strands were embedded in a regular hardened cement grout.	• Bridge cables failed after less than 2 years from the construction. • Segregation of the injected grout. • The alkaline grout contains a negligible amount of chlorides. Therefore, carbonation or chloride induced corrosion is unlikely. • Corrosion is possible in the presence of high pH and in the absence of oxygen, but it is unlikely that inside the ducts oxygen may completely be depleted. • Corrosion may hence be found in shielded areas and then can propagate. • The presence of the white grout was higher in the side opposite to that of injection, in the inclined parts of the tendons near the anchorages.
ID-19 Berlin Congress Hall. 1957 (built) - 21.05.1980 (roof failure)		
Location: Berlin, Germany	Reference: Helmerich and Zunkel (2014)	
Description	Failure characterization	Notes
• Double curved roof erected on only two bearings. • The whole structure was stabilized using an invisible circular reinforced concrete beam (ring beam) above the walls of the auditorium. • The roof consisted of: a prestressed inner roof with anchorage in the ring beam on top of the auditorium walls; a prestressed outer roof prestressing 24 concrete plates, 7 cm thick (2-4 tendons in each plate). • Each tendon was made of 7-10 prestressing wires.	• The external cantilever with the arch of the Southern roof structure collapsed suddenly • Numerous prestressing wires had failed: 8 tendons had failed completely, 2 tendons failed partly. • The majority of tendons were corroded to some extent in the failed location next to the final groove of the ring beam. • All investigated broken wires belonged to the outer roof only and were concentrated in the field of the groove in the circular ring beam in the south-east end of the failed roof cantilever.	• No early indications for failure initiation • The grouting of the tendon duct was insufficient or not even existent. • Some surfaces were covered with cauliflower-like corrosion products. • Causes of the collapse: structure planned and erected in only 1 year; non-transparent load path at the outer roof connection to the ring beam; poor execution quality;

Table A1. Case studies.

• The roof overhang up to 8 m. • A tensile (tie) member in the foundation level connected and tightened the east with the west abutments. • The tendons were designed to be in the axis of the plate with the same concrete cover of only 2.25 cm on both sides.	• The tendon duct was corroded and the broken wires showed heavy corrosion. • Hydrogen induced corrosion cracking of the tendons.	poor concrete quality; steel susceptible to stress corrosion cracking; environmental conditions; tendon bending near the anchorage caused a dense concentration of the wires in the lower part of the tendon, leading to reduced grouting between the wires and thus to too low passivation and reduced durability. • One of the insufficiencies alone would not have caused the failure.
ID-20 Florida Bridge. 2002 (built) - 2010 (tendon failure)		
Location: Florida, USA	Reference: Lau and Lasa (2016)	
Description	Failure characterization	Notes
• Segmental bridge with internal and external tendons. • Low bleed grout. • Anchor caps at low elevation.	• Severe corrosion in multiple external tendons, in wet plastic grout locations. • Deficient grout shows high moisture and free sulphate concentrations.	• At least 5 other bridges contained grout with some form of deficiency. • In high pH, sulphates may not be able to depassivate steel, but the early presence of sulphates may destabilize passive film growth. • High sulphate levels can occur even without external sulphate source.
ID-21 Annone Overpass. 1960-1962 (built) - 26.10.2016 (collapsed)		
Location: Lecco, Lombardy, Italy	Reference: Di Prisco et al. (2018)	
Description	Failure characterization	Notes
• RC deck slab on 5 precast prestressed beams. • The bridge is made of two lateral spans, supported by the abutments and the piers; and the central span, supported by the lateral spans through Gerber supports. • Not enough height below the bridge caused many collisions during the time.	• Severe shear crack at the Gerber joint. • The shear crack propagated in the collapsed joint favoured the oxidation of the reinforcement and significantly reduced the bearing capacity of the corbel in the time. It also produced a 25 mm settlement of that support. • The exceptional load crossing the bridge forced the reaction of the external dapped-end joint close to its ultimate load.	• Collapse due to overloading. • 1986: collision and subsequent repair. • 2006, 2009: collision + observed high level of oxidation. • Water seepage through the shear crack and observed concrete spalling. • Initial design mistake, but significant increase of the reinforcement in the joint. • The chloride content is not enough to directly cause corrosion but can speed up carbonation-induced corrosion.
ID-22 Bickton Meadows Footbridge. 1952 (built) - 1967 (collapsed)		
Location: Hampshire, UK	Reference: Poston and Wouters (1998), Wouters et al. (1999), Yoo et al. (2018)	
Description	Failure characterization	Notes
• Segmental construction with thin mortar joints. • Precast segments.	• Corrosion of the internal tendons lead to collapse. • Water with high chloride content infiltrated the tendons at the joints of the segments and caused corrosion in the steel strands.	• Mortar joints of poor quality: their high permeability allowed moisture, chlorides and oxygen ready access to the tendons. • Precast segments poorly constructed: they were cracked and honeycombed when delivered to the site to the extent that grout appeared at the surface of the segments during the grouting operation. • The bridge was overstressed.
ID-23 Melle Bridge. 1992 (collapsed)		
Location: Over River Schelde, Belgium	Reference: Tilly (2002), Wouters et al. (1999)	
Description	Failure characterization	Notes
• Non-balanced cantilevers having tie-downs.	• Corrosion of the post-tensioning system through a hinged joint lead to the collapse. • A petrol tanker collided with the bridge and caught fire before the collapse. • The vertical tie-down tendons were inadequately grouted and failed catastrophically.	• Voids were present in most of the ducts. • Tendons in the deck were generally free of corrosion even where they were exposed by the voids. Continued freedom from corrosion of the tendons is dependent on the ability of the concrete cover and waterproof membrane to prevent water and chlorides from getting into the ducts. • There have been cases when tendons have corroded despite the ducts being fully grouted (generally, ducts pre-formed in the concrete and without steel duct).
ID-24 Walnut Lane Bridge		
Location: Philadelphia, USA	Reference: Wouters et al. (1999)	
Description	Failure characterization	Notes
	• Improper grouting and detailing were blamed for corrosion problems.	
ID-25 Sixth South Street Viaduct		
Location: Salt Lake City, Utha, USA	Reference: Wouters et al. (1999)	
Description	Failure characterization	Notes
• The tendons were enclosed in a galvanized steel duct without the presence of grout (unbonded and unprotected).	• Corrosion distress of the post-tensioning system.	
ID-26 Niles Straits Crossing Bridge		
Location: Florida, USA	Reference: Tilly (2002)	
Description	Failure characterization	Notes
	• All of the 19 exposed strands have corroded and failed.	• A 3 m long void was found in one of the ducts at the anchorage plate.
ID-27 Braidley Road Bridge		
Location: Bournemouth, UK	Reference: Tilly (2002)	
Description	Failure characterization	Notes
• Externally post-tensioned bridge by with 19-wire strands protected by a proprietary paint and PVC coating and located within the concrete box.	• In some places the PVC coating had split longitudinally and leakage water had fallen onto the strands. • Some of the failures occurred in lightly corroded areas and others in bright and clean areas. • Stress-induced corrosion associated with incorrectly distributed stresses between individual wires is the most likely explanation.	• 4 fractured wires were detected during construction and others fractured ones during the following years. • 9 years after construction it was decided to replace all the tendons.

Table A1. Case studies.

ID-28 Wentbridge Viaduct		
Location: Yorkshire, UK	Reference: Tilly (2002)	
Description	Failure characterization	Notes
	• Leakage of water and chlorides through an inspection cover in the deck, fell onto the concrete and soaked through to the tendons causing corrosion.	• It would have been preferable to exclude the concrete encasement so that the leakage and corrosion could have been identified much earlier.
ID-29 Angel Road Viaduct. 1982 (maintenance activities) - 1993 (demolished and replaced)		
Location: Edmonthon, North London, UK	Reference: Tilly (2002)	
Description	Failure characterization	Notes
• A scheme for intermediate elastic supports was installed in 1982. • 10 spans, of which 7 were post-tensioned longitudinally to provide continuity and transversally to provide load distribution. • Prestressed rectangular beams were supported on half-joints at the ends of hammerhead cantilevers.	• Extensive corrosion of the post-tensioning tendons at the anchorages.	• A strengthening system was designed composed of steel frames fixed to the existing piers and providing elastic support to the half-joint.
ID-30 I-94 Bridge over US 81. 1958 (built) - 1992 (demolished)		
Location: Fargo, North Dakota, USA	Reference: Dickson et al. (1993)	
Description	Failure characterization	Notes
• Precast, post-tensioned concrete girder with 4 spans. • AASHTO Type II cross section with 3 post-tensioning tendons (I-beam). • The top tendon consisted of 16 6.4 mm diameter wires, while the two bottom tendons had 12 6.4 mm wires. • All post-tensioning tendons were grouted. • Mild reinforcing steel: 2 longitudinal bars in the top flange and shear stirrups.	• Cracks in the diaphragms. • Deteriorated concrete curbs. • Joints between stringers and above piers allow water and salt to leak down, causing concrete deterioration. • Evidence of surface corrosion on all the anchorages and bearing plates even through the anchorages were embedded in the concrete diaphragms.	• Evaluation of one beam after 34 years of service. • The subject girder was an interior girder with a composite cast-in-place concrete deck. • The bridge was subjected to large quantities of de-icing salts. • Low chloride levels in concrete and grout. • Possible infiltration of chlorides through the anchorages.
ID-31 Walnut Street Bridge. 1960 (built) - 1987 (demolished and replaced)		
Location: East Hartford, Connecticut, USA	Reference: Murray and Frantz (1992)	
Description	Failure characterization	Notes
• 16.5 m span simply supported multi-beam bridge. Made of 13 precast, prestressed concrete box beams. • A cast-in-place sidewalk covered the exterior beam and most of the first interior beam of each side. • Interior beams (AASHTO Type BI-36) were post-tensioned together laterally at mid span and at each end. • No horizontal bottom sections of stirrups were observed. • Longitudinal shear keys filled with grout joined the beams.	• Some of the beams were badly deteriorated with holes through the top flanges, crumbling concrete or exposed strands. • The remaining beams appeared in good conditions: no signs of severe corrosion were observed. From mid width in the top flanges only the outermost 13 mm of concrete had chloride concentrations above the corrosion threshold. • Stains on the sides of the beams indicated that water had been seeping through the grouted shear key joints between all beams.	• Chloride ion analyses were performed on 5 of the surviving prestressed concrete box beams. • The badly deteriorated beams were not available for testing. • Measured chloride levels can vary significantly from location to location in a structure.
ID-32 Harlem Avenue Bridge - Illinois Tollway. 1957-1958 (built) - 1982 (inspection)		
Location: Illinois, USA	Reference: Gustaferro et al. (1983)	
Description	Failure characterization	Notes
• Precast girders with 3 cross section types depending on the span length (generally I-beams). • Deflected strands with unbonded ends. • As many as 31 strands were deflected in some girders.	• A piece of the bottom flange of the southbound lane had loosened. • The strand at the bottom corner of the girder had corroded and broken. • There was indication that other pieces of concrete might be delaminating. • In some areas, rust stains have been seen on the webs of some of the girders and across the bottom of others. • Layers of salt on the sides of some of the girders. • Several stirrups were severely corroded. • Most of the corrosion was limited to the southmost girders on the bridge, which is a 5-span structure.	• The salt was originally applied as a de-icer for the bridge deck. The resulting brine solution then came through cracks and weep holes in the deck slab and flowed down along the sides of the girders. • The soluble chloride content was very high, about 20 times the threshold. • Many of the girders have suffered collision damage, and in few cases, some prestressing strands have been exposed. • The girder was replaced but the rest of the bridge suffered almost no damage.
ID-33 F.G. Gardiner Expressway. 1963-1964 (built) - 1980 (investigation)		
Location: Toronto, Canada	Reference: Tork (1985)	
Description	Failure characterization	Notes
• Simply supported, precast, prestressed concrete box beams supported on RC bents, covered by poured-in-place concrete topping and asphalt. • 46 spans of main roadway and 59 spans of approach ramps. • Most beams are pre-tensioned boxes with spans 18-22 m. • At two major road crossings the beams are post-tensioned boxes, spanning 27-30 m. • The beams are laterally keyed by continuous mortar keys and are lightly transversely prestressed by two strands at mid span and at quarter points. • 13 mm diameter seven-wire strand. • Pre-tensioned beams: straight strands in the bottom slabs and 4-5 draped strands in each wall. • Post-tensioned beams: 2 straight tendons in the bottom slab and 2 draped tendons in each wall, with 6- strands in each grouted tendon sheath of 60 mm diameter. • The concrete cover is 50 mm to the strand and 42 mm to the stirrups.	• Signs of gradually increasing surface deterioration: spalling of concrete; leakage at expansion joints; spalling, rust spots and cracks on beam soffits. • In both cases the prime cause for deterioration appears to be chloride penetration. • In some beams the water had leaked into the inside of the box beams. Such leakage is concentrated but not limited to the gutter areas. • The most serious aspect of deterioration in this structure is the rusting of prestressing strands at various locations at the beam soffits.	• Calcium chloride was not used in the concrete mix. • Most of the leakage occurs through transverse joints at gutters and at deck drains. • The deterioration of beam sides appears to be very limited so far.
ID-34 Botley Flyover. 1972 (built) - 1995 (monitoring)		
Location: Oxfordshire, UK	Reference: Woodward and Milne (2000)	
Description	Failure characterization	Notes
• Two structures that share a similar form of construction. • 3 span continuous overbridge, with spans of 12.7, 29 and 10.75 m. • Combination of in-situ and precast elements subsequently stressed together. • 8 external unbonded tendons consisting of 19 18 mm diameter strands run the full length of the 3 spans between anchorages positioned at the deck ends.	• Spots of corrosion started to develop on both the samples of wire and coupon exposed in the boxes fairly soon after installation.	• Only two of the end span cells have been inspected. • No evidence of water leakage. • A grease treated wrapping tape has been extensively used at the ends of the anchorage ducting presumably to seal the duct for grouting. • The bridge was in good condition and with fully functional waterproofing system. • Stressed strand samples are exposed within the box sections and weight loss coupons have been placed outside the structure.

Table A1. Case studies.

• The tendons are located within the deck voids and are deflected by deviators within the cross beams, diaphragms and intermediate web stiffeners. • Strands within each tendon are individually sheathed except at the anchorages where the tendons are enclosed in plastic ducting. • Corrosion protection is provided by a combination of grout (at the anchorages) and grease (at the web stiffeners).		
ID-35 River Camel Viaduct. July 1993 (opened to traffic) - 1995 (monitoring)		
Location: Wadebridge, Cornwall, UK		Reference: Woodward and Milne (2000)
Description	Failure characterization	Notes
• A single box beam bridge. • 9 spans (the outers being 37.5 and 42.5 m and the inner ones 54 m long). • In situ construction, built span-by-span. • Post-tensioned deck with tendons composed of 23-25 15.7 mm diameter strands inside 140 mm diameter HDPE ducts with a wall thickness of 8 mm. • The ducts are joined by heat shrink connection. • The strands, which were designed to be replaceable, protrude approximately 1.5 m at the live end anchorages. The protruding tendons are covered with an anchorage cap which is filled with a wax void filler.	• Spots of corrosion started to develop on both the samples of wires and concrete exposed in the boxes fairly soon after installation. • No evidence of pitting corrosion.	• The bridge was in good condition and with fully functional waterproofing system. • Stressed strand samples were exposed within the box sections and weight loss coupons have been placed outside the structure. • The environment within the box structure is more stable than that outside. • The corrosivity of the environment inside concrete box girder bridges is very low, less than that inside a bridge enclosure.
ID-36 Mandovi River Bridge. 1966 (built) - 1986 (collapsed)		
Location: Goa, India		Reference: Clark (2013)
Description	Failure characterization	Notes
	• Cracks were unattended for 6 years and corrosion of prestressed wires, which was noticed in 1983, was neglected until the bridge collapsed.	• The available workforce was probably not able to provide the required standard of workmanship to construct the bridge.
ID-37 Hammersmith Flyover. 1962 (built) - 2002 (maintenance)		
Location: London, UK		Reference: Clark (2013), Cousin et al. (2017)
Description	Failure characterization	Notes
• Precast segmental bridge, post-tensioned both internally and externally • 16 spans, 630 m long. • Heating system integrated into the carriageway to avoid de-icing salts, but in 1963 the necessity of de-icing salts arose. • The tendon anchors are immediately below the thin surfacing, and the tendons were simply cast into in-situ mortar boxes after stressing.	• The post-tensioning cables in ducts at the top slab over the piers could be suffering from chloride-induced corrosion. • 2 out of 8 tendons over one particular pillar were found to be badly corroded, despite being subject to inspection since 1993.	• Passive fibre-reinforced polymer strengthening or tendon replacement have been carried on. • Water ingress into the tendons caused substantial corrosion.
ID-38 A3/A31 Flyover. 1973-1976 (built) - 1978 (strengthened) - 1994 (signs of severe damage)		
Location: Guildford, Surrey, UK		Reference: Brooman and Robson (1996), Robson et al. (1997)
Description	Failure characterization	Notes
• Two span, single cell precast segmental, post-tensioned concrete superstructure supported on a reinforced central pillar and cellular wall abutments. • 240 19 mm diameter 19-wire external, plastic coated, grease filled strands contained within the void of the box. • A further 90 fully bonded strands are provided over the main pillar. • The spans are 50 m and 20 m long.	• October 1978: structural cracking of the abutment, intermediate diaphragms, the area next to the deflectors and the inner anchorage diaphragms. The cracking was attributed to a deficiency of reinforcement resisting the post-tensioning forces. • February 1994: two prestressing strands had failed, and individual wire failures were observed in other 121 strands. • The strand failures had occurred in the anchorage zone where the external strands had been grouted in ducts with epoxy grout. • Wire failure within the strands: some exhibited a characteristic spiral shape which was not being caused by wire failures, but by the original lay of the wires within the sheath.	• Stressing the cables during construction took place in two phases. • December 1974: 130 strands had been stressed. • January 1975: stop as a result of failure of 5 strands and a problem with the anchorage castings. • It is believed that all strands were left unprotected until phase two stressing was commenced (December 1975-February 1976). • 23 June 1994: the bridge was shut to all vehicles.
ID-39 Kure-tsubo Bridge. 1965 (built) - 1999 (demolished)		
Location:Japan		Reference: Tanaka et al. (2001)
Description	Failure characterization	Notes
• Post-tensioned concrete beams. • S3: third beam out of 6 beams in the third span, 39.34 m long, I-shaped. • S5: third beam out of 5 beams in the fifth span, 21.15 m long, T-shaped.	• Many tendons showed serious loss of cross sectional area. • Typical longitudinal cracks and spalling due to salt attack. • Loss of 12 tendon wires due to corrosion in a part of the web near the lower flange in the fifth span during in situ rough dissection. • No loss of tendon wires was found in the beam except for the parts where some tendons had been bent up, probably because concrete cover thickness for tendon of the part was the thinnest in the beam. • A very severe vertical inner crack was found in a cross section with bend-up of tendon in S3. The crack seemed to be caused by typical swelling of rust of some tendon wires near surface. The crack could have been aggravated by vertical load. • Light corrosion around anchorages.	• Two beams S3 and S5 for bending tests and dissection survey. • The beams have been repaired twice in 1980s and 1990s, due to corrosion of steel. • Some faults of grout were found near ends of bend-up ducts. • Two supposed penetration paths for the chlorides from exterior: from surface of filled concrete; through boundary between original concrete and filled concrete. The former route was predominant. • Remaining ratio of cross sectional area of tendon was only 21% at the failed section because of severe corrosion. • S3 failed in bending for tendon rupture. • S5 failed by concrete crushing (little tendon corrosion).
ID-40 Williamsburg Bridge. 1903 (opened to traffic)		
Location: Williams-burg, Virginia, USA		Reference: Eiselstein and Caliguri (1988)
Description	Failure characterization	Notes
• Four main support cables of 470mm diameter composed of high carbon steel wires spun together. • Each of the cables contain 7 696 six-gauge bright steel wires. • Cables covered with slushing oil, three layers of waterproofed cotton and then enclosed in sheet-iron covering.	• 1910: corrosion damage and 14 broken cables at the anchorage. • 1912: rust in the cable at the centre of the span. • 1915-1922: cable coated with oil and rewrapped with galvanized 8-wires. • 1934: water was found to run out of the cable strands in the anchorages, causing severe rusting. 320 broken or severely corroded wires were found at the anchorage. • 1934-1935: damaged strands replaced by splicing in new galvanized wire.	• Exposed to sulphates, marine air and fogs, de-icing salts. • No correlation could be made between the location of the pits on an individual wire and surface defects or flaws in the sheathing oil coating. • The size, depth and number of pits generally increased from the top of the cable to the bottom.

Table A1. Case studies.

	• 1980: significant amount of atmospheric corrosion. • 1982: wire samples evaluation. Corrosion and pitting damage. In some cases, the pits occupy 1/3 of the diameter of the cable.	
ID-41 Building slab over a parking area. 1972 (built) - 1982 (inspection)		
Location: USA	Reference: Schupack and Suarez (1982)	
Description	Failure characterization	Notes
• Slab post- tensioned in two directions with unbonded greased and paper wrapped 15 mm mono-strand tendons. • 70x100 m cast-in-place flat plate, 240 mm thick. • Each slab is used as a building platform over a parking area to support low-raise multiple dwellings (wooden framed).	• Heavy pitting and loss of metal where end anchorage pockets have been improperly filled or not filled at all. In this locations water was able to penetrate and accumulate inside the plastic sheathing.	• Some tendons failed about 40 days after stressing. • Additional sporadic failures continued to occur, more frequently over columns, in areas of high negative moments and where the geometry of the tendons resulted in the sharpest curvatures.
ID-42 Sewage Digesters. 1950 (built) - 1980 (inspection)		
Location: USA	Reference: Schupack and Suarez (1982)	
Description	Failure characterization	Notes
• 24 in. diameter and 10 m high structure. • Built with the wire wound system in which the wire is pulled through a die to induce the prestress.	• Ordinary corrosion and stress corrosion cracking, resulting from inadequate shotcrete protection caused by poor details. • Embrittlement corrosion.	• The corrosion of the wires was induced by leakage of sewage material. The material liberated hydrogen sulphide, which came through the pipe openings.
ID-43 Parking structure		
Location: USA	Reference: Schupack and Suarez (1982)	
Description	Failure characterization	Notes
• Cast-in-place, concrete slabs supported by a beam and columns steel frame. • Mono-strand tendons.	• Obvious protrusion of a strand about 5 m beyond the edge of the concrete slab, about 4 years after construction. • Some of the anchorage pocket mortar plugs appeared to have shrunk away and were loose.	• No particular corrosion was found on the strand, but high chloride content was detected (coming from de-icing salts). • The anchorage pocket was packed with a mortar which may or may not have contained calcium chloride.
ID-44 Roof of hotel structure		
Location: USA	Reference: Schupack and Suarez (1982)	
Description	Failure characterization	Notes
• Mono-strand 15 mm tendon greased and plastic sheathed. • The structure has been in service for about 5 years.	• Two failed tendons projecting about 1 m into an adjacent room. • Irregularly shaped patches of localized corrosion were observed on the wire surfaces both at and remote from the fractures.	• The failure occurred a short distance away from a vertical opening in the concrete slab through which the two tendons crossed. • It is possible that the plastic sheath may have been damaged at the contact point with the sides of the slab opening or with the reinforcement of a column adjacent to the opening.
ID-45 Bridge in Seoul. 1997 (opened to traffic) - 2006 (tendon failure)		
Location: Seoul, Republic of Korea	Reference: Yoo et al. (2018), Yoo et al. (2020)	
Description	Failure characterization	Notes
• Segmental concrete box girder bridge. • 8-spans continuous structure. • 4 internal tendons and 6 external tendons were installed on either side of the box girder (straight tendons). • The tendons were filled with grout. • 15-19 seven-wire steel strands per tendon.	• Failure of an external tendon above the third pillar. • Corrosion of the strands occurred when water infiltrated the external tendon via air vents. • Corrosion was detected in the strands of 4 out of 6 tendons in the section where the tendon failure had occurred.	• When the pavement was replaced, a waterproofing layer was damaged, making it easy for water and chlorides to infiltrate through the air vents. • Test results showed that the reduction in tensile strength was greater than the section loss.
ID-46 Bridge in Seoul. 1998 (opened to traffic) - 2006 (investigation)		
Location: Seoul, Republic of Korea	Reference: Yoo et al. (2020)	
Description	Failure characterization	Notes
• Double cell box girder bridge. • 8 external tendons with 27–wire strands. • The tendons were filled with cementitious grout.	• The failed wire was found near the bottom of a deviation block.	• The air vents were located inside the box girder, so chloride ions and water had not infiltrated from outside the bridge. • The sulphate content of the grout could be considered high.
ID-47 Vaux sur Seine Bridge. 1951 (built) - 1981 (maintenance)		
Location: France	Reference: Godart (2001)	
Description	Failure characterization	Notes
• Continuous bridge composed of 3 spans, made of two box beams. • For each box, the external prestressing consists of a belt of 4 tendons. • Each tendon is made of 30 wires with a diameter of 5 mm, coated by grease with strong consistency, to the image of what was done at the time for the cables of suspension bridges. • The tendons are anchored at their ends in massive crossbeams.	• Rupture by corrosion of some tendon wires inside the downstream box girder. In this location, permanent ventilation of the interior of the box girder had been suppressed by bird nests in the ventilation openings.	• Absence of cracking in the concrete. • Additional prestressing was applied.
ID-48 Villeneuve Saint-Georges Bridge. 1953 (built) - 1978/1979 (tendon failure)		
Location: Paris, France	Reference: Godart (2001)	
Description	Failure characterization	Notes
• 3 span bridge made of 3 box girders with variable height. • External prestressing consists of a total of 102 helicoid tendons made of 193 wires with 4.1 mm diameter. • The tendons are deviated using RC rocker bearing provided with cast steel hinges in order to have a practically uniform distribution of the compressive stresses in the concrete under loads. • The technology for anchoring the tendons is similar to that used for suspension bridges: cast steel sockets filled with an alloy of lead, antimony and tin. On the sockets, 4 threaded rods are fixed which are used for the prestressing by jacks. • Tendons are protected by just grease.	• Abnormal vibration of certain tendons was observed during the passage of heavy vehicles and some wires were broken.	• A favourable atmosphere for corrosion was prevailing within the box girders because the holes for inspection existing in the upper slab under the roadway were not tight. • In 1980 a doubtful tendon was replaced and all tendons were re-tensioned. The inspection holes were closed and new side accesses were bored in the webs of the boxes. Grease was then applied to re-protect the whole tendons.
ID-49 Can Bia Bridge. 1953 (built) - 1984 (demolished)		
Location: France	Reference: Godart (2001)	
Description	Failure characterization	Notes
• Only one span 61 m-long box beam bridge. • External prestressing made of 58 tendons of 12 wires with a 7 mm diameter. • 9 transverse diaphragms are used as deviators and some tendons are anchored in the upper slab.	• 1960: 30 wires were broken. • 1980: 56 wires were broken and a cracking developing in the transverse diaphragms and at the ends of the box girder was noticed.	• Tendons present at the same time traditional corrosion by dissolution and stress corrosion. • The most damaged tendons were those anchored in the upper slab. This was because the absence of a

Table A1. Case studies.

• All tendons are simply coated with a bitumen paint.		waterproofing layer made it possible for water to infiltrate by upper sealings. • The bitumen paint was only partial and did not surround each wire.
ID-50 Bridge over the Durance river. 1986 (built) - 1994 (tendon failure)		
Location: France	Reference: Godart (2001)	
Description	Failure characterization	Notes
• 6 spans, two parallel box girders bridge. • External prestressing made for each box consisted of 32 tendons (19 strands with a 15 mm diameter), located inside HPDE ducts grouted with cement.	• Rupture of a tendon inside the downstream box girder, broken right in front of its anchoring within the crossbeam on which it is anchored. • 21 wires presented strong corrosion by dissolution. • 88 wires presented a striction and had thus broken during the final rupture. • An opening of the 64 anchoring caps of the downstream box girder was operated, showing: traces of oxidation in 41% of the caps, traces of corrosion in 12% of the caps, 31% of the heads in satisfactory condition, 16% of the heads very corroded, 5% of them presented flows of oil or an oil-water mixture.	• The sheath was empty of grout and partially filled with water over a 2.5 m length in front of the anchoring plate. • The pH measured on the water collected in the anchoring caps was high. • 1996: the broken cable was replaced and the bridge was put under high monitoring. • 2000: replacement of all the tendons of the downstream box girder. • During the removal of tendons, it was noticed in the trumpets a whitish paste sometimes accompanied by moisture and corroded wires.
ID-51 Saint-Cloud Viaduct. 1974 (built) - 1979 (additional external prestressing) - 1998 (tendon failure)		
Location: Paris, France	Reference: Godart (2001)	
Description	Failure characterization	Notes
• Multicellular box girder bridge with 4 webs in the box girder. • Internal prestressing. • 1979: addition of external prestressing deviated in a vertical plane. • Tendon consisted of 12 strands with 15.2 mm diameter and was injected by a cement grout with admixture.	• One of the additional tendons which were in the Northern side cell broke in its middle. The rupture occurred in a section located between two deviators and near the lower slab, close to a hole of re-grouting. • The energy brutally released during the rupture made the tendon buckle at its ends and made one of the anchoring heads move back from approximately 1 m, whereas this head was not dismountable.	• The autopsy of the broken end of the tendon showed that there remained a pocket of grout having the consistency of a wet sandy paste without any coherence whose pH lays between 12 and 14. • Prestressing wires were sensitive to corrosion and a majority of them presented this type of cracking.
ID-52 Rivière d’Abord Bridge. 1991 (built)		
Location: France	Reference: Godart (2001)	
Description	Failure characterization	Notes
• 3 spans box girder bridge. • Dismountable external prestressing which is placed in metal tubes curved inside the crossbeams and deviators. • Tendon made of 19 strands with 15 mm diameter.	• Rupture of a tendon occurred at an anchoring located in the upper part of a segment over a pillar. • Much corrosion and some broken wires were detected. • Rupture process: loss of section per dissolution, retaking of the efforts by healthy wires, then sudden failure of healthy wires accompanied by striction.	• Autopsy showed the presence of much whitish paste on the surface of the tendon and in the indicated anchorage. • Conglomerates of healthy grout and whitish paste were also observed in some zones of the tendon. • Water was not observed, but the whitish products were sometimes wet.

Appendix B

The present appendix aims to provide an immediate understanding of the case studies characteristics by means of Table B1 and Table B2.

Table B1 reports a summary of the information included in Appendix A. For each case study the following characteristics have been reported:

- type of structure and prestressing;
- tendon and grouting description;
- characterization of corrosion products and causes;
- presence of warning signs;
- description of the failure mechanism and the associated damage.

In Table B2 key words have been assigned to each case study, according to the following categories:

- structure;
- tendon ducts;
- level of damage;
- failure location;
- failure causes;
- corrosion causes;
- warning signs.

Table B1. Summary of the most important specifics for each structure. Data deduced but not clearly stated in the literature papers have been indicated in red.

ID-1 Ynys-y-Gwas Bridge							
Age at failure: 32 years		Location: Wales, UK		Prestressing system: internal post-tension		Number of spans: 1	
Structure description	Tendon description	Warning signs	Grout condition	Source of corrosion	Corrosion products	Failure mechanism	Damage description
Simply supported segmental deck by 8 precast I-section beams.	12 5 mm diameter straight wires housed in a straight duct. Cardboard tubes around the tendons where they passed between the segments and the insertion of asbestos packing between the beams.	None.	Most longitudinal ducts were well grouted. Evidence of grout leakage at the longitudinal joints during construction.	Chlorides penetrating from the deck through the longitudinal joints between the beams. De-icing salts main source of chlorides.	Magnetite and reddish-brown oxides of iron	The I-beams collapsed as a single unit.	All the tendons examinated were corroded where they crossed the joints. In other placed they were corroded very little.
ID-2 S. Stefano Viaduct							
Age at failure: 45 years		Location: Sicily, Italy		Prestressing system: internal post-tension		Number of spans: 4	
Structure description	Tendon description	Warning signs	Grout condition	Source of corrosion	Corrosion products	Failure mechanism	Damage description
Simply supported segmental deck by 7 box beams.	6 tendons consituted by 18 5 mm diameter wires; 2 tendons consituted by 12 5 mm diameter wires.	None.	Complete lack of grout sealing for a significant length of tendons.	Holes of 40 mm diameter for prestressing tendons were made in situ by a concrete hammer drill. Inadequate protection of prestressing reinforcement.	-	Progressive failure begun by the beam on the seashore side.	Substantial reduction in the tendons cross section, just in correspondence of the parts where the sealing protection was absent/insufficient.
ID-3 Sorell Bridge							
Age at failure: 45 years		Location: Tasmania, Australia		Prestressing system: internal post-tension		Number of spans: 34	
Structure description	Tendon description	Warning signs	Grout condition	Source of corrosion	Corrosion products	Failure mechanism	Damage description
Simply supported deck by precast T-section beams, transversally connected.	2 parabolically-draped tendons made of 18 high-tensile 5 mm diameter wires, located in ducts formed using inflatable rubber tubes. This yielded to tendons housed in bare concrete.	1978: corrosion detected on the pillars and cross heads;1993: cracking along the web on one of the interior beams following the path of the post-tensioning tendons;2000: 51 beams showed the same crack pattern.	Calcium chloride added during construction.	Internal chlorides.	Some of the corrosion products were indicative of the involvement of bacterial activity in the corrosion process.	Demolished.	Strand corrosion: general and pitting corrosion; minimal rust staining despite substantial section loss; the strands had corroded more severely along the top and sides, with irregular semi-circular, concave corrosion profiles. Conventional reinforcement corrosion: generally in good condition; observed some areas of spalling and cracking of the concrete.
ID-4 Petrulla Viaduct							
Age at failure: about 30 years		Location: Sicily, Italy		Prestressing system: internal post-tension		Number of spans: 13	
Structure description	Tendon description	Warning signs	Grout condition	Source of corrosion	Corrosion products	Failure mechanism	Damage description
Simply supported deck made of 4 precast and prestressed concrete I-beams and 5 transverse beams.	5 tendons per beam realized by 12 0.6 in. diameter strands, positioned in a corrugated metal duct of 70 mm diameter.	Severe and characteristic crack pattern present in all the beams adjacent to the one that collapsed.	Inadequate grout composition (clear mortar and not Portland cement) and filling. Inadequate distance among the ducts employed.	The anchor region of some tendons is on the extrados. Inadequate waterproofing cover of the joints and insufficient concrete cover. Periodic water infiltrations that promoted chloride-induced corrosion.	-	Breakage of the tendons with subsequent loss of prestress. Increase in shear stress and consequent inward rotation of the lower flanges, hence forming of a plastic hinge in the mid-span of a bridge beam.	Diffused oxidation in the prestressing cables, severe corrosion of the metallic sheathing, accelerated by the large absence of the protective grout inside the cables.
ID-5 Fossano Bridge							
Age at failure: 24 years		Location: Piedmont, Italy		Prestressing system: internal post-tension		Number of spans: -	
Structure description	Tendon description	Warning signs	Grout condition	Source of corrosion	Corrosion products	Failure mechanism	Damage description
Simply supported deck, constituted by a multiple-box post-tensioned beam and by a casted in-situ slab.	8 parabolic cables.	-	The cables did not have sufficient grout protection in the collapsed joint area.	-	-	-	Causes of collapse unknown: hypothesis of tendon corrosion at the joints due to water infiltration and de-icing salts.
ID-6 Polcevera Bridge							
Age at failure: 51 years		Location: Ligury, Italy		Prestressing system: cable-stayed bridge, internal post-tensioned deck		Number of spans: 11	
Structure description	Tendon description	Warning signs	Grout condition	Source of corrosion	Corrosion products	Failure mechanism	Damage description
Cable-stayed concrete bridge, with a five sector box section.	4 cables per each balanced system. The cables were made of 24 permanent tendons for dead loads and 28 permanent tendons for live loads. The tendons were enclosed in a metallic protective membrane filled with grout.	1981: Morandi highlighted the inefficiency of the drainage system;1991-1992: most of the ducts did not have grout and the strands showed extensive corrosion, with some cables having loose strands. Severe oxidation of the metallic protective membrane.	Deficiency of grout in the tendon ducts.	Chlorides and sulphuric dioxide attacked the metal ducts and the tendons.	-	Rupture of the first cable-stay near the seaside, at the connection between the stay and the saddle top of tower 9, yielding to the collapse of the deck on the west side of the pylon and hence to the collapse of Tower 9 balanced system and two buffer beams. Combination of	Pitting corrosion.22% of strands with 50-60% of corrosion;78% of strands with 30-50% of corrosion.

Table B1. Summary of the most important specifics for each structure. Data deduced but not clearly stated in the literature papers have been indicated in red.

						fatigue and corrosion of the cables.	
ID-7 Mid-Bay Bridge							
Age at failure: 7 years		Location: Destin, Florida		Prestressing system: external post-tension		Number of spans: 141	
Structure description	Tendon description	Warning signs	Grout condition	Source of corrosion	Corrosion products	Failure mechanism	Damage description
Segmental precast box girders held together by 6 post-tensioning tendons (3 on each side).	Each tendon was constituted by 19 spirally wound 5/8 in. diameter 7-wire strands within a grouted 4 in. diameter polyethylene duct. The centre lengths of the tendons were draped downward from the anchorage through deviation blocks along the length of the span.	Cracking of the polyethylene ducts.	Grout voids, bleed water and soft chalky grout in the affected areas.	A variety of factors led to the failures of external tendons, including the penetration of salt water into the external tendons and the preponderance of grout voids.	Acid corrosion products.	Failure of individual wires primarily due to corrosion and subsequent elevated tensile stresses that resulted from the reduced cross section of the wires.	Tendon corrosion mostly along the inclines, associated with grout voids and bleed water.
ID-8 Carpineto Viaduct							
Age at failure: 44 years		Location: Basilicata, Italy		Prestressing system: cable-stayed bridge, internal post-tensioned deck		Number of spans: 3	
Structure description	Tendon description	Warning signs	Grout condition	Source of corrosion	Corrosion products	Failure mechanism	Damage description
Similar to Polcevera Bridge.	240 parallel tendons 0.5 in. diameter, protected by a concrete rectangular duct made of precast blocks. The ducts were post-tensioned by other 80 0.5 in. diameter tendons.	Concrete cover spalling.	-	Carbonation induced corrosion.	-	2013: adding of an external prestress system.	Mild general corrosion and a more severe one on some tendons. Prestress in tendons is reduced up to 20%.
ID-9 Lowe’s Motor Speedway							
Age at failure: 5 years		Location: North Carolina, USA		Prestressing system: pre-tensioned		Number of spans: 4	
Structure description	Tendon description	Warning signs	Grout condition	Source of corrosion	Corrosion products	Failure mechanism	Damage description
Simply supported, precast, double T-section beams located side by side. The beams are connected longitudinally by weald shear connectors along the flange.	Some strands were straight and some were harped to a low point at mid span, where a single hold-down was used. 22 1/2 in. diameter strands.	Longitudinal cracks along the stem soffit at mid span directly under the grout plug location. Corrosion staining around the grout plugs in several beams. No evidence of water seepage.	Calcium chloride grout used as concrete filler in the cavity left by the mandrel used to depressing the strands from above.	Grout chemical composition. Water infiltration at the hold-down location.	-	One span of the bridge collapsed with 107 people over it.	Rusted half-inch steel cables protruding from the broken concrete spans.3-foot cracks underneath three remaining spans. Severe corrosion in the form of pitting and loss of cross sectional area in all the beams limited to the hold-downs location.
ID-10 Luling Bridge							
Age at failure: 18 years		Location: Louisiana, USA		Prestressing system: steel deck, cable-stayed		Number of spans: 3	
Structure description	Tendon description	Warning signs	Grout condition	Source of corrosion	Corrosion products	Failure mechanism	Damage description
Cable-stayed bridge. Deck made of twin steel trapezoidal box girders.	6.35 mm diameter cold down stress relieved wires encased in a high-density polyethylene duct and injected with Portland cement grout. The stay-cables were arranged in two planes and grouped by pairs or fours.	1985: cracks in the sheathing. Subsequently filled with epoxy and wrapped with UV protection tape.1995: damage of the wrapping. Exposed and rusted wires, unplugged grout ports and extensive water leakage, cementitious grout efflorescence and rust at the deck level anchorage sockets.	Grout voids.	Water leakage.	-	Cable substitution.	Longitudinal and transverse split in the PE pipe; budges and holes in the PE pipe; tape damage; grout voids; delamination.
ID-11 Sunshine Skyway Bridge							
Age at failure: 13 years		Location: Florida, USA		Prestressing system: internal post-tension		Number of spans: 29	
Structure description	Tendon description	Warning signs	Grout condition	Source of corrosion	Corrosion products	Failure mechanism	Damage description
3 types of prestressed concrete structures: low level approaches, high level approaches and main span area. High level substructure: post-tensioned hollow elliptical column segments.	Vertical tendons in the columns housed in a 75 mm diameter smooth polyethylene duct (primary duct), externally located along the inner wall in the upper part of the column. In the thick wall region, in the bottom part, the primary duct was encased in the 127 mm diameter corrugated polyethylene secondary duct, cast inside the wall of the precast segment.	Cracks in numerous pillar caps. These cracks were very large and exhibited visible signs of water penetration and damage.	Possible grout deficiencies based on construction records. Grout voids detected in the trumpet areas. The primary and secondary ducts were not concentric. This condition eliminated the grout protection over a portion of the tendon.	Water with high chloride concentration infiltrated inside the columns through the pillar caps.	-	August 2000: severe tendon corrosion in column 133NB.11/17 strands in the SE tendon leg had failed in the external region, immediately below the column cap. The NE tendon leg exhibited minor surface as well as pitting corrosion, but no strand failures were observed. Both tendon legs had split polyethylene duct in the corroded region.	Water in the column interiors; segment joint leaks adjacent to the tendons; ungrouted tendons; severe splitting in the polyethylene ducts.
ID-12 Varina Enon Bridge							

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Age at failure: 17 years		Location: Virginia, USA		Prestressing system: external post-tensioning		Number of spans: 28	
Structure description	Tendon description	Warning signs	Grout condition	Source of corrosion	Corrosion products	Failure mechanism	Damage description
Cable-stayed bridge. Deck made of box girders constituted by precast segments.	External longitudinal post-tensioning made of 8 tendons grouted in ducts that run through the deviator blocks inside the box girders.	None.	Compromised alkalinity of the grout and presence of voids due to bleed water formation.	Compromised alkalinity of the grout and presence of voids.	-	3 years after the investigation one of the tendons was completely severed due to severe corrosion.	Tendon corrosion. Past routine investigations identified voids in the cables, which were subsequently filled with grout.
ID-13 Post-tensioned bridge in the Midwest							
Age at failure: 25 years		Location: Watson (Oklahoma, Louisiana, Texas), USA		Prestressing system: external post-tension		Number of spans: 25	
Structure description	Tendon description	Warning signs	Grout condition	Source of corrosion	Corrosion products	Failure mechanism	Damage description
3 boxes adjacent to each other.	Each tendon is made up of several spirally wound, 1/2-5/8 in. diameter 7-wire strands inside a grouted 4 in. diameter galvanized metal duct.	Efflorescence, small and large cracks, several spalled areas on the underside of the top slab.	Numerous small and some large voids in the grout surrounding the tendons in different parts of the structure.	Compromised alkalinity of the grout and presence of voids.	-	Moderate to high corrosion rate in the tendons.	Cracks on the riding deck; active cracks on the webs and diaphragms; corrosion-related damage on the underside of the riding surface; voids along the tendons.
ID-14 San Francisco – Oakland Bay Bridge							
Age at failure: immediately after construction		Location: California, USA		Prestressing system: internal post-tension		Number of spans: 14	
Structure description	Tendon description	Warning signs	Grout condition	Source of corrosion	Corrosion products	Failure mechanism	Damage description
Precast segmental box girder bridge.	Internal ducts were left ungrouted for up to 15-17 months during construction.	Rust coloured water discharged from ungrouted tendon ducts during routine cleaning operation.	Not grouted.	Rainwater from the deck entered the duct through improperly sealed grout tubes.	-	Strands with moderate corrosion and indication of hallow pitting. Transverse cracks and failures in some wires.	Cracking and/or moisture extrusion and signs of effervescence from the concrete at cracks in the walls.
ID-15 Ringling Causeway Bridge							
Age at failure: 8 years		Location: Florida, USA		Prestressing system: internal and external post-tension		Number of spans: 11	
Structure description	Tendon description	Warning signs	Grout condition	Source of corrosion	Corrosion products	Failure mechanism	Damage description
Segmental bridge with internal and external tendons. Deck made of 3 box girders.	12 tendons in each cross section. Each tendon contained 22 15 mm diameter 7-wire strands encased in a HDPE duct pressure-grouted with cementitious grout. The external tendons were draped with a linear transition between the high and low points of the tendon path.	None.	Deficient grout. In its most severe manifestation, it remained unhardened, soft and rich of sulphur ions.	Corrosion was the direct result of the segregation of the cementitious grout material.	-	2011: corrosion failure of two longitudinal external post-tensioning tendons, completely ruptured near the high-point deviators and lying on the bottom of the span.	13 other tendons had evidence of strand corrosion damage in the form of localized pitting, wire breaks or both.
ID-16 Long Key Bridge							
Age at failure: 3 years		Location: Florida, USA		Prestressing system: external post-tension		Number of spans: 103	
Structure description	Tendon description	Warning signs	Grout condition	Source of corrosion	Corrosion products	Failure mechanism	Damage description
Precast, concrete, segmental, box girder bridge with external post-tensioning. Substructure: precast concrete V-piers resting on laminated neoprene bearings atop water-level footings. Each footing rests on two drilled shafts.	All reinforced steel is epoxy coated.	Spalling of concrete.	-	The corrosion attack is the result of high chloride penetration in the splash zone and progressive corrosion under the epoxy coating of the reinforcing steel.	-	1986: spalling of concrete attributed to corrosion.	Cracks, concrete spalling.
ID-17 Niles Channel Bridge							
Age at failure: 16 years		Location: Florida, USA		Prestressing system: external post-tension		Number of spans: -	
Structure description	Tendon description	Warning signs	Grout condition	Source of corrosion	Corrosion products	Failure mechanism	Damage description
Precast segmental bridge.	External tendons arranged in a configuration such that the centre lengths of the tendons are draped downward from the anchorages through deviation blocks. along the length of the span. The anchorages are made of ductile cast iron anchors and forged steel wedge plates.	None.	Grout voids, bleed water and soft chalky grout in the affected areas. Lowered pH could develop at the interface between the grout and the void area by reaction with CO2 leaking in from the external atmosphere. Chloride concentration increases may occur there by penetration into the void area by salty runoff from the bridge surface.	Corrosion took place in the transition zone between grout and air space, while the metal completely embedded in grout remained in the passive condition.	-	Failed tendon at an expansion joint.	Corrosion mainly near anchorages, associated with deficient grout.
ID-18 Italian bridge							
Age at failure: 2 years		Location: Italy		Prestressing system: external post-tension		Number of spans: -	

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Structure description	Tendon description	Warning signs	Grout condition	Source of corrosion	Corrosion products	Failure mechanism	Damage description
Segmental box girder bridge.	27 strands encased in a high polyethylene duct, injected with a cementitious grout. The grout was mixed at construction site with w/c 0.32 and the addition of a commercial admixture specific for grouts.	None.	Whitish unhardened paste characterized by an alkaline pH and a high content of sulphate ions. The alkaline grout contains a negligible amount of chlorides. The presence of the white grout was higher in the direction opposite to that of injection, in the inclined parts of the tendons near the anchorages.	Corrosion is possible in the presence of high pH and in the absence of oxygen, but it is unlikely that inside the ducts oxygen may be completely depleted. Corrosion may hence be found in shielded areas and then can propagate.	-	Severe corrosion attacks in areas where the grout was segregating.	Deep localized attacks that resembled the form of pitting attacks.
ID-19 Berlin Congress Hall							
Age at failure: 23 years		Location: Germany		Prestressing system: internal post-tension		Number of spans: -	
Structure description	Tendon description	Warning signs	Grout condition	Source of corrosion	Corrosion products	Failure mechanism	Damage description
Double curved roof erected on only two bearings. The roof consisted of a prestressed inner roof with anchorage in the ring beam on top of the auditorium walls; a prestressed outer roof prestressing 24 concrete plates, 7 cm thick.	Each tendon was made of 7-10 prestressing wires, encased in metal ducts axially embedded in the plates (2-4 tendons per plate) with the same concrete cover of 2.25 cm on both sides.	None.	Insufficient or not even existent grout.	Poor design detailing and execution. Poor concrete quality. Steel susceptible to stress corrosion cracking. Environmental conditions.	Some surfaces were covered with cauliflower-like corrosion products.	The external cantilever with the arch of the Southern roof structure collapsed suddenly.	Numerous prestressing wires had failed (8 completely, 2 partly) due to hydrogen-induced corrosion. The tendon duct was corroded.
ID-20 Florida Bridge							
Age at failure: 8 years		Location: Florida, USA		Prestressing system: internal and external post-tension		Number of spans: -	
Structure description	Tendon description	Warning signs	Grout condition	Source of corrosion	Corrosion products	Failure mechanism	Damage description
Segmental bridge with internal and external tendons. Anchor caps at low elevation.	-	None.	Wet plastic grout, with high moisture and free sulphate concentrations.	In high pH, sulphates may not be able to depassivate steel, but the early presence of sulphates may destabilize passive film growth. High sulphate levels can occur even without external sulphate source.	-	Severe corrosion in multiple external tendons, in wet plastic grout locations.	-
ID-21 Annone Overpass							
Age at failure: 54 years		Location: Lombardy, Italy		Prestressing system: pre-tension		Number of spans: 3	
Structure description	Tendon description	Warning signs	Grout condition	Source of corrosion	Corrosion products	Failure mechanism	Damage description
RC deck slab on 5 precast prestressed beams. Not enough height below the bridge caused many collisions in the time.	-	Numerous collisions in the time and subsequent repairs. Observed high level of corrosion. Water seepage through the shear crack and observed concrete spalling.	-	The chloride content is not enough to directly cause corrosion, but can speed up carbonation-induced corrosion.	-	Collapse due to overloading.	Severe shear crack at the Gerber joint. The shear crack propagated in the collapsed joint favouring the oxidation of the reinforcement and significantly reducing the bearing capacity. It also produced a 25 mm settlement of the support.
ID-22 Bickton Meadows Footbridge							
Age at failure: 15 years		Location: Hampshire, UK		Prestressing system: internal post-tension		Number of spans: -	
Structure description	Tendon description	Warning signs	Grout condition	Source of corrosion	Corrosion products	Failure mechanism	Damage description
Segmental construction with thin mortar joints.	-	Precast segments poorly constructed: they were cracked and honeycombed when delivered to the site to the extent that grout appeared at the surface of the segments during the grouting operation.	-	Water with high chloride content infiltrated the tendons at the joints of the segments and caused corrosion in the steel strands.	-	Corrosion of the internal tendon lead to collapse.	Mortar joints of poor quality: their high permeability allowed moisture, chlorides and oxygen ready access to the tendons. The bridge was overstressed.
ID-23 Melle Bridge							
Age at failure: -		Location: Belgium		Prestressing system: internal post-tension		Number of spans: -	
Structure description	Tendon description	Warning signs	Grout condition	Source of corrosion	Corrosion products	Failure mechanism	Damage description
Non-balanced cantilevers having tie-downs.	Vertical tie-down tendons.	-	Voids were present in most of the ducts. The vertical tie-down tendons were inadequately grouted.	Corrosion of the post-tensioning system through a hinged joint.	-	Corrosion of the post-tensioning through formation of a hinged joint. A petrol tanker collided with the bridge and caught fire before the collapse.	Tendons in the deck were generally free of corrosion even where they were exposed by the voids.
ID-24 Walnut Lane Bridge							
Age at failure: -		Location: Philadelphia, USA		Prestressing system: internal post-tension		Number of spans: -	

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Structure description	Tendon description	Warning signs	Grout condition	Source of corrosion	Corrosion products	Failure mechanism	Damage description
-	-	-	Improper grouting and detailing.	Improper grouting and detailing.	-	Improper grouting and detailing was blamed for corrosion problems.	-
ID-25 Sixth South Street Viaduct							
Age at failure: -		Location: Utah, USA		Prestressing system: internal post-tension		Number of spans: -	
Structure description	Tendon description	Warning signs	Grout condition	Source of corrosion	Corrosion products	Failure mechanism	Damage description
-	Tendons in a galvanized steel duct without the presence of grout.	-	Not grouted.	Absence of grouting.	-	Corrosion damage of the post-tensioning system.	-
ID-26 Niles Straits Crossing Bridge							
Age at failure: -		Location: Florida, USA		Prestressing system: external post-tension		Number of spans: -	
Structure description	Tendon description	Warning signs	Grout condition	Source of corrosion	Corrosion products	Failure mechanism	Damage description
-	Strands encased in grouted ducts.	-	-	Presence of voids in the duct.	-	All of the 19 exposed strands have corroded and failed.	A 3 m long void was found in one of the ducts at the anchorage plate.
ID-27 Braidley Road Bridge							
Age at failure: 9 years		Location: Bournemouth, UK		Prestressing system: external post-tension		Number of spans: -	
Structure description	Tendon description	Warning signs	Grout condition	Source of corrosion	Corrosion products	Failure mechanism	Damage description
Concrete box girder bridge.	19-wire strands protected by a proprietary paint and a PVC coating. The tendons were located within the concrete box beam.	4 fractured wires during construction and others fractured during the following years.	-	Even if leakage water had fallen onto the strands, some of the failures occurred in lightly corroded areas and others in bright and clean areas. Hence, stress corrosion associated with incorrectly distributed stresses between individual wires is the most likely explanation.	-	Fractured wires, replaced 9 years after construction.	In some places the PVC coating had split longitudinally and leakage water had fallen onto the strands.
ID-28 Wentbridge Viaduct							
Age at failure: -		Location: Yorkshire, UK		Prestressing system: internal post-tension		Number of spans: -	
Structure description	Tendon description	Warning signs	Grout condition	Source of corrosion	Corrosion products	Failure mechanism	Damage description
-	Tendons encased in concrete.	None.	-	Leakage of water and chlorides through an inspection cover in the deck fell onto the concrete and soaked through to the tendons.	-	Water leakage and tendon corrosion.	-
ID-29 Angel Road Viaduct							
Age at failure: 11 years		Location: North London, UK		Prestressing system: internal post-tension		Number of spans: 10	
Structure description	Tendon description	Warning signs	Grout condition	Source of corrosion	Corrosion products	Failure mechanism	Damage description
Prestressed rectangular beams supported on half-joints at the ends of hammerhead cantilevers.	Longitudinal prestressing to provide continuity; transversal prestressing to provide load distribution.	Extensive corrosion of the post-tensioning tendons at the anchorages.	-	Problems with the anchorages.	-	Extensive corrosion of the post-tensioning tendons at the anchorages.	-
ID-30 I-94 Bridge over US 81							
Age at failure: 34 years		Location: North Dakota, USA		Prestressing system: internal post-tension		Number of spans: 4	
Structure description	Tendon description	Warning signs	Grout condition	Source of corrosion	Corrosion products	Failure mechanism	Damage description
Precast, concrete AASHTO Type II concrete girders (I-section beams).	3 post-tensioning tendons in each beam: the top tendon was made of 16 6.4 mm diameter wires, the two bottom tendons were made of 12 6.4 mm wires. All tendons were grouted.	Cracking diaphragms, deteriorating concrete curbs. Joints between stringers and above piers are allowing water and salt to leak down. Evidence of surface corrosion on all anchorages and bearing plates.	Low chloride levels in concrete and grout.	Possible infiltration of chlorides through the anchorages.	-	Demolished.	-
ID-31 Walnut Street Bridge							
Age at failure: 27 years		Location: Connecticut, USA		Prestressing system: internal post-tension		Number of spans: 1	
Structure description	Tendon description	Warning signs	Grout condition	Source of corrosion	Corrosion products	Failure mechanism	Damage description
Simply supported multi-beam bridge made of 13 AASHTO Type BI-36 concrete box beams. A cast-in-place sidewalk covered the exterior beam and most of the first interior beam of each side.	The beams were post-tensioned together laterally at mid span and at each end.	Stains on the sides of the beams indicated that water had been seeping through the grouted shear key joints between all beams.	-	Water seepage through the key joints.	-	Demolished.	Holes through the top flanges, crumbling concrete or exposed strands in the badly deteriorated beams. The remaining beams appeared in good conditions.
ID-32 Harlem Avenue Bridge - Illinois Tollway							
Age at failure: 24 years		Location: Illinois, USA		Prestressing system: pre-tension		Number of spans: 5	
Structure description	Tendon description	Warning signs	Grout condition	Source of corrosion	Corrosion products	Failure mechanism	Damage description
Girders with 3 cross section types depending on the	As many as 31 deflected strands	Many of the girders have suffered collision damage.	The soluble chloride content was very	The de-icing salt brine solution came through cracks and	-	A piece of the bottom flange of the	The strand at the bottom corner of the girder had corroded

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span (I-section beams).	with unbonded ends in each girder.	Rust stains on the web of some of the girders and across the bottom of others. Layers of salt on the sides of some of the girders.	high, about 20 times the threshold.	weep holes in the deck slab and flowed down along the sides of the girders.		southbound lane had loosened.	and broken. Delaminating concrete. Several stirrups were severely corroded.
ID-33 F.G. Gardiner Expressway							
Age at failure: 16 years		Location: Canada		Prestressing system: pre-tensioned and internal post-tensioned spans		Number of spans: 105	
Structure description	Tendon description	Warning signs	Grout condition	Source of corrosion	Corrosion products	Failure mechanism	Damage description
Simply supported precast concrete box beams. The beams were lightly transversely prestressed by two strands at mid span and at quarter points.	Pre-tensioned spans: straight strands in the bottom slabs and 5 draped strands in each wall. Post-tensioned spans: 2 straight tendons in the bottom slab and 2 draped tendons in each wall, with 6 strands in each grouted tendon sheath of 60 mm diameter. 13mm diameter 7-wire strands.	Spalling of concrete; leakage at expansion joints; spalling; rust spots and cracks on beam soffits.	Calcium chloride was not used in the concrete mix.	Chloride penetration. In some beams the water had leaked into the inside of the box through transverse joints at gutters and at deck drains.	-	Rusting of prestressing strands at various locations at the beam soffits.	-
ID-34 Botley Flyover							
Age at failure: 23 years		Location: Oxfordshire, UK		Prestressing system: internal post-tension		Number of spans: 3	
Structure description	Tendon description	Warning signs	Grout condition	Source of corrosion	Corrosion products	Failure mechanism	Damage description
Continuous overbridge made of a combination of in-situ and precast box elements subsequently stressed together.	8 external unbonded tendons consisting of 19 18 mm diameter strands run the full length of the 3 spans and are deflected by deviators. Strands within each tendon are individually sheathed except at the anchorages where the tendons are enclosed in plastic ducting. Combinations of grout (anchorages) and grease (web stiffeners) provide corrosion protection.	None.	In good condition with fully functional waterproofing system.	Environment corrosivity.	-	Spots of corrosion on both the samples located inside the boxes fairly soon after installation.	No evidence of water leakage. A grease treated wrapping tape had been extensively used at the ends of the anchorage ducting, presumably to seal the duct for grouting.
ID-35 River Camel Viaduct							
Age at failure: 2 years		Location: Cornwall, UK		Prestressing system: internal post-tension		Number of spans: 9	
Structure description	Tendon description	Warning signs	Grout condition	Source of corrosion	Corrosion products	Failure mechanism	Damage description
Single box beam bridge.	Tendons composed of 23-25 15.7mm diameter strands inside 140 mm diameter HDPE ducts with a wall thickness of 8 mm. The strands were designed to be replaced. The protruding tendons are covered with an anchorage cap filled with a wax void filler.	None.	In good condition with fully functional waterproofing system.	Environment corrosivity.	-	Spots of corrosion on both the samples located inside the boxes fairly soon after installation.	No evidence of pitting corrosion. The corrosivity of the environment inside the concrete box girders is very low, less than that inside a bridge enclosure.
ID-36 Mandovi River Bridge							
Age at failure: 20 years		Location: Goa, India		Prestressing system: internal post-tension		Number of spans: -	
Structure description	Tendon description	Warning signs	Grout condition	Source of corrosion	Corrosion products	Failure mechanism	Damage description
-	-	1983: cracks and corrosion of prestressing wires.	-	Poor execution.	-	Collapse.	Corrosion of prestressing wires.
ID-37 Hammersmith Flyover							
Age at failure: 40 years		Location: London, UK		Prestressing system: internal and external post-tension		Number of spans: 16	
Structure description	Tendon description	Warning signs	Grout condition	Source of corrosion	Corrosion products	Failure mechanism	Damage description
Precast segmental bridge, post-tensioned both internally and externally. Heating system integrated into the carriageway.	The tendon anchors are immediately below the thin concrete surface. The tendons were simply cast into in-situ mortar boxes after stressing.	None.	-	Water ingress into the tendons. Chloride-induced corrosion.	-	2 out of 8 tendons over one particular pillar were found to be badly corroded, despite being subject to inspection since 1993.	Passive fibre-reinforced polymer strengthening or tendon replacement have been carried on.
ID-38 A3/A31 Flyover							
Age at failure: 18 years		Location: Surrey, UK		Prestressing system: external post-tension		Number of spans: 2	
Structure description	Tendon description	Warning signs	Grout condition	Source of corrosion	Corrosion products	Failure mechanism	Damage description
Voided single cell precast segmental superstructure.	240 19 mm diameter 19-wire external, plastic coated, grease filled strands	Problem with the anchorage castings.	-	It is believed that all strands were left unprotected until	-	1978: structural cracking on the abutments, intermediate	1994: strand failure in the anchorage zone where the external strands had

Table B1. Summary of the most important specifics for each structure. Data deduced but not clearly stated in the literature papers have been indicated in red.

	contained within the void of the boxes. A further 90 fully bonded strands are provided over the main pillar.			phase two stressing was commenced.		diaphragms, the area next to the deflectors and the inner anchorage diaphragms. Deficiency of reinforcement and post-tensioning forces. 1994: two prestressing strands have failed, and individual wire failures were observed in other 121 strands.	been grouted in ducts with epoxy grout. Some wires exhibited a characteristic spiral shape which was not being caused by wire failures, but by the original lay of the wires within the sheath.
ID-39 Kure-tsubo Bridge.							
Age at failure: 34 years		Location: Japan		Prestressing system: internal post-tension		Number of spans: -	
Structure description	Tendon description	Warning signs	Grout condition	Source of corrosion	Corrosion products	Failure mechanism	Damage description
Only concrete beams: third span made of 6 I-section beams; fifth span made of 5 T-beams.	-	Longitudinal cracks and spalling due to salt attack. Steel corrosion in 1980s and 1990s.	Some faults of grout were found near ends of bend-up ducts.	Chloride-induced corrosion. Two possible penetration paths: from surface of filled concrete, through boundary between original concrete and filled concrete.	-	S3 failed in bending for tendon rupture: loss of 12 tendon wires in a part of the web near the lower flange. S5 failed by concrete crushing (with little tendon corrosion).	Loss of tendons only where they had been bend-up. A very severe vertical inner crack in a cross section with bend-up of tendon in S3. The crack seemed to be caused by swelling of rust of some tendon wires near surface. The crack would have been aggravated by vertical load. Light corrosion around anchorages.
ID-40 Williamsburg Bridge							
Age at failure: 79 years		Location: Virginia, USA		Prestressing system: suspension bridge		Number of spans: -	
Structure description	Tendon description	Warning signs	Grout condition	Source of corrosion	Corrosion products	Failure mechanism	Damage description
4 main support cables.	6-gauge bright steel wires spun into 470 mm diameter cables. Cables covered with slushing oil, three layers of waterproofed cotton and then enclosed in sheet-iron covering.	1915-1922: cable coated with oil and rewrapped with galvanized 8-wires.	-	Exposed to sulphates, marine air and fogs, de-icing salts. No correlation could be made between the location of the pits on an individual wire and surface defects or flaws in the sheathing oil coating.	-	1910: corrosion damage and 14 broken cables at the anchorage. 1912: rust in the cable at the centre of the span. 1934: water was found to run out of the cable strands in the anchorages.	1934: severe rusting. 320 broken or severely corroded wires in the anchorage. 1982: wire samples examination. Corrosion and pitting damage. The size, depth and number of pits generally increased from the top of the cable to the bottom.
ID-41 Building slab over a parking area							
Age at failure: 10 years		Location: USA		Prestressing system: internal post-tension		Number of spans: -	
Structure description	Tendon description	Warning signs	Grout condition	Source of corrosion	Corrosion products	Failure mechanism	Damage description
Post-tensioned in two directions, 70x100 m cast-in-place flat plate, 240 mm thick.	Unbonded greased and paper wrapped 15 mm mono-strand tendons.	Some tendons failed about 40 days after stressing and additional sporadic failures continued to occur, more frequently over columns, in areas of high negative moments and where the geometry of the tendons resulted in the sharpest curvatures.	Anchorage pockets improperly filled or not filled at all.	Water infiltration inside the plastic sheathing.	-	Heavy pitting and loss of metal at anchorage points.	-
ID-42 Sewage Digesters							
Age at failure: 30 years		Location: USA		Prestressing system: internal post-tension		Number of spans: -	
Structure description	Tendon description	Warning signs	Grout condition	Source of corrosion	Corrosion products	Failure mechanism	Damage description
24 in. diameter and 10 m high structure. Built with the wire wound system in which the wire is pulled through a die to induce the prestress.	-	-	Inadequate shotcrete protection.	Corrosion induced by leakage of sewage material, stress corrosion cracking and embrittlement corrosion.	-	Stress corrosion cracking.	-

Table B1. Summary of the most important specifics for each structure. Data deduced but not clearly stated in the literature papers have been indicated in red.

ID-43 Parking structure							
Age at failure: 4 years		Location: USA		Prestressing system: internal post-tension		Number of spans: -	
Structure description	Tendon description	Warning signs	Grout condition	Source of corrosion	Corrosion products	Failure mechanism	Damage description
Cast-in-place, concrete slabs supported by a beam and a column steel frame.	Mono-strand tendons.	-	The anchorage pocket was packed with a mortar which may or may not have contained calcium chloride.	High chloride content from de-icing salts.	-	Protrusion of a strand about 5 m beyond the edge of the concrete slab.	No particular corrosion on the strand. Some of the anchorage pocket mortar plugs appeared to have shrunk away and were loose.
ID-44 Roof of hotel structure							
Age at failure: 5 years		Location: USA		Prestressing system: internal post-tension		Number of spans: -	
Structure description	Tendon description	Warning signs	Grout condition	Source of corrosion	Corrosion products	Failure mechanism	Damage description
-	Mono-strand 15 mm tendon, greased and plastic sheathed.	-	-	It is possible that the plastic sheath may have been damaged at the contact point with the sides of the slab opening or with the reinforcement of a column adjacent to the opening.	-	Two failed tendons projecting about 1 m into and adjacent room.	Irregularly shaped patches of localized corrosion on the wire surfaces, both at and remote from the fractures.
ID-45 Bridge in Seoul							
Age at failure: 9 years		Location: Republic of Korea		Prestressing system: internal and external post-tension		Number of spans: 8	
Structure description	Tendon description	Warning signs	Grout condition	Source of corrosion	Corrosion products	Failure mechanism	Damage description
Segmental concrete continuous box girder bridge.	4 internal tendons and 6 external tendons were installed on either side of the box girder (straight tendons). The tendons were filled with grout. 15-19 7-wire steel strands per tendon.	-	-	When the pavement was replaced, a waterproofing layer was damaged and so water and chlorides infiltered the external tendons through the air vents.	-	Failure of an external tendon above the third pillar.	Corrosion was detected in the strands of 4 out of 6 tendons in the section where the tendon failure had occurred.
ID-46 Bridge in Seoul							
Age at failure: 8 years		Location: Republic of Korea		Prestressing system: external post-tension		Number of spans: -	
Structure description	Tendon description	Warning signs	Grout condition	Source of corrosion	Corrosion products	Failure mechanism	Damage description
Double cell box girder bridge.	8 external tendons with 27-wire strands. The tendons were filled with cement grout.	-	High sulphate content.	The air vents were located inside the box girder, so chloride ions and water had not infiltrated from outside the bridge.	-	A failed wire near the bottom of a deviation block.	-
ID-47 Vaux sur Seine Bridge							
Age at failure: 30 years		Location: France		Prestressing system: external post-tension		Number of spans: 3	
Structure description	Tendon description	Warning signs	Grout condition	Source of corrosion	Corrosion products	Failure mechanism	Damage description
Two box beam continuous bridge.	Each tendon is made of 30 wires with 5 mm diameter, coated by grease with strong consistency.	None.	-	Permanent ventilation of the interior of the box girder had been suppressed by bird nests in the ventilation openings, allowing moisture to cumulate inside the box girder.	-	Rupture of some tendon wires inside the downstream box girder.	Absence of cracking in the concrete.
ID-48 Villeneuve Saint-Georges Bridge							
Age at failure: 26 years		Location: France		Prestressing system: external post-tension		Number of spans: 3	
Structure description	Tendon description	Warning signs	Grout condition	Source of corrosion	Corrosion products	Failure mechanism	Damage description
Three box girders bridge.	102 helicoid tendons made of 193 wires with 4.1 mm diameter. The tendons are just protected by grease.	Abnormal vibration of certain tendons was observed during the passage of heavy vehicles.	-	Holes for inspection existing in the upper slab under the roadway were not tight.	-	Some wires were broken.	-
ID-49 Can Bia Bridge							
Age at failure: 31 years		Location: France		Prestressing system: external post-tension		Number of spans: 1	
Structure description	Tendon description	Warning signs	Grout condition	Source of corrosion	Corrosion products	Failure mechanism	Damage description
Box beam bridge, with 9 transverse diaphragms used as deviators.	58 tendons made of 12 wires with 7 mm diameter, simply coated with a bitumen paint.	1960: 30 wires were broken.	-	Absence of waterproofing layer made it possible for water to infiltrate by upper sealings.	-	56 wires were broken.	Cracking developing in the transverse diaphragms and at the ends of the box girder.
ID-50 Bridge over the Durance river							
Age at failure: 8 years		Location: France		Prestressing system: external post-tension		Number of spans: 6	
Structure description	Tendon description	Warning signs	Grout condition	Source of corrosion	Corrosion products	Failure mechanism	Damage description
Two parallel box girders bridge.	32 tendons made of 19 strands with 15 mm diameter, located inside HDPE ducts grouted with cement.	None.	High pH. Whitish paste sometimes accompanied by moisture and corroded wires.	The sheath was empty of grout and partially filled with water over a length of 2.5 m in front of the anchoring plate.	-	Rupture of a tendon, broken right in front of its anchoring.	21 wires presented a strong corrosion by dissolution. 88 wires presented a striction and had thus broken during the final rupture.

Table B1. Summary of the most important specifics for each structure. Data deduced but not clearly stated in the literature papers have been indicated in red.

ID-51 Saint-Cloud Viaduct							
Age at failure: 19 years		Location: France		Prestressing system: external post-tension		Number of spans: -	
Structure description	Tendon description	Warning signs	Grout condition	Source of corrosion	Corrosion products	Failure mechanism	Damage description
Multicellular box girder with 4 webs bridge.	Tendons made of 12 strands with 15.2 mm diameter, injected by a cement grout with admixture.	None.	Grout having the consistency of a wet sandy paste without any coherence whose pH lays between 12 and 14.	Grouting.	-	One of the tendons broke in its middle, in a section located between two deviators and near the lower slab, close to a hole of re-grouting.	-
ID-52 Rivière d'Abord Bridge							
Age at failure: -		Location: France		Prestressing system: external post-tension		Number of spans: 3	
Structure description	Tendon description	Warning signs	Grout condition	Source of corrosion	Corrosion products	Failure mechanism	Damage description
Box girder bridge.	External prestressing placed in metal tubes curved inside the crossbeams and deviators. Tendon made of 19 strands with 15 mm diameter.	None.	Wet whitish paste on the surface of the tendon and in the anchorage; conglomerates of healthy grout and whitish paste in some zones of the tendon.	Grouting.	-	Rupture of a tendon occurred at an anchoring located in the upper part of a segment over a pillar.	-

Table B2. Keywords describing the case studies.

ID-1 Ynys-y-Gwas Bridge

Structure	Prestressing system	Tendon ducts	Level of damage	Failure location	Failure causes	Corrosion causes	Warning signs
Segmental bridge, I-section beams.	Internal post-tension.	Straight tendons in smooth grouted ducts. Cardboard ducts at the joints.	Collapsed.	Joint.	Conceptual design mistakes.	External chlorides (road salt).	No.

ID-2 S. Stefano Viaduct

Structure	Prestressing system	Tendon ducts	Level of damage	Failure location	Failure causes	Corrosion causes	Warning signs
Segmental bridge, box beams.	Internal post-tension.	Grouted ducts in holes hammer drilled on site.	Collapsed.	Outer beam's middle span.	Too low concrete cover, execution, conceptual design mistakes.	External chlorides (air-form sea water).	No.

ID-3 Sorell Bridge

Structure	Prestressing system	Tendon ducts	Level of damage	Failure location	Failure causes	Corrosion causes	Warning signs
T-section beams.	Internal post-tension.	Ducts formed using inflatable rubber tubes: tendons encased in concrete.	Demolished.	Beams' web.	Conceptual design mistakes, inappropriate materials, too low concrete cover.	Internal chlorides, external chlorides (liquid sea water).	Yes.

ID-4 Petrulla Viaduct

Structure	Prestressing system	Tendon ducts	Level of damage	Failure location	Failure causes	Corrosion causes	Warning signs
I-section beams.	Internal post-tension.	Corrugated metal duct.	Collapsed.	Beam mid span cross section.	Inappropriate materials, execution, conceptual design mistakes.	External chlorides (road salt).	Yes.

ID-5 Fossano Bridge

Structure	Prestressing system	Tendon ducts	Level of damage	Failure location	Failure causes	Corrosion causes	Warning signs
Box beams.	Internal post-tension.	-	Collapsed.	Joints.	Execution.	-	-

ID-6 Polcevera Bridge

Structure	Prestressing system	Tendon ducts	Level of damage	Failure location	Failure causes	Corrosion causes	Warning signs
Innovative structure, cable-stayed.	Cable-stayed.	Metallic protective membrane filled with grout.	Collapsed.	Cable-stays.	Execution, fatigue.	External chlorides (air-form sea water), external sulphates.	Yes.

ID-7 Mid-Bay Bridge

Structure	Prestressing system	Tendon ducts	Level of damage	Failure location	Failure causes	Corrosion causes	Warning signs
Segmental bridge, box beams.	External post-tension, internal post-tension.	Spirally wound strands in grouted polyethylene ducts.	Tendon failure.	External tendons.	Grouting.	External chlorides (road salt), grouting.	Yes.

ID-8 Carpineto Viaduct

Structure	Prestressing system	Tendon ducts	Level of damage	Failure location	Failure causes	Corrosion causes	Warning signs
Innovative structure, cable-stayed.	Cable stayed.	Concrete, post-tensioned, rectangular duct made of precast blocks.	Maintenance.	Cable-stays.	Cracks, fatigue.	Carbonation.	Yes.

ID-9 Lowe’s Motor Speedway

Structure	Prestressing system	Tendon ducts	Level of damage	Failure location	Failure causes	Corrosion causes	Warning signs
Double T-section beams.	Pre-tension.	-	Collapsed.	One span at the hold-down positions.	Conceptual design mistakes, inappropriate materials.	Internal chlorides, external chlorides (road salt).	Yes.

ID-10 Luling Bridge

Structure	Prestressing system	Tendon ducts	Level of damage	Failure location	Failure causes	Corrosion causes	Warning signs
Steel deck, cable-stayed.	Cable-stayed.	HDPE ducts filled with Portland cement grout.	Tendon failure.	Cable-stays.	Execution, inappropriate materials, cracks.	External chlorides (air-form sea water).	Yes.

ID-11 Sunshine Skyway Bridge

Structure	Prestressing system	Tendon ducts	Level of damage	Failure location	Failure causes	Corrosion causes	Warning signs
Innovative structure.	External post-tension.	Primary smooth PT duct and secondary corrugated PT duct.	Tendon failure.	Pillars.	Execution, cracks.	External chlorides (liquid sea water).	Yes.

ID-12 Varina Enon Bridge

Structure	Prestressing system	Tendon ducts	Level of damage	Failure location	Failure causes	Corrosion causes	Warning signs
Segmental bridge, cable-stayed.	External post-tension, internal post-tension.	Grouted ducts.	Tendon failure.	External tendons.	Grouting.	Grouting.	No.

ID-13 Post-tensioned bridge in the Midwest

Structure	Prestressing system	Tendon ducts	Level of damage	Failure location	Failure causes	Corrosion causes	Warning signs
Box beams.	External post-tension, internal post-tension.	Spirally wound strands inside a grouted galvanized metal duct.	Maintenance.	External tendons.	Grouting, cracks.	Grouting.	Yes.

ID-14 San Francisco – Oakland Bay Bridge

Structure	Prestressing system	Tendon ducts	Level of damage	Failure location	Failure causes	Corrosion causes	Warning signs
Segmental bridge, box beams.	Internal post-tension.	Ungrouted internal ducts.	Maintenance.	Internal tendons.	Execution.	External chlorides (liquid sea water).	Yes.

ID-15 Ringling Causeway Bridge

Structure	Prestressing system	Tendon ducts	Level of damage	Failure location	Failure causes	Corrosion causes	Warning signs
Segmental bridge, box beams.	External post-tension, internal post-tension.	HDPE duct pressure-grouted with cementitious grout.	Tendon failure.	External tendons at high point deviators.	Grouting.	Grouting.	No.

ID-16 Long Key Bridge

Structure	Prestressing system	Tendon ducts	Level of damage	Failure location	Failure causes	Corrosion causes	Warning signs
Segmental bridge, box beams.	External post-tension, internal post-tension.	Epoxy coated steel.	Maintenance.	RC pillars.	Cracks.	External chlorides (liquid sea water).	Yes.

Table B2. Keywords describing the case studies.

ID-17 Niles Channel Bridge							
Structure	Prestressing system	Tendon ducts	Level of damage	Failure location	Failure causes	Corrosion causes	Warning signs
Segmental bridge.	External post-tension, internal post-tension.	-	Tendon failure.	External tendons.	Grouting.	Grouting.	No.
ID-18 Italian bridge							
Structure	Prestressing system	Tendon ducts	Level of damage	Failure location	Failure causes	Corrosion causes	Warning signs
Segmental bridge, box beams.	External post-tension, internal post-tension.	HDPE ducts filled with cementitious grout with w/c 0.32 and commercial addition specific for grout.	Tendon failure.	External tendons	Grouting	Grouting.	No.
ID-19 Berlin Congress Hall							
Structure	Prestressing system	Tendon ducts	Level of damage	Failure location	Failure causes	Corrosion causes	Warning signs
Innovative structure.	Internal post-tension.	Metal ducts.	Collapsed.	Roof.	Execution, inappropriate materials, conceptual design mistakes, too low concrete cover.	Carbonation.	No.
ID-20 Florida Bridge							
Structure	Prestressing system	Tendon ducts	Level of damage	Failure location	Failure causes	Corrosion causes	Warning signs
Segmental bridge.	External post-tension, pre-tension, internal post-tension.	-	Tendon failure.	External tendons.	Grouting.	Grouting.	No.
ID-21 Annone Overpass							
Structure	Prestressing system	Tendon ducts	Level of damage	Failure location	Failure causes	Corrosion causes	Warning signs
-	Pre-tension.	-	Collapsed.	Joints.	Conceptual design mistakes, accident, overloading.	External chlorides (road salt).	Yes.
ID-22 Bickton Meadows Footbridge							
Structure	Prestressing system	Tendon ducts	Level of damage	Failure location	Failure causes	Corrosion causes	Warning signs
Segmental bridge.	Internal post-tension.	-	Collapsed.	Joints.	Execution, cracks.	External chlorides (road salt).	Yes.
ID-23 Melle Bridge							
Structure	Prestressing system	Tendon ducts	Level of damage	Failure location	Failure causes	Corrosion causes	Warning signs
Innovative structure.	Internal post-tension.	-	Collapsed.	Joints.	Execution, exposed to accident.	External chlorides (road salt).	-
ID-24 Walnut Lane Bridge							
Structure	Prestressing system	Tendon ducts	Level of damage	Failure location	Failure causes	Corrosion causes	Warning signs
-	Internal post-tension.	-	Maintenance.	-	Execution, conceptual design mistakes.	-	-
ID-25 Sixth South Street Viaduct							
Structure	Prestressing system	Tendon ducts	Level of damage	Failure location	Failure causes	Corrosion causes	Warning signs
-	Internal post-tension.	Tendons in a galvanized steel duct without the presence of grout.	Maintenance.	-	Conceptual design mistakes.	-	-
ID-26 Niles Straits Crossing Bridge							
Structure	Prestressing system	Tendon ducts	Level of damage	Failure location	Failure causes	Corrosion causes	Warning signs
-	External post-tension, internal post-tension.	Strands encased in grouted ducts.	Tendon failure.	-	Execution.	-	-
ID-27 Braidley Road Bridge							
Structure	Prestressing system	Tendon ducts	Level of damage	Failure location	Failure causes	Corrosion causes	Warning signs
Box beams.	External post-tension, internal post-tension.	Tendons protected by a proprietary paint and a PVC coating, located within the concrete box beam.	Maintenance.	External tendons.	Structural deficiencies, conceptual design mistakes.	External chlorides (road salt).	Yes.
ID-28 Wentbridge Viaduct							
Structure	Prestressing system	Tendon ducts	Level of damage	Failure location	Failure causes	Corrosion causes	Warning signs
-	Internal post-tension.	Tendons encased in concrete.	Maintenance.	Superstructure.	Conceptual design mistakes.	External chlorides (road salt).	No.
ID-29 Angel Road Viaduct							
Structure	Prestressing system	Tendon ducts	Level of damage	Failure location	Failure causes	Corrosion causes	Warning signs
Box beams.	Internal post-tension.	-	Demolished.	Anchorages.	Execution.	External chlorides (road salt).	Yes.
ID-30 I-94 Bridge over US 81							
Structure	Prestressing system	Tendon ducts	Level of damage	Failure location	Failure causes	Corrosion causes	Warning signs
I-section beams.	Internal post-tension.	All tendons are grouted.	Demolished.	Superstructure.	Execution.	External chlorides (road salt).	Yes.
ID-31 Walnut Street Bridge							
Structure	Prestressing system	Tendon ducts	Level of damage	Failure location	Failure causes	Corrosion causes	Warning signs
Box beams.	Internal post-tension.	-	Demolished.	Joints.	Execution.	External chlorides (road salt).	Yes.
ID-32 Harlem Avenue Bridge - Illinois Tollway							
Structure	Prestressing system	Tendon ducts	Level of damage	Failure location	Failure causes	Corrosion causes	Warning signs
I-section beams.	Pre-tension.	Strands with unbonded ends.	Maintenance.	Beam bottom flange.	Exposed to accident, cracks.	External chlorides (road salt).	Yes.
ID-33 F.G. Gardiner Expressway							
Structure	Prestressing system	Tendon ducts	Level of damage	Failure location	Failure causes	Corrosion causes	Warning signs
Box beams.	Internal post-tension, pre-tension.	Grouted post-tensioning tendons.	Maintenance.	Beam soffits.	Conceptual design mistakes.	External chlorides (road salt).	Yes.

Table B2. Keywords describing the case studies.

ID-34 Botley Flyover							
Structure	Prestressing system	Tendon ducts	Level of damage	Failure location	Failure causes	Corrosion causes	Warning signs
Segmental bridge, box beams.	Internal post-tension.	Strands within each tendon are individually sheathed except at the anchorages where the tendons are enclosed in plastic ducting. Combinations of grout (anchorages) and grease (web stiffeners) provide corrosion protection.	Maintenance.	Samples.	-	External chlorides (air-form wea water).	No.

ID-35 River Camel Viaduct							
Structure	Prestressing system	Tendon ducts	Level of damage	Failure location	Failure causes	Corrosion causes	Warning signs
Box beams.	Internal post-tension.	HDPE ducts.	Maintenance.	Samples.	-	External chlorides: (air-form sea water).	No.

ID-36 Mandovi River Bridge							
Structure	Prestressing system	Tendon ducts	Level of damage	Failure location	Failure causes	Corrosion causes	Warning signs
	Internal post-tension.		Collapsed.		Execution.		Yes.

ID-37 Hammersmith Flyover							
Structure	Prestressing system	Tendon ducts	Level of damage	Failure location	Failure causes	Corrosion causes	Warning signs
Segmental bridge.	External post-tension, internal post-tension.	The tendons were simply cast into in-situ mortar boxes after stressing.	Maintenance.	Tendons over a pillar.	Conceptual design mistakes.	External chlorides (road salt).	No.

ID-38 A3/A31 Flyover							
Structure	Prestressing system	Tendon ducts	Level of damage	Failure location	Failure causes	Corrosion causes	Warning signs
Segmental bridge, box beams.	External post-tension, internal post-tension.	Plastic coated, grease filled strands contained within the void of the boxes.	Tendon failure.	Superstructure.	Execution, structural deficiency.	External chlorides (road salt).	Yes.

ID-39 Kure-tsubo Bridge.							
Structure	Prestressing system	Tendon ducts	Level of damage	Failure location	Failure causes	Corrosion causes	Warning signs
I-section beams, T-section beams.	Internal post-tension.	Bend-up tendons at anchorages.	Demolished.	Mid span tested beams.	Execution, conceptual design mistakes.	External chlorides (road salt).	Yes.

ID-40 Williamsburg Bridge							
Structure	Prestressing system	Tendon ducts	Level of damage	Failure location	Failure causes	Corrosion causes	Warning signs
Suspension bridge.	Suspension tendons.	Cables covered with slushing oil, three layers of waterproofed cotton and then enclosed in sheet-iron covering.	Maintenance.	Anchorages.	Execution, conceptual design mistakes.	External chlorides (road salt, air-form sea water), external sulphates.	Yes.

ID-41 Building slab over a parking area							
Structure	Prestressing system	Tendon ducts	Level of damage	Failure location	Failure causes	Corrosion causes	Warning signs
Parking slab.	Internal post-tension.	Unbonded greased and paper wrapped mono-strand tendons.	Maintenance.	Anchorages.	Execution, conceptual design mistakes.	External chlorides (road salt).	Yes.

ID-42 Sewage Digesters							
Structure	Prestressing system	Tendon ducts	Level of damage	Failure location	Failure causes	Corrosion causes	Warning signs
Cylindrical container.	Internal post-tension.	-	Maintenance.	Pipes.	Execution.	External sulphates.	-

ID-43 Parking structure							
Structure	Prestressing system	Tendon ducts	Level of damage	Failure location	Failure causes	Corrosion causes	Warning signs
Parking slab.	Internal post-tension.	Mono-strand tendons.	Tendon failure.	Slab.	Inappropriate materials, conceptual design mistakes.	External chlorides (road salt).	-

ID-44 Roof of hotel structure							
Structure	Prestressing system	Tendon ducts	Level of damage	Failure location	Failure causes	Corrosion causes	Warning signs
Roof.	Internal post-tension.	Mono-strand 15 mm tendon, greased and plastic sheathed.	Tendon failure.	Slab.	Conceptual design mistakes.	Carbonation.	-

ID-45 Bridge in Seoul							
Structure	Prestressing system	Tendon ducts	Level of damage	Failure location	Failure causes	Corrosion causes	Warning signs
Segmental bridge, box beams.	External post-tension, internal post-tension.	The ducts were filled with grout.	Tendon failure.	External tendons.	Conceptual design mistakes, execution.	External chlorides (road salt).	-

ID-46 Bridge in Seoul							
Structure	Prestressing system	Tendon ducts	Level of damage	Failure location	Failure causes	Corrosion causes	Warning signs
Box beams.	External post-tension, internal post-tension.	The ducts were filled with cementitious grout.	Tendon failure.	External tendons.	Grouting.	Grouting.	-

ID-47 Vaux sur Seine Bridge							
Structure	Prestressing system	Tendon ducts	Level of damage	Failure location	Failure causes	Corrosion causes	Warning signs
Box beams.	External post-tension, internal post-tension.	The ducts were filled with grease with strong consistency.	Maintenance.	External tendons.	-	External chlorides (air-form sea water).	-

ID-48 Villeneuve Saint-Georges Bridge							
Structure	Prestressing system	Tendon ducts	Level of damage	Failure location	Failure causes	Corrosion causes	Warning signs
Box beams.	External post-tension, internal post-tension.	The ducts were filled with grease.	Tendon failure.	External tendons.	Conceptual design mistakes, execution.	External chlorides (air-form sea water).	Yes.

Table B2. Keywords describing the case studies.

ID-49 Can Bia Bridge							
Structure	Prestressing system	Tendon ducts	Level of damage	Failure location	Failure causes	Corrosion causes	Warning signs
Box beams.	External post-tension, internal post-tension.	Tendons coated with bitumen paint.	Demolished.	External tendons.	Conceptual design mistakes.	External chlorides (road salt).	Yes.
ID-50 Bridge over the Durance river							
Structure	Prestressing system	Tendon ducts	Level of damage	Failure location	Failure causes	Corrosion causes	Warning signs
Box beams.	External post-tension, internal post-tension.	HDPE ducts filled with cement.	Tendon failure.	External tendons.	Grouting.	Grouting.	No.
ID-51 Saint-Cloud Viaduct							
Structure	Prestressing system	Tendon ducts	Level of damage	Failure location	Failure causes	Corrosion causes	Warning signs
Box beams.	External post-tension, internal post-tension.	Cement grout with admixture.	Tendon failure.	External tendons.	Grouting.	Grouting.	No.
ID-52 Rivière d’Abord Bridge							
Structure	Prestressing system	Tendon ducts	Level of damage	Failure location	Failure causes	Corrosion causes	Warning signs
Box beams.	External post-tension, internal post-tension.	Metal ducts.	Tendon failure.	External tendons.	Grouting.	Grouting.	No.

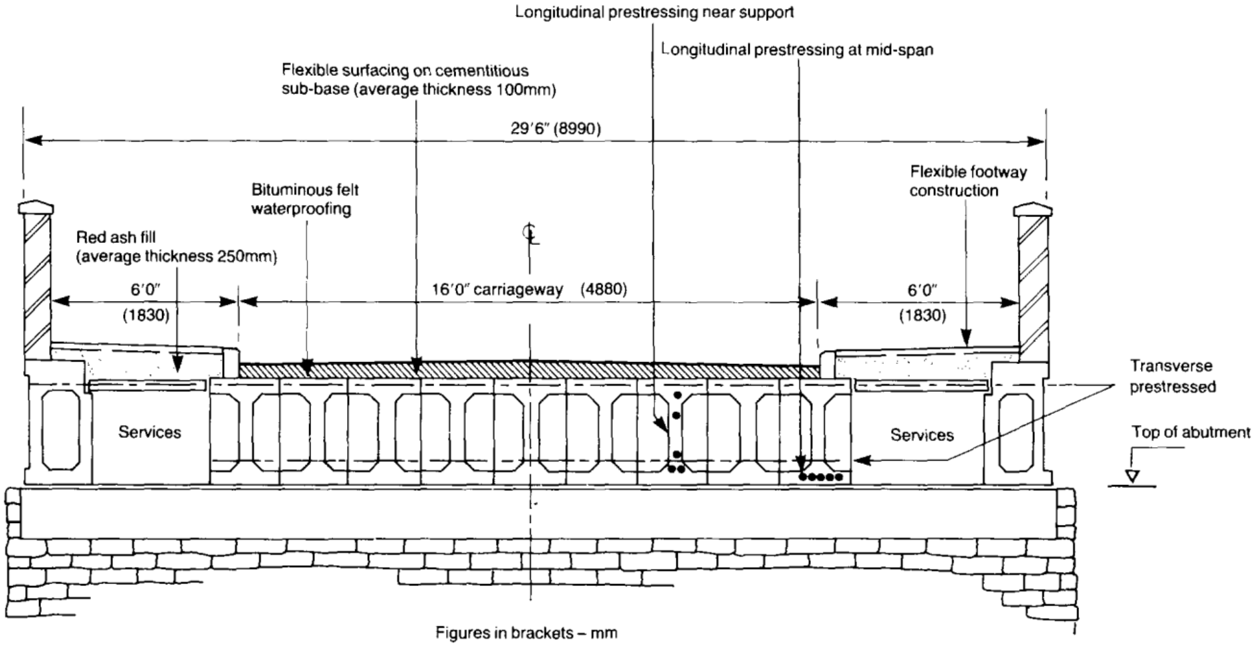
Appendix C

The present Appendix displays the most significant images of the structures analysed in the literature survey.

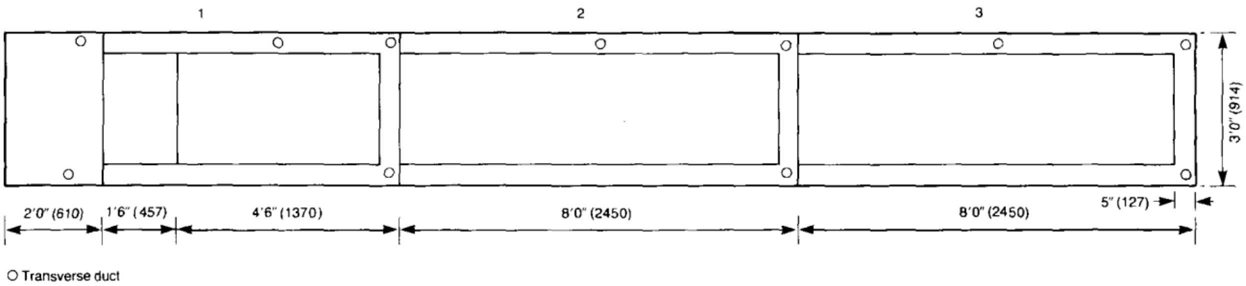
The images are named as ID-xx.y, where ID-xx is the identification number of the structure and y is the image number.

It must be noted that no significant image has been provided in the literature papers for some structures. Hence, the following structures are not present in this Appendix: ID-22, ID-23, ID-24, ID-25, ID-26, ID-27, ID-29, ID-34, ID-35, ID-36, ID-40, ID-41, ID-43, ID-44, ID-46, ID-47, ID-48, ID-49, ID-50, ID-51 and ID-52.

ID-1 Ynys-y-Gwas Bridge

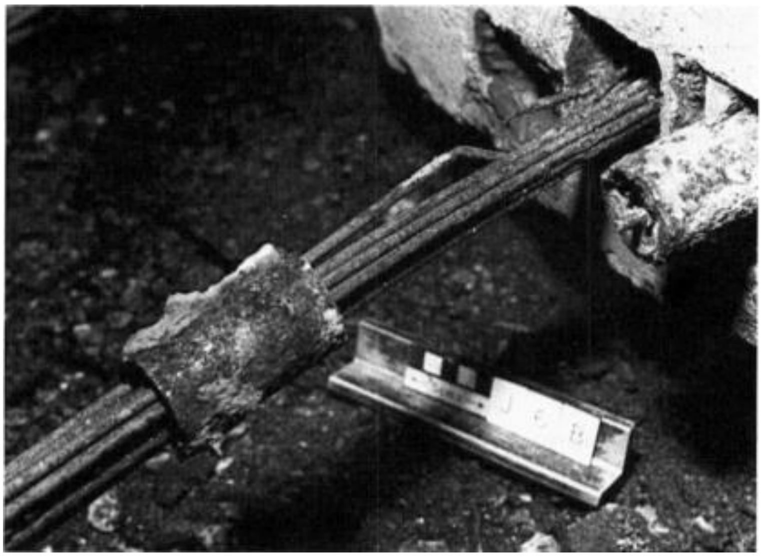


ID-1.1. Cross section of Ynys-y-Gwas bridge (Woodward and Williams, 1988).

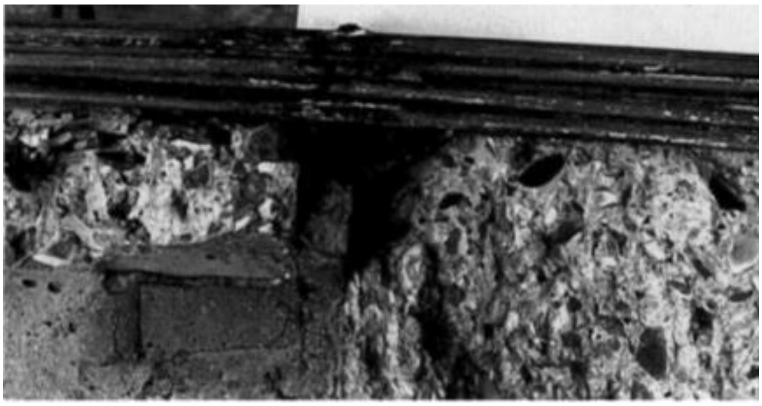


ID-1.2. Longitudinal section of I-beam in Ynys-y-Gwas bridge (Woodward and Williams, 1988).

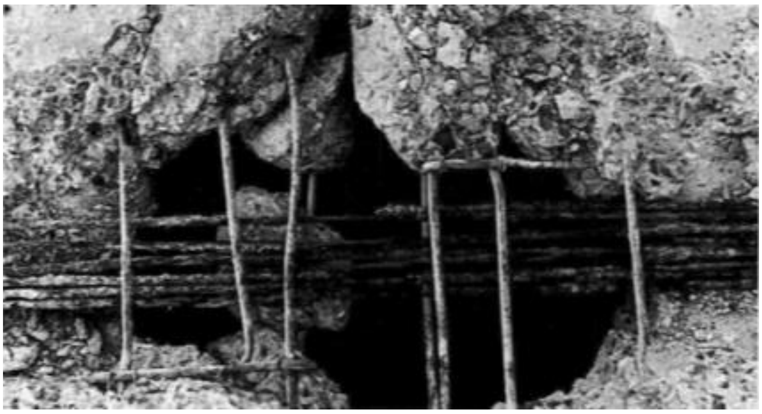
ID-1.3. Cardboard tube across transverse joint (Woodward and Williams, 1988).



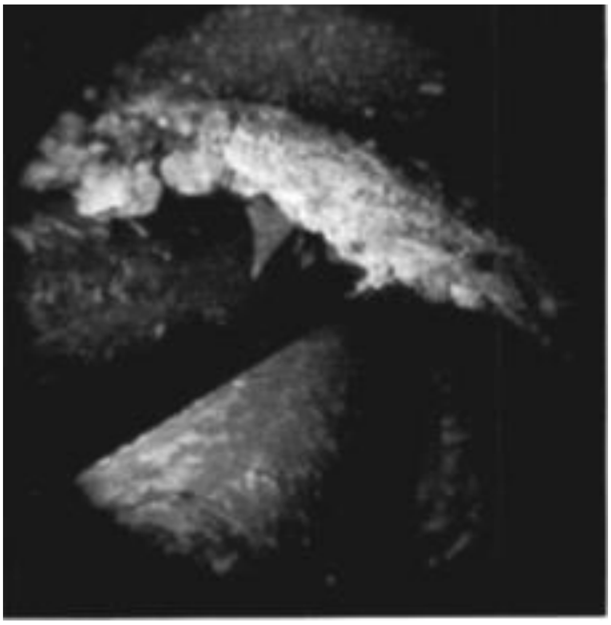
ID-1.4. Metal sleeve over longitudinal tendon: corrosion of tendons at joints (Woodward and Williams, 1988).



ID-1.5. Longitudinal tendon crossing a transverse joint: corrosion at localized joint (Woodward and Williams, 1988).

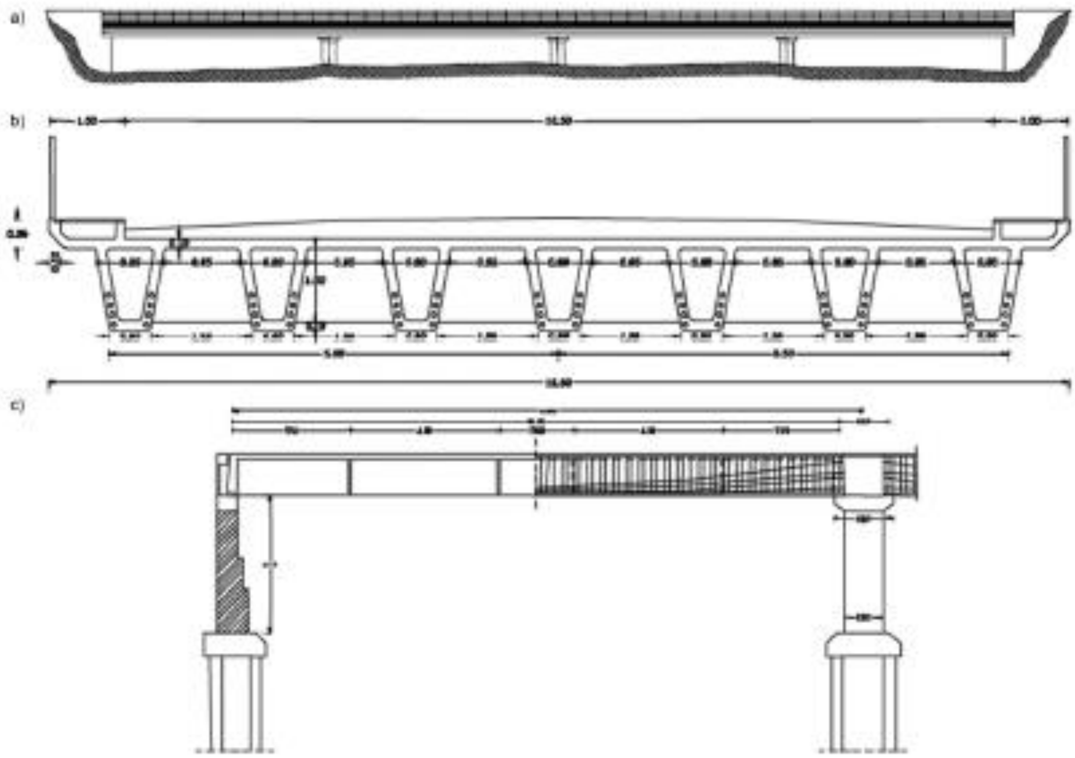


ID-1.6. Transverse tendon crossing a longitudinal joint: duct poorly grouted and corrosion on wires within segments (Woodward and Williams, 1988).



ID-1.7. Void at top of longitudinal duct: patches of cement paste on exposed wires (Woodward and Williams, 1988).

ID-2 S. Stefano Viaduct

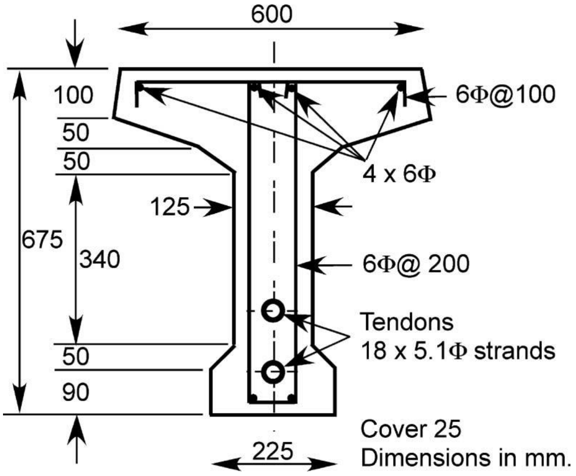


ID-2.1. S. Stefano Viaduct: a) front view; b) transversal; and c) longitudinal section (Colajanni et al, 2016).

ID-2.2. S. Stefano Viaduct: a) beam shore side; b) details of corrosion phenomena on the shore side beam; c) bottom view of the deck; and d) damage on the beam mount side beam (Colajanni et al, 2016).

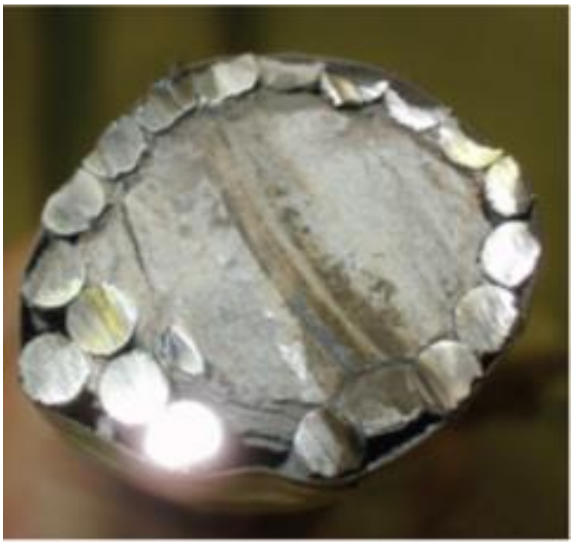
ID-2.3. S. Stefano Viaduct: a) collapse of the viaduct; b) slippage of cables; c) opening of joints; and d) rotation of the deck (Colajanni et al, 2016).

ID-3 Sorell Bridge



ID-3.1. Beam cross-section showing post-tensioning details (Papè and Melchers, 2011).

ID-3.2. Typical longitudinal web cracking along a beam (Papè and Melchers, 2011).



ID-3.3. Cross-sectional view of one of the most severely corroded tendons. Note the concave corrosion profiles at top and right. The central part is grout. The tape just visible around the outside as applied during recovery to keep the tendon together at the cross-sectional cut. There is no tendon duct (Papè and Melchers, 2011).

ID-3.4. Prestressing strand with corrosion products including dark-green-coloured rust (Papè and Melchers, 2011).

ID-4 Petrulla Viaduct

ID-4.1. Collapse mechanism of the bridge (Anania et al, 2018).

ID-4.2 Bridge beam: mid span fracture (Anania et al, 2018).

ID-4.3. Tendons in the bridge after collapse (Anania et al, 2018).

ID-4.4. Expulsion of the ducts head anchorages. Global view of the expulsion at the head of the girder beam (Anania et al, 2018).

ID-4.5. No gap among the tendons (Anania et al, 2018).

ID-4.6. Congestion of strands in the mid span of the bridge beams (Anania et al, 2018).

ID-4.7. View of the non-Portland cement grout for the bonding of tendons and advanced corrosion of both duct and strands (Anania et al, 2018).

ID-4.8. Cracking in the other bridge spans (Anania et al, 2018).

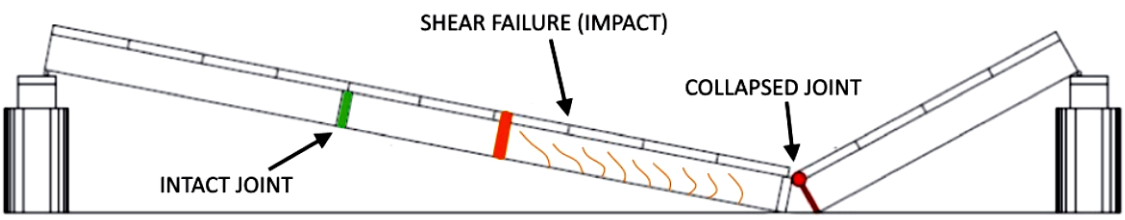
ID-4.9. Detailed view of vertical mild reinforcement expelled by the rotation of the lower flange (Anania et al, 2018).

ID-4.10. Cracking on the bridge span due to tensile tress and to the expulsion of the stirrups (Anania et al, 2018).

ID-5 Fossano Bridge

ID-5.1. Collapse mechanism of the bridge (https://torino.repubblica.it/cronaca/2017/04/18/news/crolla_il_ponte_della_tangenziale_di_fossano_schiacciata_un_auto_dei_carabinieri-163288432/#gallery-slider=163289532)

ID-5.2. Bridge beam: mid span fracture (https://torino.repubblica.it/cronaca/2017/04/18/news/crolla_il_ponte_della_tangenziale_di_fossano_schiacciata_un_auto_dei_carabinieri-163288432/#gallery-slider=163295934)

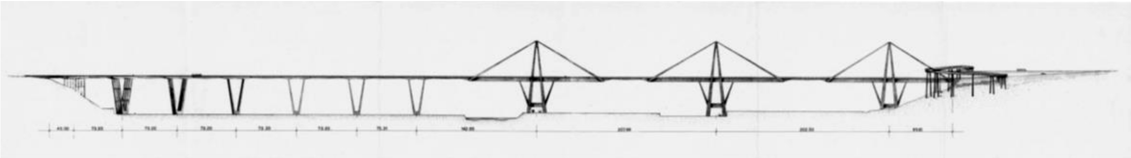


ID-5.3. Collapse mechanism (Bazzucchi et al, 2018).

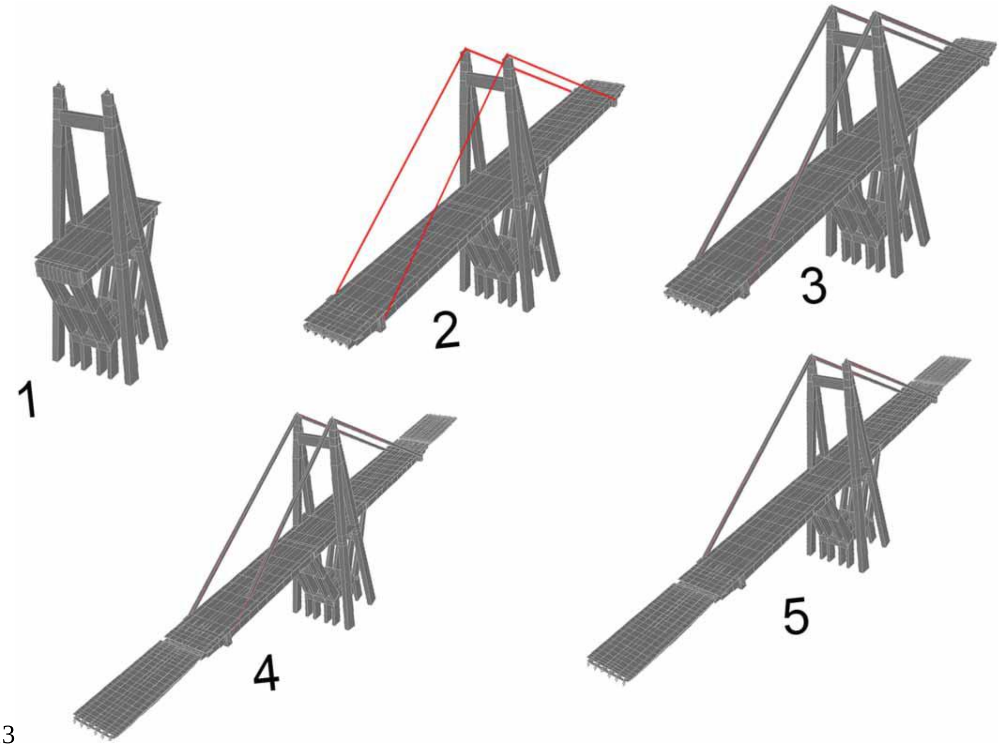
ID-5.4. Prestressing cables in the collapsed joint area (a); external concrete conditions (b) (Bazzucchi et al, 2018).

ID-5.5. Prestressing cables extracted and analysed. It is possible to note the direct correlation between grout content and oxidation rate of both sheathing and strands (Bazzucchi et al, 2018).

ID-6 Polcevera Bridge



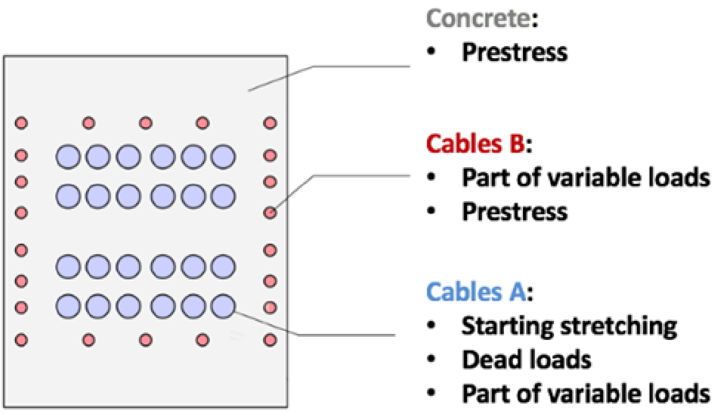
ID-6.1. View of Morandi Proposal: Project winner of an international competition (Nuti et al, 2020).



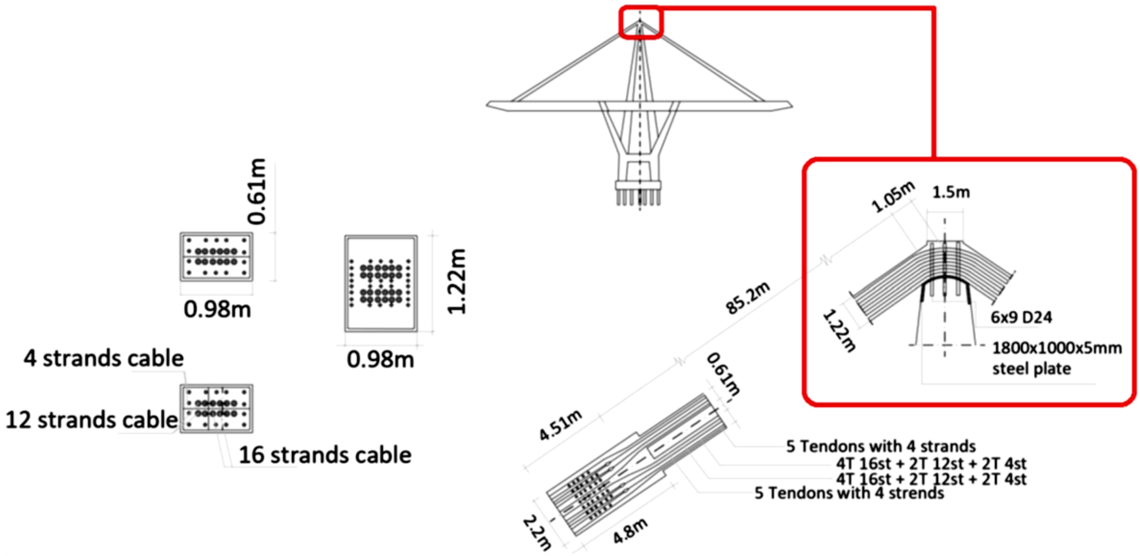
13

ID-6.2. Illustration of the four construction stages, plus the case where the S-W stay is removed (Calvi et al, 2019).

Figure 6.3. Involved structure in the collapse: tower and Gerber decks (Bazzucchi et al, 2018).



ID-6.4. Stays cross section (Domaneschi et al, 2020).



ID-6.5 Typical view of the stay cable system with the saddle detail from the design tables (Morgese et al, 2020).

ID-6.6. Details of top part of the suspension cables, strongly corroded in 1991 (Nuti et al, 2020).

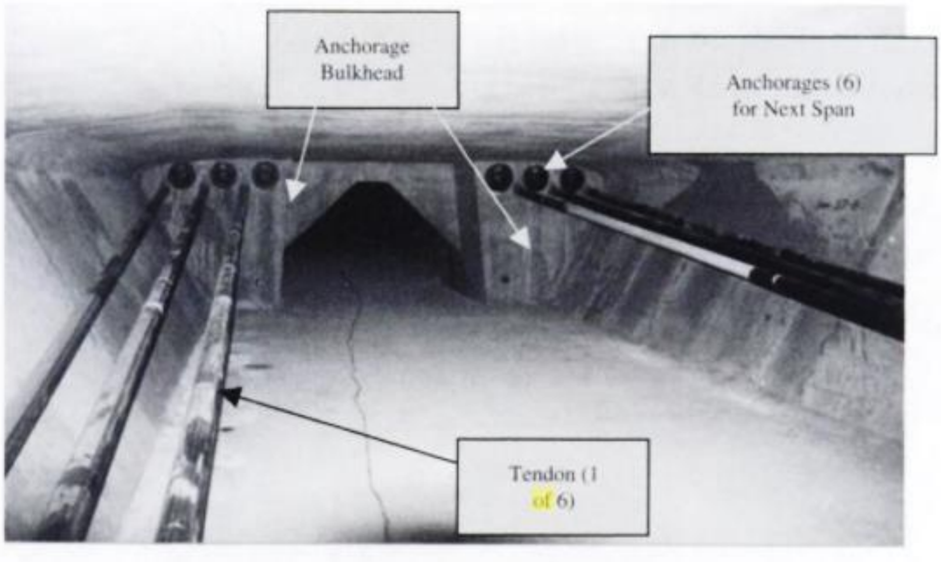
ID-6.7. View of cables toward the support in 2011 (top) and 2013 (middle). Zoom of the cables in 2013 (bottom) where corrosion and partial pitting can be appreciated (Nuti et al, 2020).

ID-6.8. Pit corrosion in the debris after failure (Nuti et al, 2020).

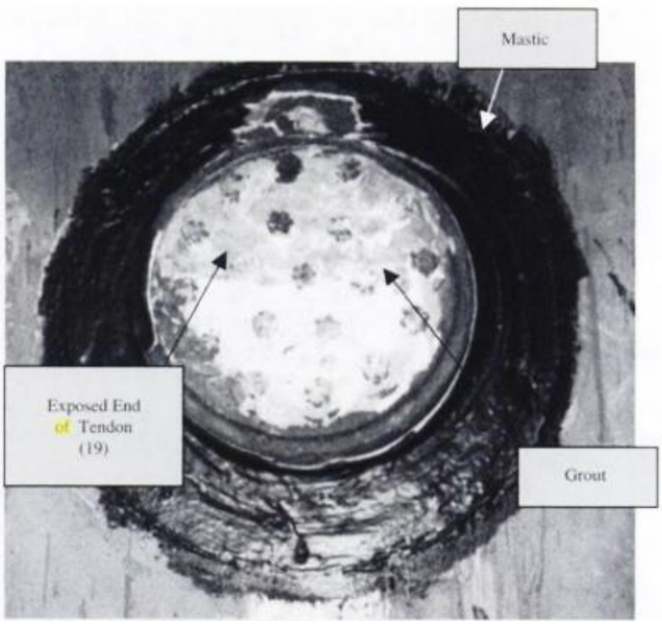
ID-6.9. Pitting corrosion of prestressing tendons (Morgese et al, 2020).

ID-7 Mid-Bay Brdige

ID-7.1. View of the Mid-Bay bridge, Destin, Florida (Venugopalan and Powers, 2003).



ID-7.2. Typical view of the anchorages and the tendons (Venugopalan and Powers, 2003).



ID-7.3. A typical end anchorage assembly (Venugopalan and Powers, 2003).

ID-7.4. Broken wire in one of the strands of Tendon 2 of Span 40-A (Venugopalan and Powers, 2003).

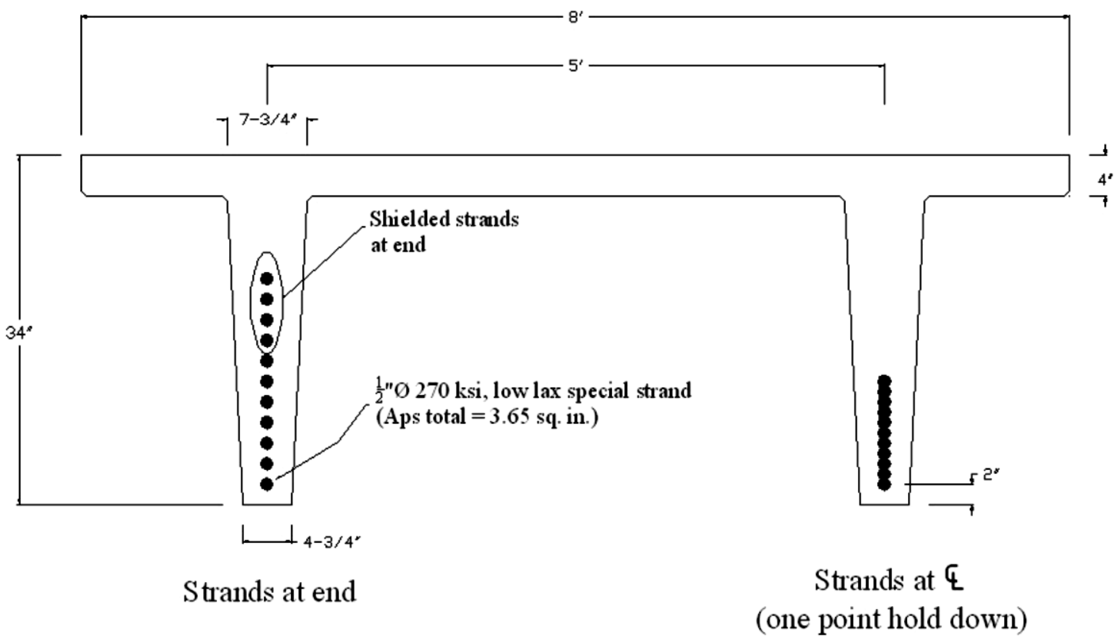
ID-8 Carpineto Viaduct

ID-8.1. Bridge overview (https://www.stradeeautostrade.it/ponti-e-viadotti/il-viadotto-strallato-carpineto-i-2/)

ID-8.2. Stays overview (https://www.stradeeautostrade.it/ponti-e-viadotti/il-viadotto-strallato-carpineto-i-2/)

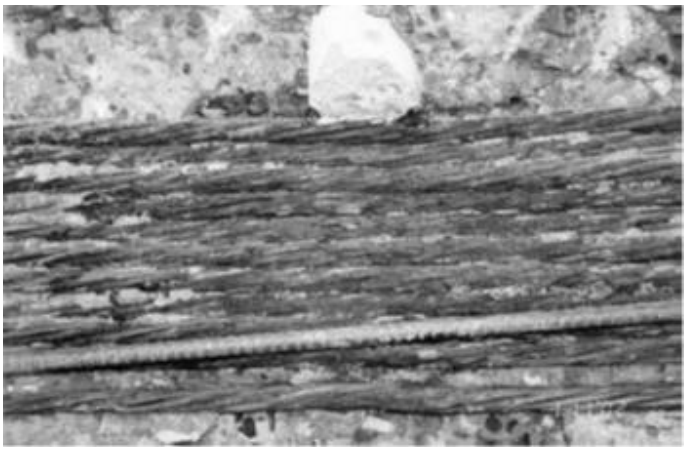
ID-9 Lowe's Motor Speedway

ID-9.1. Collapsed span of pedestrian bridge (Poston and West, 2005).



ID-9.2. Double-T beam cross-section (Poston and West, 2005).

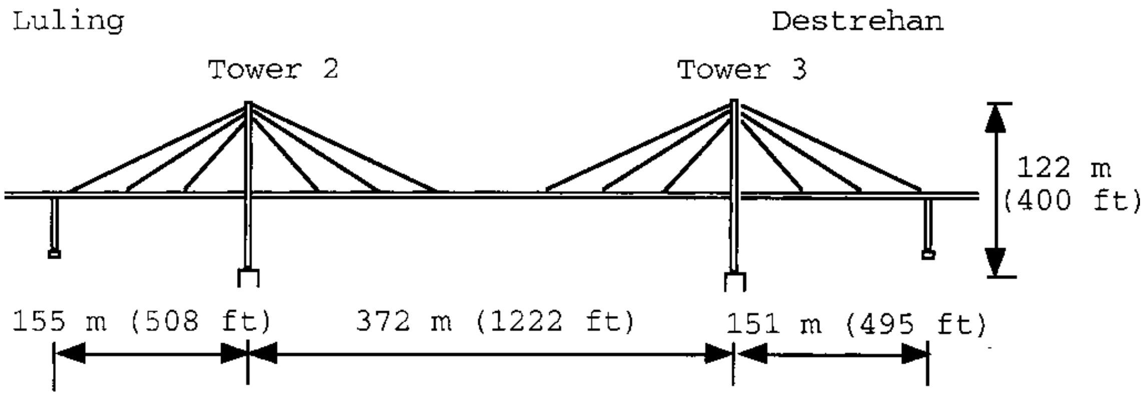
ID-9.3. Strand from one of the collapsed double-T's beams (Poston and West, 2005).



ID-9.4. Condition of strands in double-T beams that did not collapse (Poston and West, 2005).

ID-9.5. Longitudinal crack in double-T beams stem directly under the grout plug location (Poston and West, 2005).

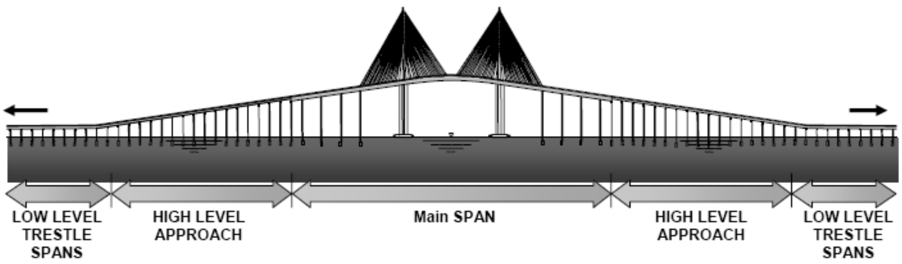
ID-10 Luling Bridge



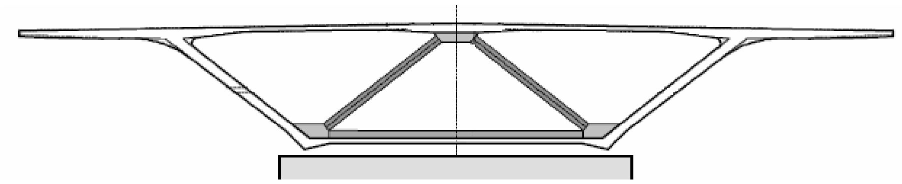
ID-10.1. Luling Bridge configuration (Elliott and Heimsfield, 2003).

ID-10.2. Corrosion of wires at PE split (Mehrabi, 2009).

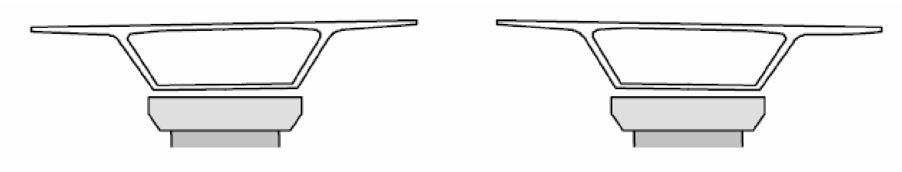
ID-11 Sunshine Skyway Bridge



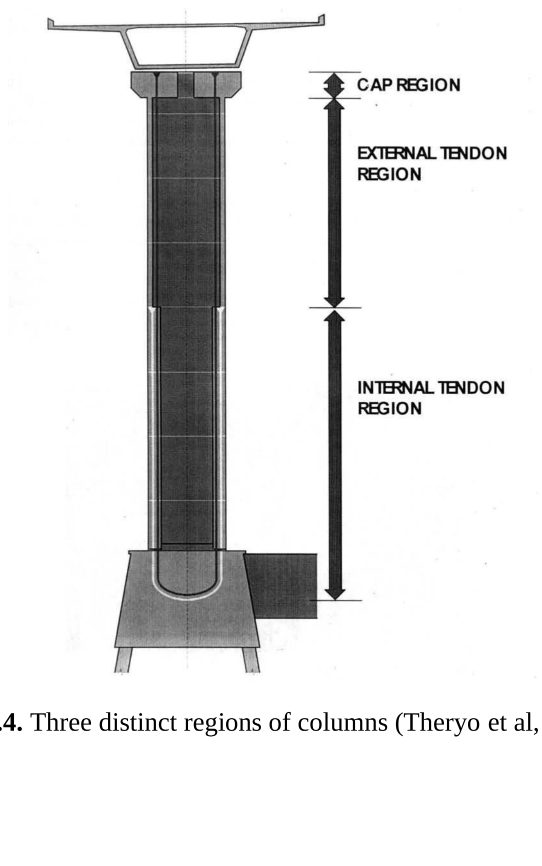
ID-11.1. Sunshine Skyway geometry (Sayers, 2007).



ID-11.2. Cross-section of concrete sections for main span (Sayers, 2007).

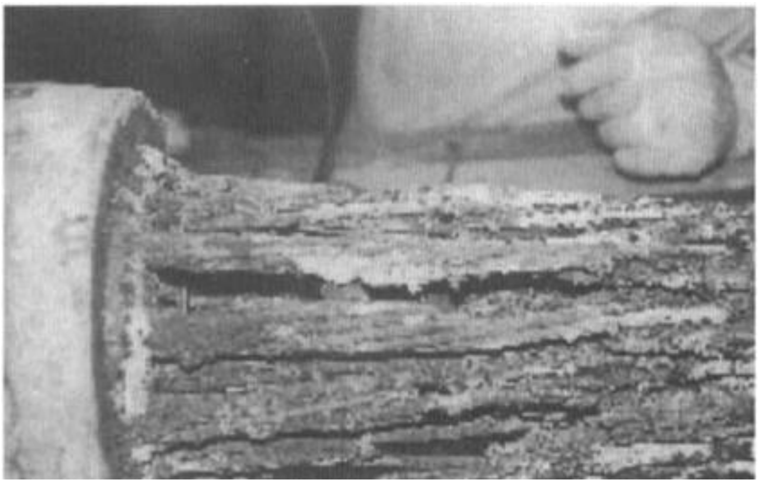


ID-11.3. Cross-section of pre-cast concrete sections for approach spans (Sayers, 2007).



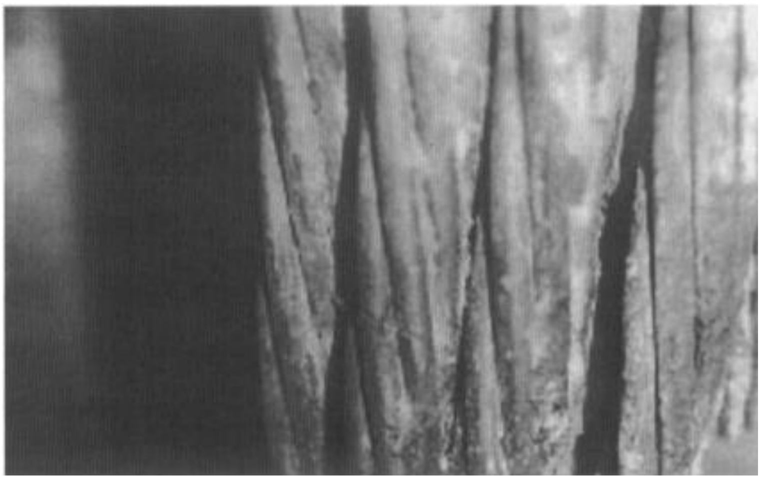
ID-11.4. Three distinct regions of columns (Theryo et al, 2011).

ID-11.5. Severe corrosion and failure just below the cap on the SE tendon in column 133 NB (Theryo et al, 2011).



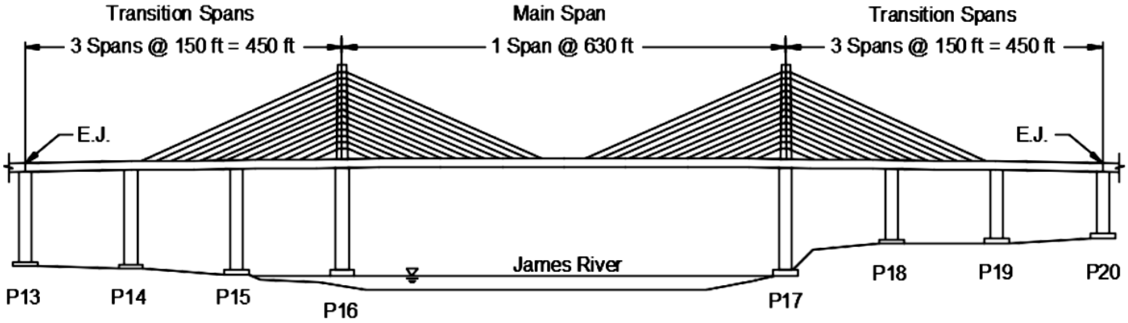
ID-11.6. Condition of strand inside the trumpet (Theryo et al, 2011).

ID-11.7. Cracked PE duct (Theryo et al, 2011).

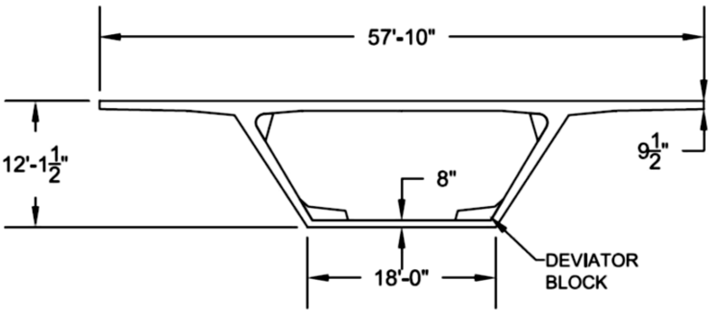


ID-11.8. Severe corrosion and strand failure in the NE tendon recess area at the bottom of segment 1 in column 131 SB (Theryo et al, 2011).

ID-12 Varina Enon Bridge



ID-12.1. Elevation of Main Span Unit (Brodsky, 2020).



ID-12.2. Typical Segment Dimensions (Lindley 2019).

ID-13 Post-tensioned bridge in the Midwest

ID-13.1. A view of the cast-in-place box girder bridge (Venugopalan, 2008).

ID-13.2. Presence of efflorescence, delamination, and spall observed on post-tensioned box girders (Venugopalan, 2008).

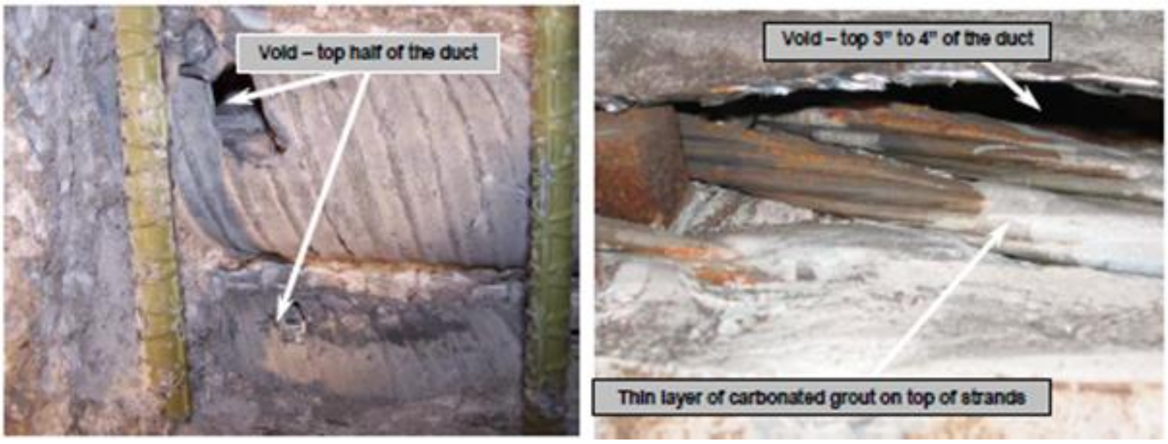


Figure 13.3. Voids (with a thin layer of chalky material) at different sections of the tendon. (Venugopalan, 2008).

ID-14 San Francisco-Oakland Bay Bridge

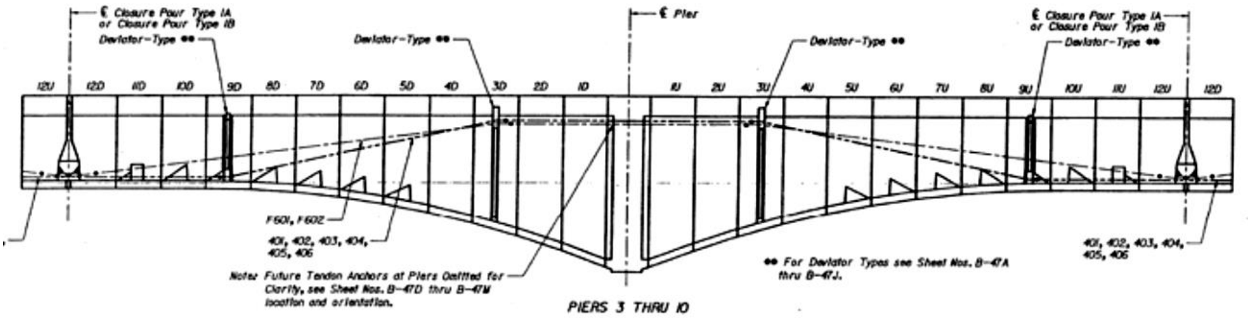
ID-14.1. Close-up view of an anchorage head at tendon location E3E-CO4S (continuity tendon) showing signs of corrosion from water collecting at the anchorage (Reis, 2007).

ID-14.2. View of interior web wall showing a crack and effervescence (Reis, 2007).

ID-14.3. View of a crack showing effervescence (Reis, 2007).

ID-15 Ringling Causeway Bridge

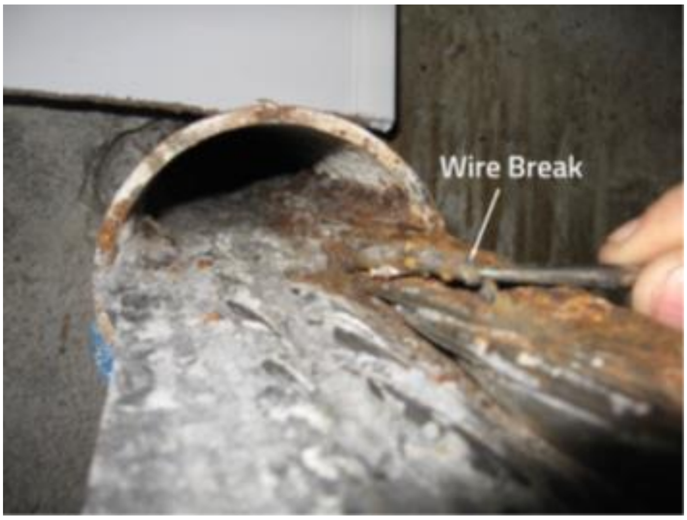
ID-15.1. General view of Ringling Bridge (Ahern et al, 2018).



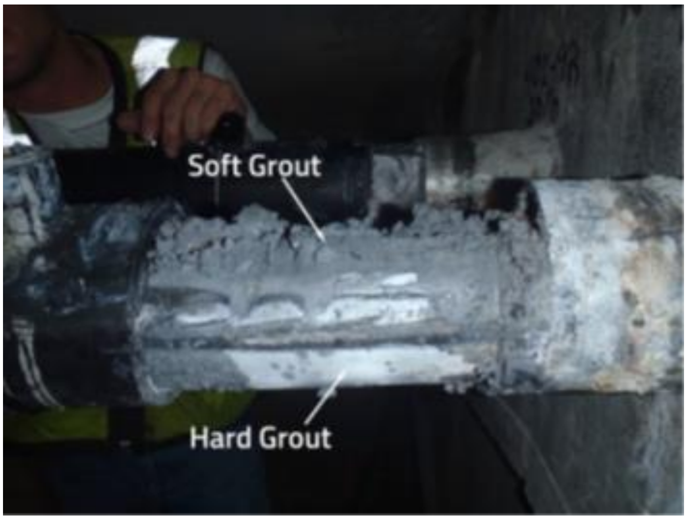
ID-15.2. Typical tendon profile (Ahern et al, 2018).

ID-15.3. Segment of failed tendon discovered in January 2011 with evidence of corrosion damage. Duct opened in laboratory during investigation (Ahern et al, 2018).

ID-15.4. Detentioned PT Tendon discovered in July 2011 (Ahern et al, 2018).



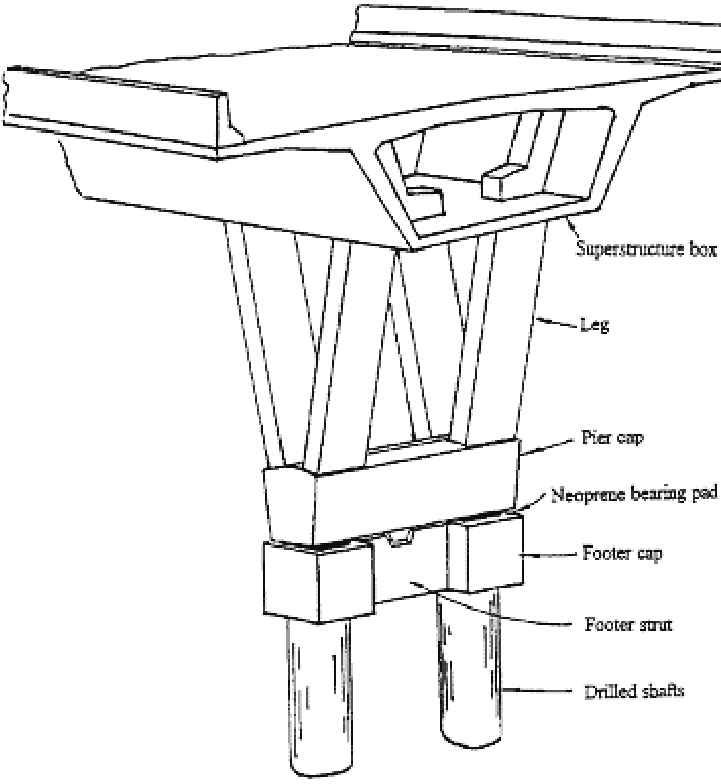
ID-15.4. Corrosion of strands and wire breaks identified in other external PT tendons (Ahern et al, 2018).



ID-15.5. Segregation of the grout material observed near the high points of the tendon profile (Ahern et al, 2018).

ID-15.6. Corrosion of a strand embedded in deficient grout. Pink colour shows the Ph indicator (phenolphthalein) sprayed on the grout surface (Lau and Lasa, 2016).

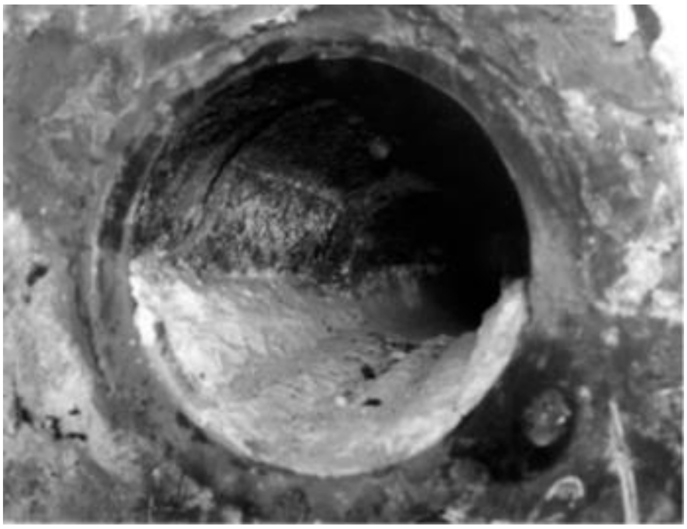
ID-16 Long Key Bridge



ID-16.1. Standard V-pillar (Moreton, 1998).

ID-17 Niles Channel Bridge

ID-17.1. Failed tendon of Niles Channel Bridge. June 1999 (Powers et al, 2002).



ID-17.2. Anchor at failed tendon showing chalky grout, partial grout filling and heavy corrosion (Powers et al, 2002).

ID-18 Italian bridge

ID-18.1. Example of penetrating corrosion attacks observed on a wire of the failed cable (Bertolini and Carsana, 2011).

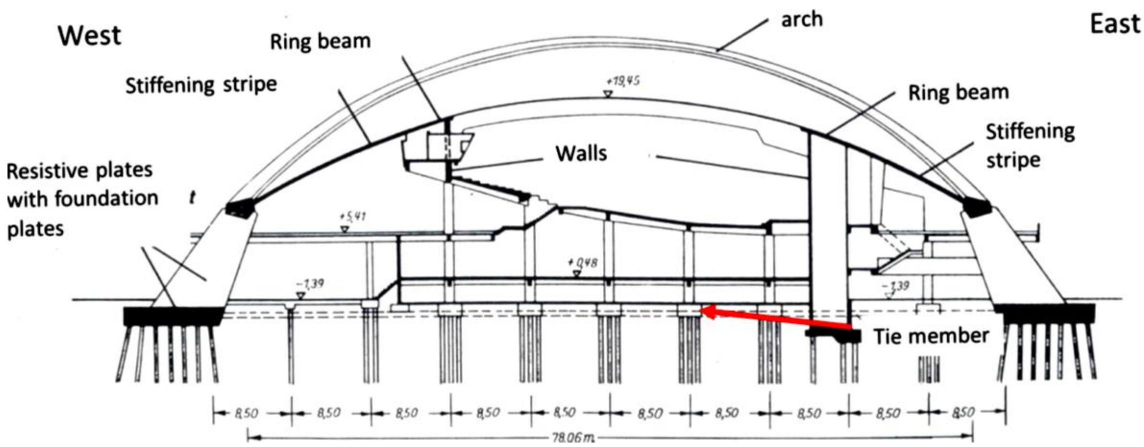
ID-18.2. Example of whitish segregated grout embedding corroding strands (Bertolini and Carsana, 2011).

ID-18.3. Example of corrosion attacks on a prestressing strand in contact with the whitish segregated grout (Bertolini and Carsana, 2011).

ID-18.4. Example of failed wires in a prestressing strand in contact with the whitish segregated grout (Bertolini and Carsana, 2011).

ID-19 Berlin Congress Hall

ID-19.1. Original structure of the congress hall before sudden collapse, photograph of 1960 (Helmerich and Zunkel, 2014).



ID-19.2. East–west section of the original Berlin Congress Hall (1957–1980) (Helmerich and Zunkel, 2014).

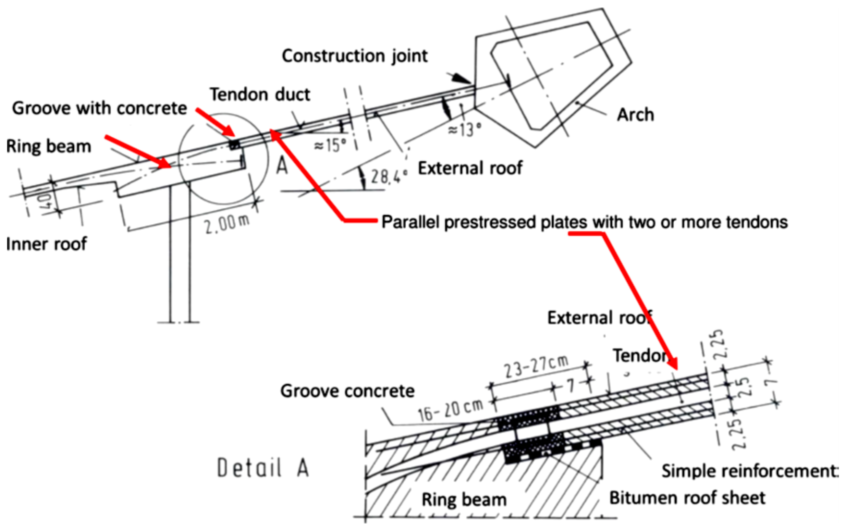
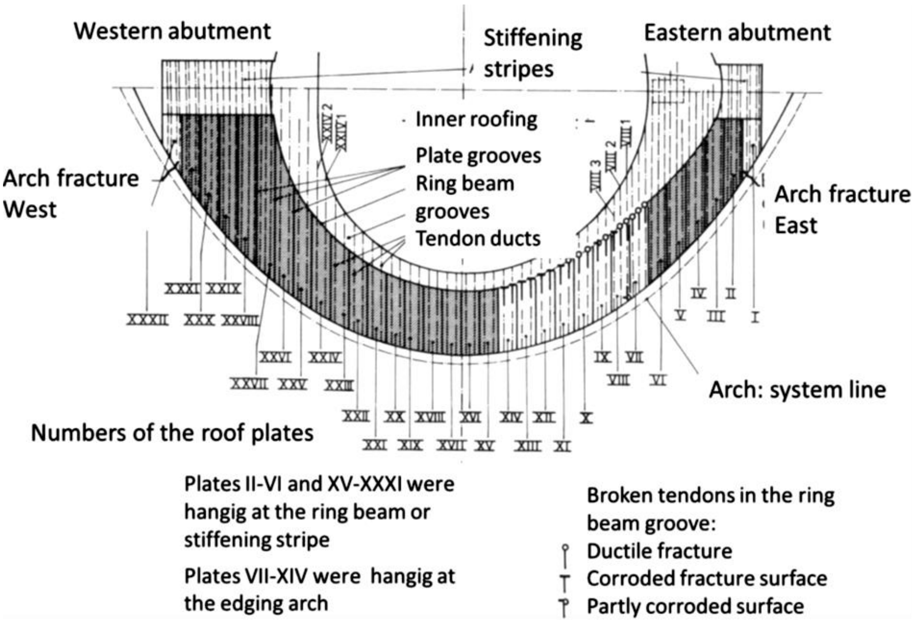
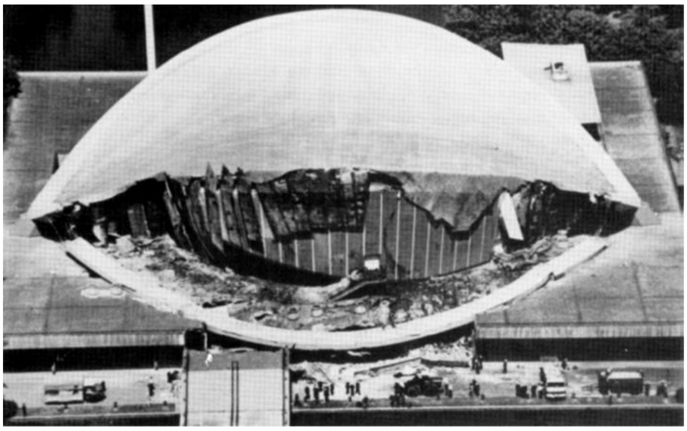


Figure 19.3. Connection of the inner and the external roof in a ring beam with detailing (Helmerich and Zunkel, 2014).



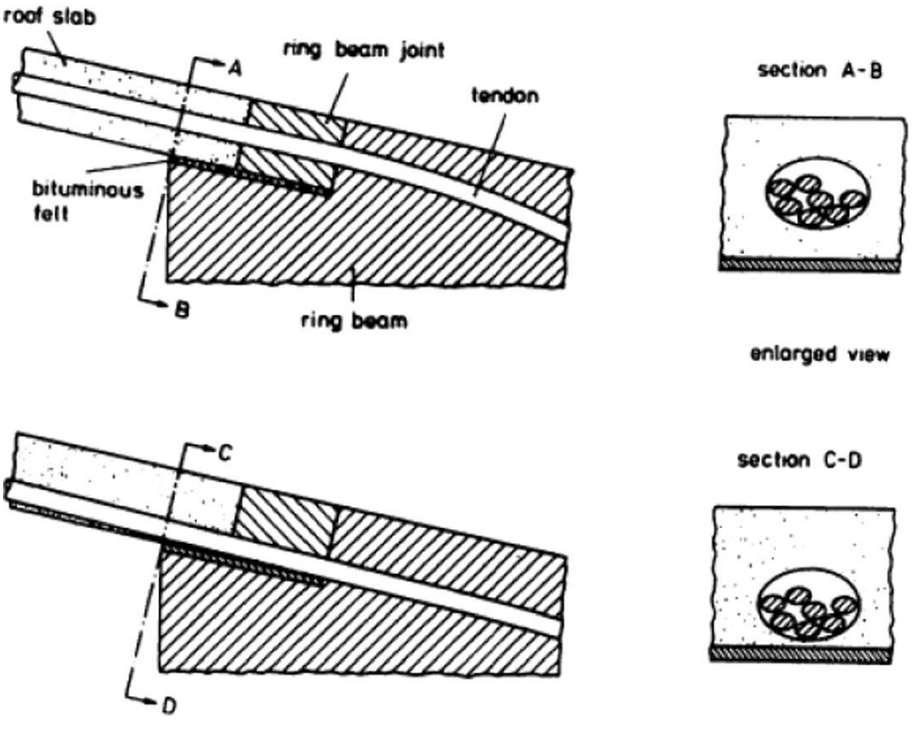
ID-19.4. Ground view with the location of corroded and broken tendons (Helmerich and Zunkel, 2014).



ID-19.5. View from the South on the collapsed roof overhang in 1980 (Helmerich and Zunkel, 2014).

ID-19.6. Remaining bituminized roofing on a completely failed, non-grouted and heavily corroded tendon (Helmerich and Zunkel, 2014).

ID-19.7. Prestressing wires are almost not embedded in the protective grout (left) or insufficient grouted (right). Only one broken wire (left) shows a non-corroded brittle broken fracture surface. (Helmerich and Zunkel, 2014).

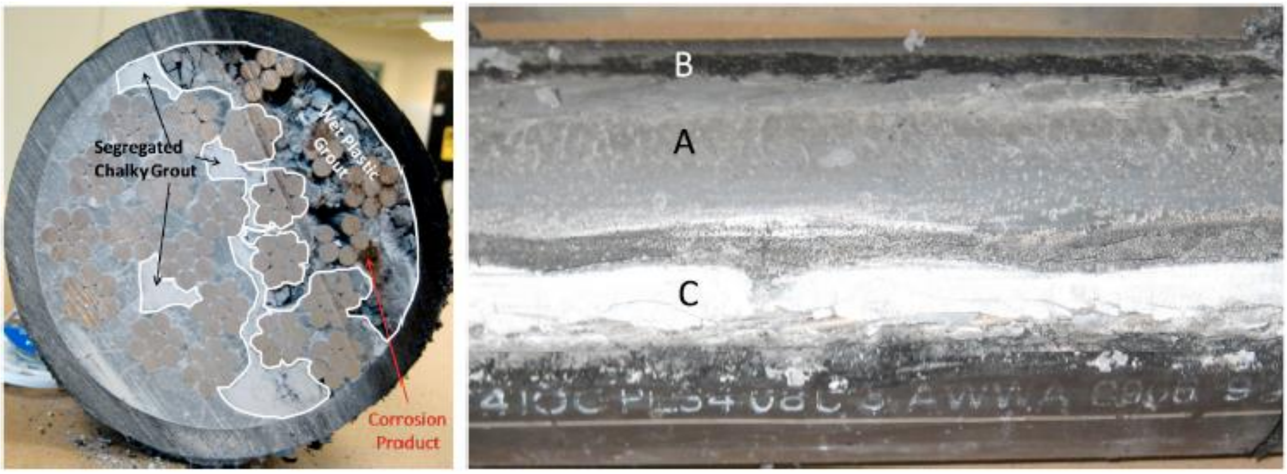


ID-19.8. Intended (upper) and real location (lower) of tendons (left) and wires in the tendon duct (right) (Helmerich and Zunkel, 2014).

ID-20 Florida Bridge

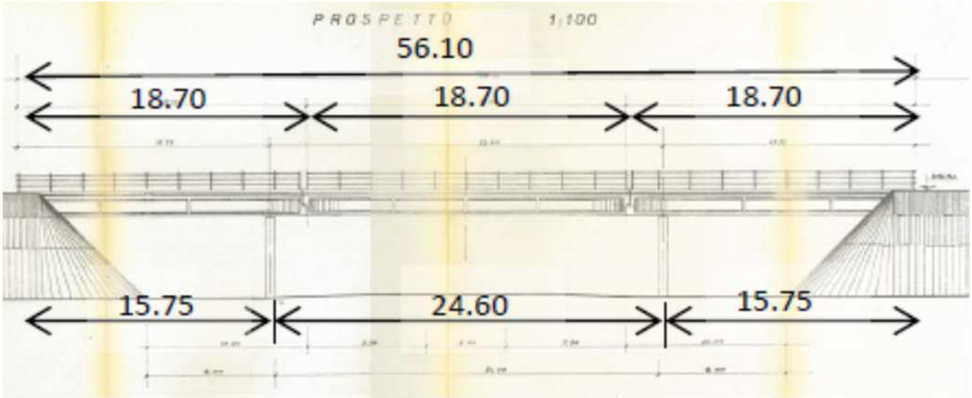
ID-20.1. Bridge overview (Lau and Lasa, 2016).

ID-20.2. Corroded tendon (Lau and Lasa, 2016).

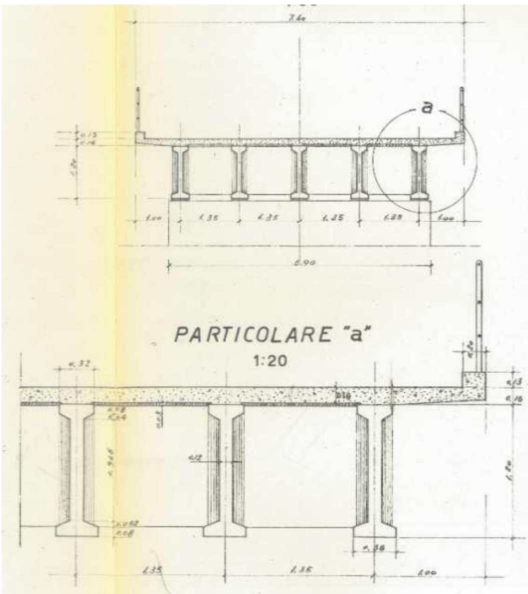


ID-20.3. Grout segregation appearance. (A) Wet plastic grout. (B) Dark band of sedimented silica fume. (C) White chalky grout (Permeh et al, 2016).

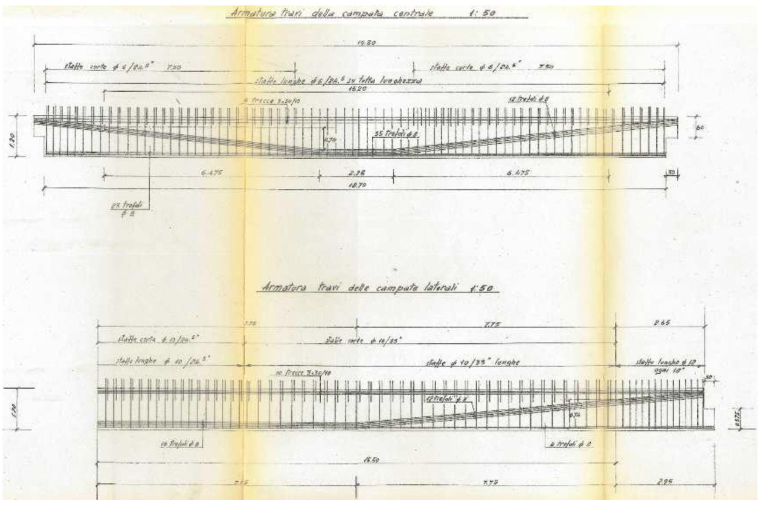
ID-21 Annone Overpass



ID-21.1. Original design drawings of the bridge: side view (Di Prisco et al, 2018).



ID-21.2. Original design drawings of the bridge: cross-section (Di Prisco et al, 2018).



ID-21.3. Original design drawings of the bridge: longitudinal reinforcement (Di Prisco et al, 2018).

ID-21.4. Lateral impacts occurred in 2006 due to trucks circulating on SS.36 towards Lecco: location(Di Prisco et al, 2018).

ID-21.5. Lateral impacts occurred in 2006 due to trucks circulating on SS.36 towards Lecco: particular of the damaged zone (Di Prisco et al, 2018).

ID-21.6. Damage observed on internal surfaces of the prefabricated beams in 2006 (Di Prisco et al, 2018).

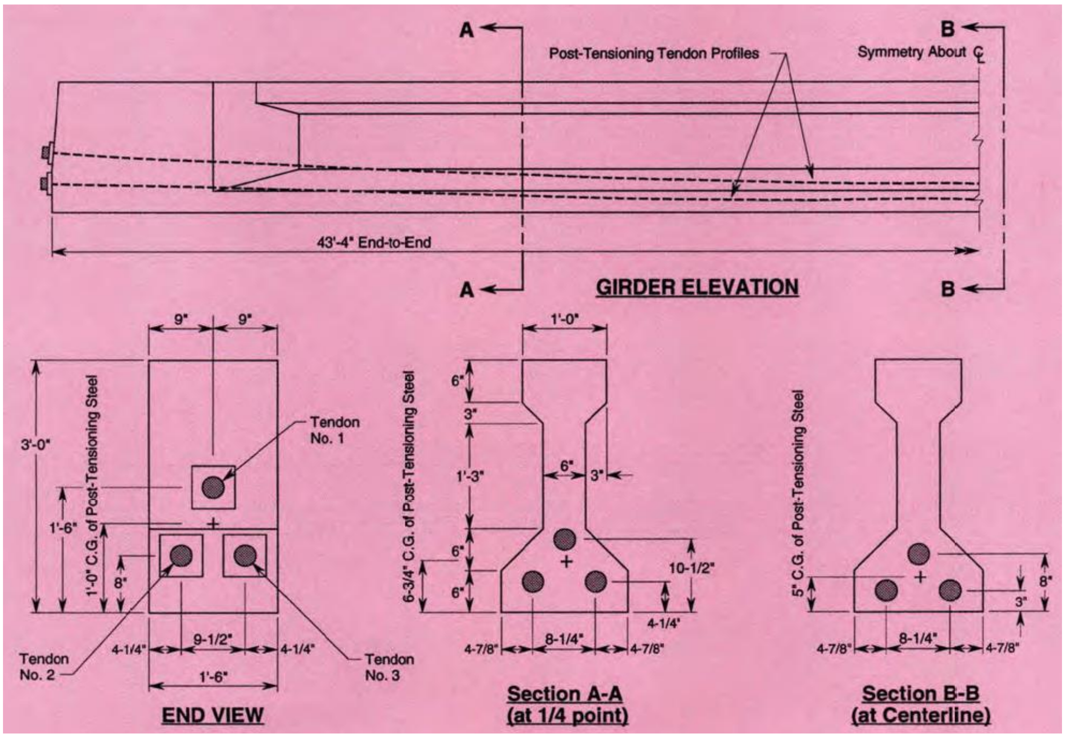
ID-21.7. Critical dapped-end joint view before the collapse: side view (Di Prisco et al, 2018).

ID-21.8. Critical dapped-end joint view before the collapse: bottom view (Di Prisco et al, 2018).

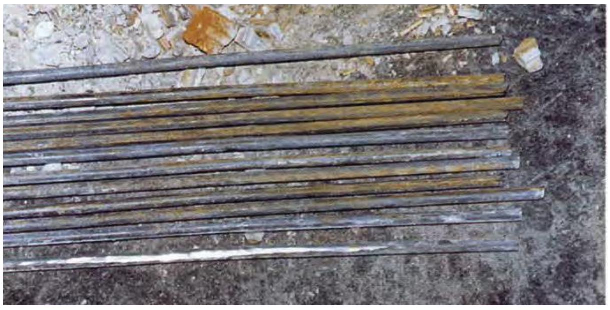
ID-28 Wentbridge Viaduct

ID-28.1. Corrosion of external tendons that had been encased in concrete (Tilly, 2002).

ID-30 I-94 Bridge over US 81



ID-30.1. Location of post-tensioning tendons (Dickson et al, 1993).

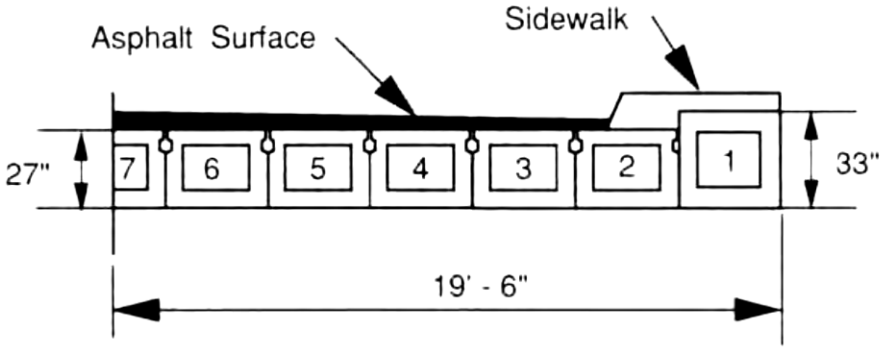


ID-30.2. Typical minor surface corrosion seen on post-tensioning wires removed from duct. No pitting or fractures were noted (Dickson et al, 1993).

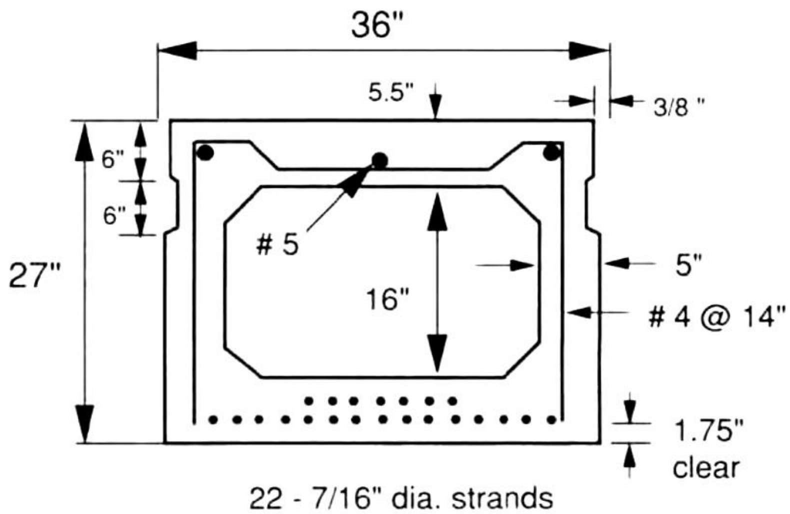
ID-30.3. Corrosion of wires at anchorage plate is greater than that exhibited inside ducts. (Dickson et al, 1993).

ID-31 Walnut Street Bridge

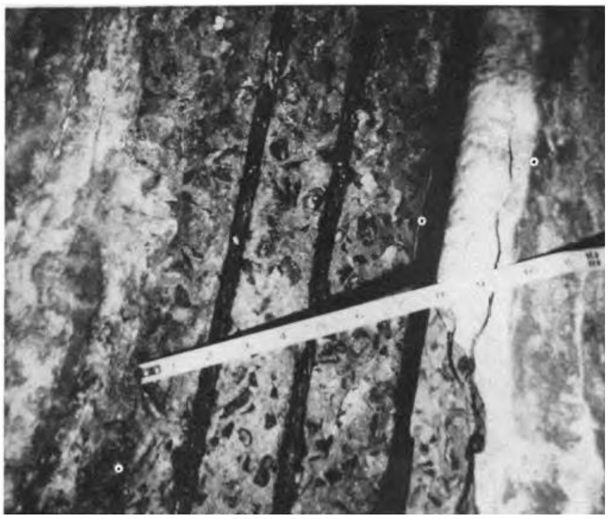
ID-31.1. General view of bridge (Murray and Frantz, 1992).



ID-31.2. Bridge cross section, viewed from north end (Murray and Frantz, 1992).



ID-31.3. Beam cross section (Type B1-36) (Murray and Frantz, 1992).

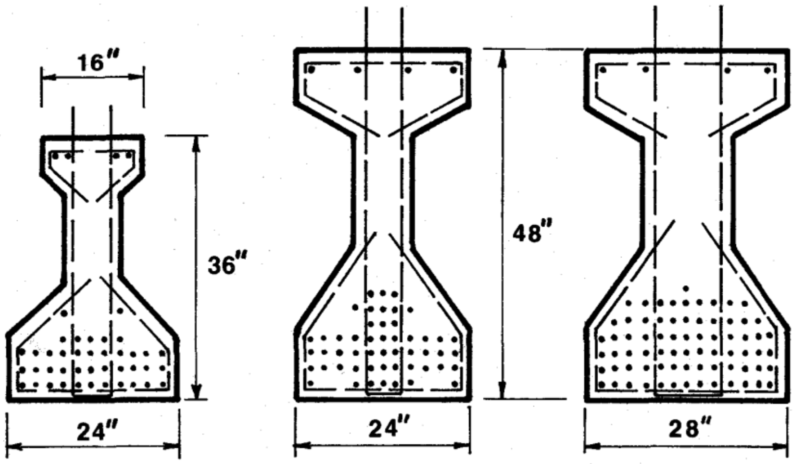


ID-31.4. Spalled concrete and exposed strands in beam 2 (Murray and Frantz, 1992).

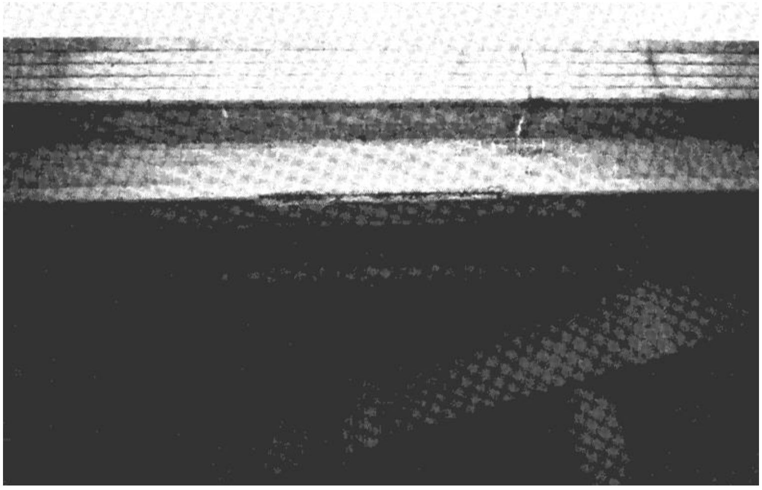
ID-31.5. Stains on beams (Murray and Frantz, 1992).

ID-31.6. Ruptured strand hanging down into river (Murray and Frantz, 1992).

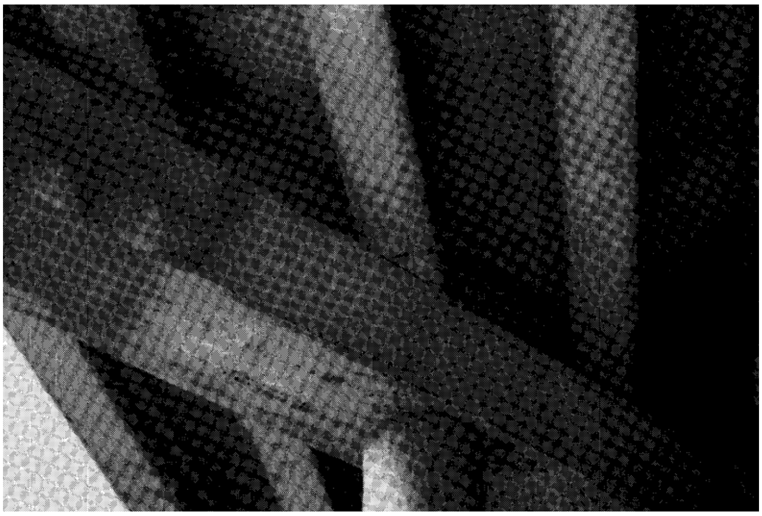
ID-32 Harlem Avenue Bridge – Illinois Tollway



ID-32.1. Typical bridge girder sections used on Illinois Tollway bridges (Gustaferro et al, 1983).

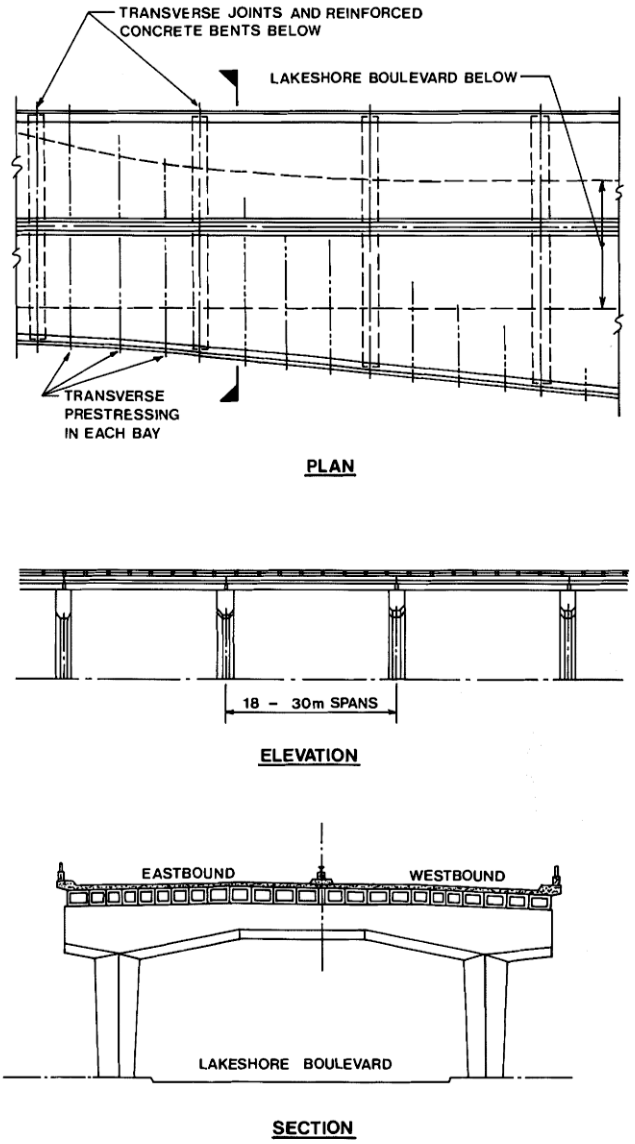


ID-32.2. Spalled girder on Harlem Avenue overpass (Gustaferro et al, 1983).

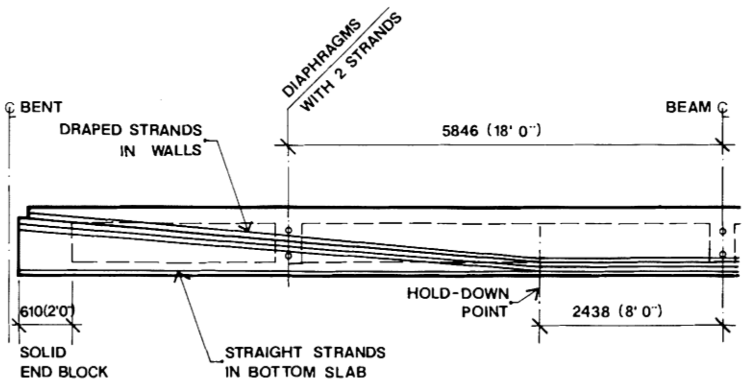


ID-32.3. Corroded strapping across bottom of girder on Harlem Avenue overpass. (Gustaferro et al,1983).

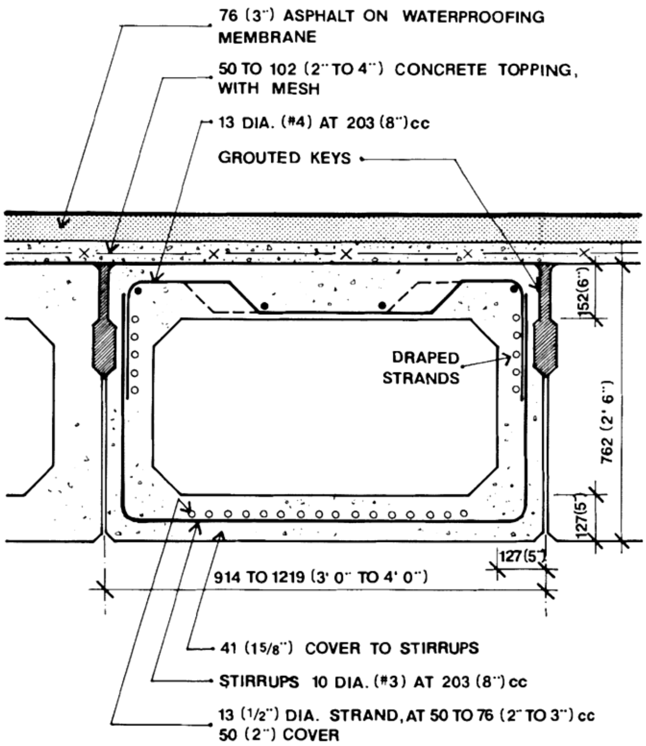
ID-33   F.G. Gardiner Expressway



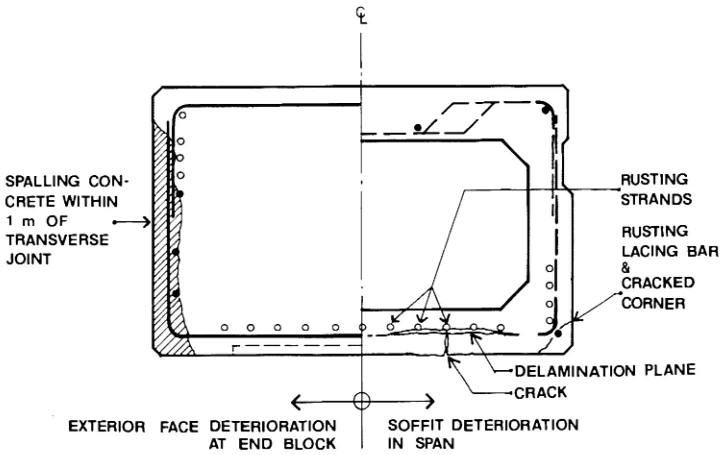
ID-33.1. Typical layout (Tork, 1985).



ID- 33.2. Schematic elevation of pre-tensioned box beam (Tork, 1985).



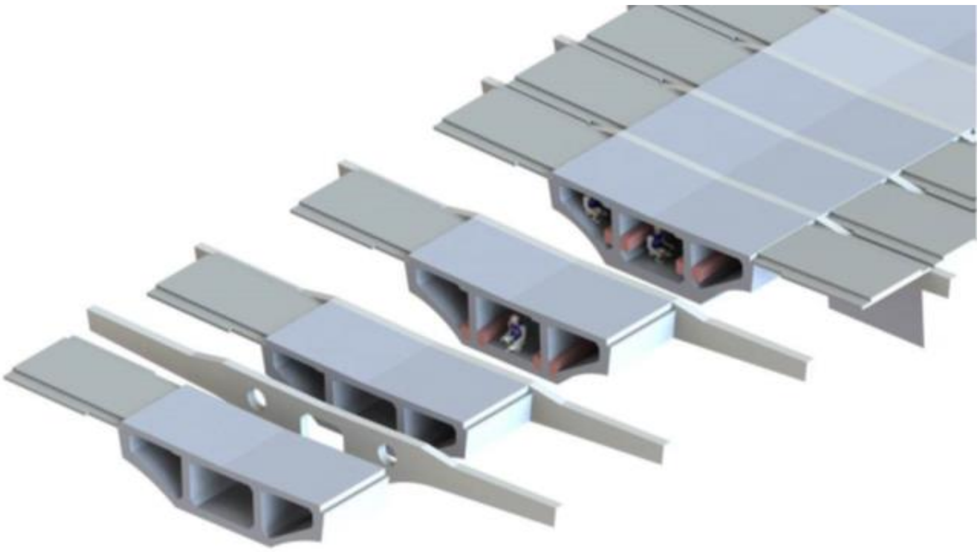
ID-33.3. Typical pre-tensioned box beam cross section (Tork, 1985).



ID-33.4. Typical beam deterioration (Tork, 1985).

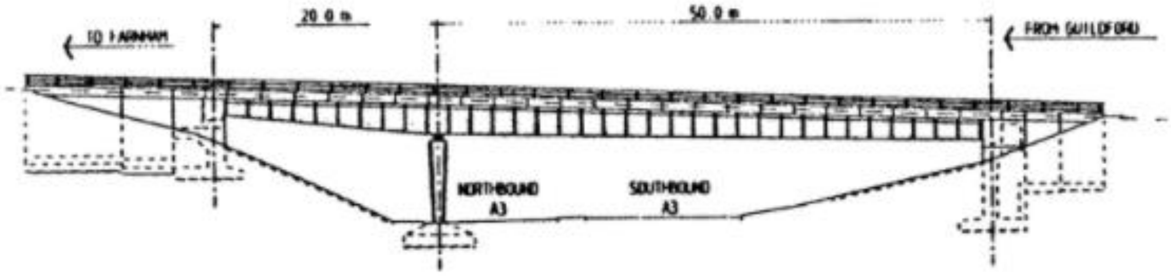
ID-37 Hammersmith Flyover

ID-37.1. The Hammersmith Flyover before remedial works (Cousin et al, 2017).

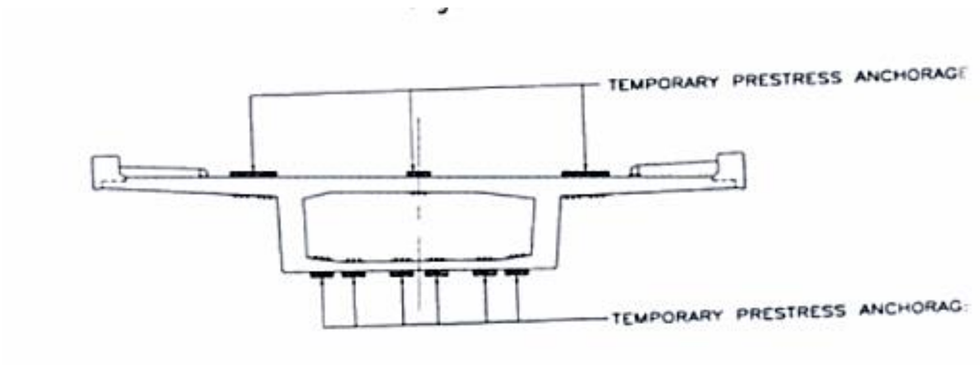


ID-37.2. Simplified exploded view of original construction (Cousin et al, 2017).

ID-38 A3/A31 Flyover

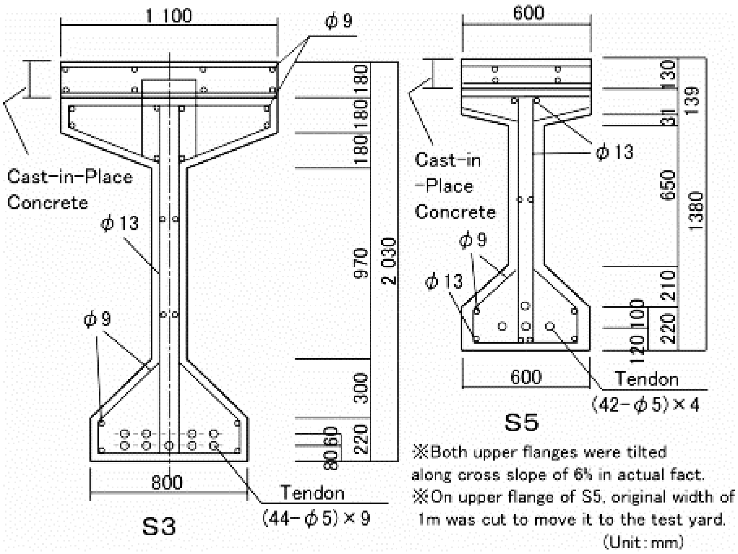


ID-38.1. Elevation of bridge (Brooman and Robson, 1996).

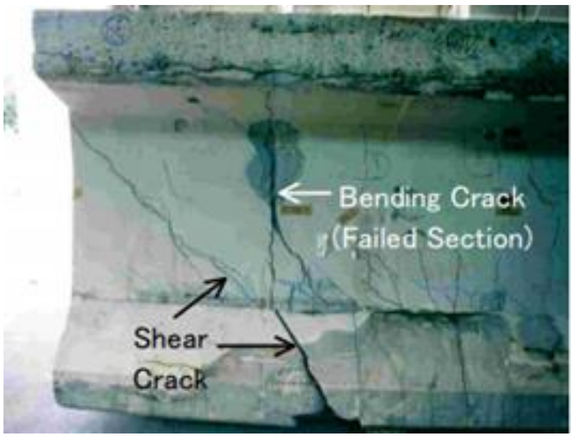


ID-38.2. Cross section showing position of temporary prestress at anchorages (Robson, 1997).

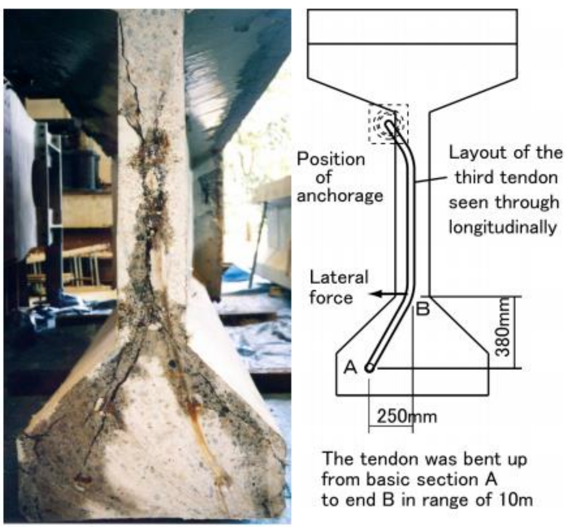
ID-39 Kure-tsubo Bridge



ID-39.1. Configuration of specimens (Tanaka et al, 2001).

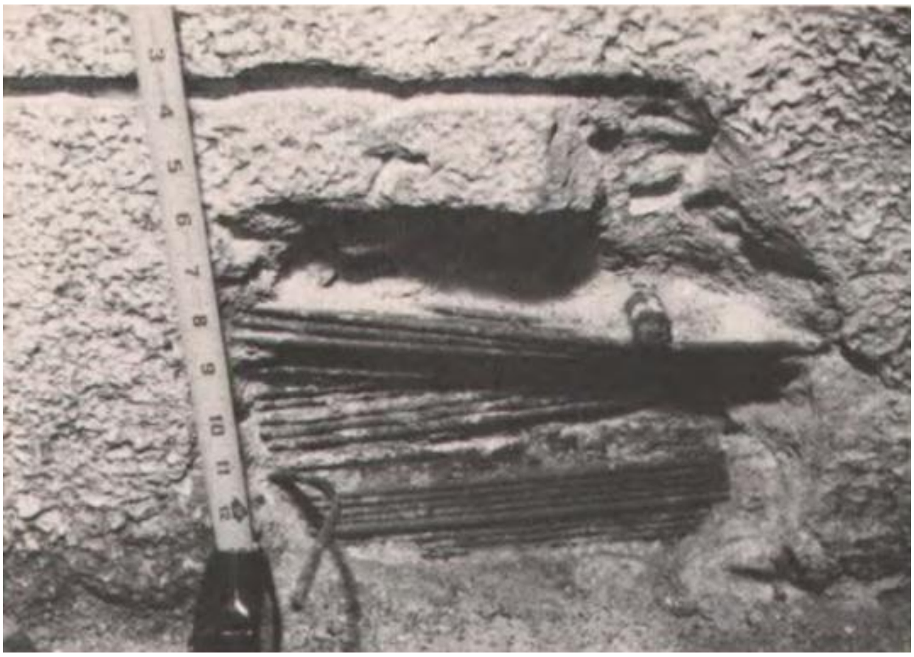


ID-39.2. Cracks around failed section of S3 (Tanaka et al, 2001).



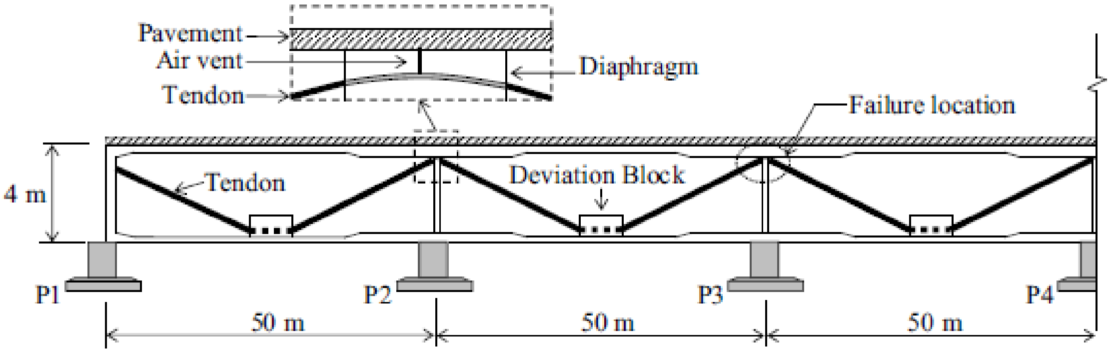
ID-39.3. Inner crack at 6.1 m from north end of S3 (Tanaka et al, 2001).

ID-42 Sewage Digesters

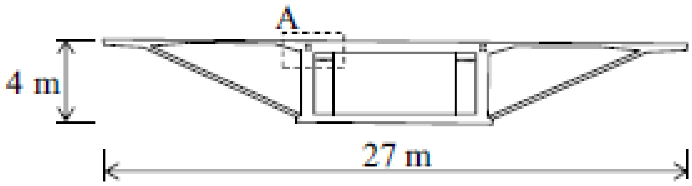


ID-42.1. Corroded wires bundled around a pipe. Shotcrete protection did not penetrate bundle and was not bonded to tank wall (Schupack and Suarez, 1982).

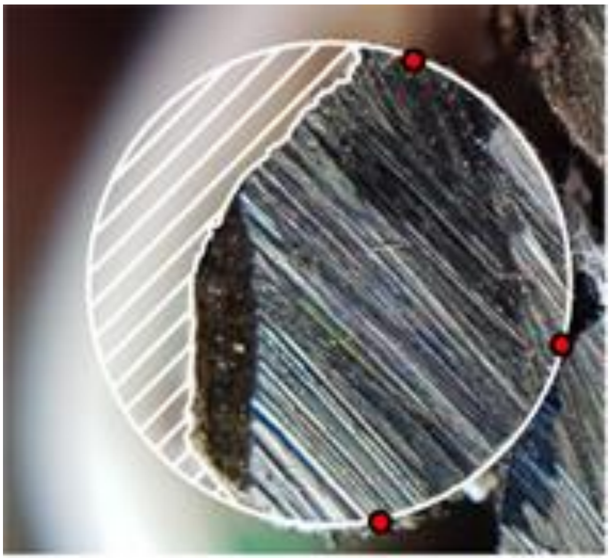
ID-45 Bridge in Seoul



ID-45.1. Overview of the bridge: side view (Yoo et al, 2018).



ID-45.2. Overview of the bridge: section view (Yoo et al, 2018).



ID-45.3. Measuring section loss due to corrosion: identifying the corroded area. (Yoo et al, 2018).

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