A collapse-oriented structural monitoring strategy for bridges

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A collapse-oriented structural monitoring strategy for bridges

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ABSTRACT: In general terms, structural health monitoring aims to assess the existing safety of the structure whilst ascertaining its resilience in the future. The available monitoring technologies and associated techniques are many, with appropriate selection primarily informed by the type of structure and scope of monitoring. Examples include satellite interferometry coupled with specific in-situ measurements, or photogrammetry supported with non-contact vibration measures. This manuscript describes the design and the preliminary results of a bespoke partial collapse-focused structural monitoring strategy for bridges, with particular emphasis on bridges that are near or beyond design life and expected to remain operational. The approach takes its roots from the fact that structural robustness is the antonym of progressive collapse: studying the collapse mechanisms, often triggered by specific conditions, and preventing their chain-activation, implicitly means providing robustness to the whole structure. Considering that the contingent structural design itself anticipates the activation of such triggering configurations by anomalous response to external loads, the strategy proposed herein was to monitor the evolution of such critical configurations and their potential activation. The analysis considered material durability aspects by considering the evolution of the load paths during the bridge's service life based on dynamic environmental conditions and the effects on structural members and components. In turn, this serves to identify the critical triggering conditions that lead to certain service failures or unsafe to remain operational. The approach was applied to case studies in Italy and Australia, with outcomes informing practical implications for design.

1 INTRODUCTION

Road and railway infrastructures are the backbone of the economy of modern countries. The world's infrastructure is valued at approximately €37 trillion (Van Breugel, 2017). The increasing demand for goods and the growing importance of logistics require the infrastructures to be efficient and safe. A malfunction of a transportation system causes delays and can severely impact the economy. The collapse of the Polcevera (Morandi) Bridge in Italy on 14 August 2018, which caused 43 fatalities, cut the national road highway network and caused indirect losses of €359m in the immediate wake of the collapse, with estimated annual losses to the Italian economy in the vicinity of €1bn (Abarca et al. 2022). At a global scale, as an example, the costs associated with the six days closure of the Suez Canal in 2021 caused by the grounding of Evergreen's 'Ever Given' containership on Maersk shipping company only, are about $88.79m (Tran et al., 2025).

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Europe stands out as a central hub in the global roads' dataset, featuring over a thousand kilometers of road bridges that exceed 100 meters in length (CEDR, 2019). Recently, concerns about safety have arisen due to the aging of existing civil engineering infrastructure. Notably, transport bridges constructed post-1945 were designed with a lifespan of 50 to 100 years (Gkoumas et al., 2019). Failures in infrastructure can lead to severe human and economic losses, as seen in the tragic incidents of the Morandi Bridge in Genoa. A study across three European countries revealed that over 30% of highway bridges have deficiencies. The cost of renovations is substantial, exceeding €400 billion for the 27 EU countries. Maintenance, costing between €4 and €6 billion annually, is the only viable solution (O'Brien et al., 2005). Regular maintenance and repairs can extend the service life of civil engineering infrastructures, ultimately mitigating negative economic, environmental, and climate impacts.

In such a framework, inspection and structural health monitoring represent the only practical solutions to adequately ensure the safety and functionality of each bridge and, therefore, the infrastructure. The former is the set of on-site activities periodically carried on to visually check the presence of defects on the structure; the latter is the process of tracking changes in the material and geometric characteristics of the bridge over time through periodic sampling of response measurements. Structural Health Monitoring (SHM) is an important process for assessing the health of infrastructure and detecting damage or deterioration over time (Chen, 2018). This involves the continuous or periodic collection of data from the monitored bridges. The sensors that can be used in SHM can be classified into two classes. Contact sensors include accelerometers, which measure the acceleration of a structure to detect vibrations and dynamic responses (Martucci et al., 2023); linear variable differential transformer (LVDT), which measure displacement and deformation with high precision; inclinometers, which measure the angle of tilt or inclination of a structure; strain gauges, which measure the strain (deformation) experienced by girder beams; force cells or receivers to measure the release of ultrasonic stress waves in materials, namely acoustic emissions (Farhadi et al., 2024). Non-contact sensors include radar or sonar, which uses radio waves or acoustic waves, respectively, to measure the distance and displacement of a structure; photogrammetry, which uses photographic images to measure and analyze the geometry and deformation of structures; and satellite LiDAR (Light Detection and Ranging), which uses laser pulses to create detailed 3D models of structures and measure their deformation and displacement (Kaartinen et al., 2022). Based on the adopted sensors, kinematic quantities (e.g. displacements, velocities, accelerations, strains), static quantities (e.g. stresses and forces) or dynamic quantities (vibration frequencies, vibration modes, damping) are obtained.

With such a wide variety of alternatives, choosing the most suitable monitoring system and the placement of sensors play a crucial role. Such issue is addressed by experts, depending on many points, such as: the type of structure, the presence of existing damages or issues on the system, the available budget for sensors and acquisition system, the need for continuous or periodical measurements, the ability to access the structure during the monitoring, etc. Based on the previous choices, the most appropriate position of the sensors must be determined (Hassani and Dackermann, 2023). Furthermore, by first considering the potential collapse mechanisms of a bridge, the arrangement of SHM systems can be refined such that areas of high significance to the load-carrying capacity or structural robustness of a bridge are more heavily monitored. Taking a collapse-oriented approach to SHM also allows for structural risk and reliability to be readily considered. By quantifying transient loading patterns that a monitored bridge is subject to, as well as the measured (or expected) random variations in the material properties, workmanship, section modulus or area, etc., the structural reliability of a bridge may be estimated and both monitored over time or predicted through the consideration of transient structural deterioration models (such as the linear or multi-linear corrosive section loss models for steel and reinforced concrete structures, respectively) and projected changes to applied loading (for example, a predictive traffic growth model, such as is proposed by Gargett and Cosgrove (2003)). This reliability-based approach would allow for repairs and retrofits to be triaged based on whether a bridge no longer satisfies, or is predicted to soon no longer satisfy, a minimum structural reliability index that considered the economic consequences and potential loss of life associated with a failure, and the relative cost of implementing safety measures – such as a repair, retrofit or replacement of the bridge (JCSS, 2002).

The present paper addresses the problem of sensor placement based on the potential failure modes leading to the collapse of the bridge. First, a short discussion on structural collapse is reported (Section 2), and then a more detailed analysis of the approach is described (Section 3). Finally, an example is reported (Section 4), along with the conclusions (Section 5).

2 COLLAPSE OF STRUCTURES

In the last four years, several major bridge collapses have been recorded worldwide. In Italy alone, in the period between 2000 and 2023, at least 240 partial or total collapses have been evidenced (D'Angelo, 2025). In the USA, the most spectacular was the failure of the 2.6 km long Francis Scott Key Bridge in Baltimora, USA, due to the collision of a container ship against one of its piers. Although the causes of most of the collapses are found in extreme loading scenarios, such as barge impact, train derailment, flooding or fire, a few cases can be referred to factors associated to ageing and maintenance of the structure (e.g. Fern Hollow Bridge in Pittsburg, Pennsylvania USA on 28/01/2022; Paninsky Bridge in Vyazma, Russia on 08/04/2024; Carola Bridge in Dresden, Germany on 11/09/2024; Juscelino Kubitschek de Oliveira bridge in Esterito, Brazil on 23/12/2024).

When dealing with structural failures, it is important to point out the main features of a progressive collapse: (i) the initial failure must be local; (ii) the failure must spread in a manner to other members (or parts); and (iii) the final collapse state must be disproportional to the initial failure (Kiakojouri et al., 2021). There is, thus, a consequential effect, from an initial event to a final state, from a localized part of the structure to the total (or partial) collapse. The initial event can refer to, for example, the impact of a ship against one of the piers or the removal of one of the piers. Although the effects are similar, in the former case we refer to a "threat-dependent" scenario, i.e. an initial damage that is the effect of an event on the structure (in this simple example, the impact of a vessel with a given tonnage travelling with a specific direction and velocity). The latter case is referred to as a "threat-independent" damage as the pier removal is not linked to a specific event (it can be caused by an impact, an explosion, a settlement, hydraulic drag during flooding, etc.).

It is worth mentioning that the risk of failure due to extreme loading scenarios can be mitigated through various strategies, first by controlling the occurrence of such events or limiting the damage to a few members. For example, the piers of the bridges crossing waterways can be equipped with impact-absorbing fenders to dissipate the collision force caused by a ship. Alternatively, the single components can be strengthened to resist actions that are larger than the design loads required in the construction codes. On the other hand, the risk of collapse can be mitigated by providing the bridge sufficient robustness, which is the "*ability of the structure not to be damaged by events like fire, explosion, impact or consequences of human errors, to an extent disproportionate to the original cause*" (ISO 2394, 1998). This can be achieved by providing alternative load paths in the event of failure of one element or by dividing the entire bridge into structurally independent subsystems, thereby keeping collapse size to a minimum.

When the hazard is related to ageing or material degradation it is necessary to identify the critical components and concentrate the efforts to check if their structural safety is still satisfied. This operation requires a deep knowledge of the structural functioning of the bridge structure and a clear understanding of the effects that can be generated in the case of failure of a single component.

2.1 *Hierarchical robustness relationships between bridge components*

Differently from frame structures in buildings, an inherent hierarchy between elements can be observed in bridges, with elements that support and others that are supported. This idea lies at multiple scales, from the single component to the overall assembly. Each component of the bridge is made of various elements, such as a concrete deck consisting of a grillage of main beams connected by transverse beams over which a slab lays. Similarly, the bridge substructure is composed of piers with a cap beam and piles. The foundations are usually made of separate piles connected at the top by a slab or a beam. The failures at single elements can occur. For example, in prestressed beams, if one of the tendons degrades due to corrosion, the forces can be redistributed among the remaining tendons. However, this redistribution is not always sufficient to prevent failure. In ordinary concrete beams (without prestressing), the usual amount of reinforcement is larger than required to support external loads, but damage to one element can still compromise the overall capacity. In a concrete bridge deck, the arrangement of elements is intended to foster robustness, but damage to one element can reduce the capacity of the entire deck. Beam grillage, designed to transfer force, may not always provide adequate robustness if one of the beams fails. Similarly, concrete box beams have inherent redundancy, but redistribution between elements may not always prevent failure. For piles, extra reinforcement is often added to counteract undesired phenomena, but this does not guarantee against failure during the curing phase (De Biagi et al., 2022).

The robustness of a bridge can be understood by examining the arrangement of its elements. This helps in understanding how damage to one element can lead to a local or total collapse of the structure. Given the wide variety of static schemes in bridges, a general approach has been proposed to address progressive damage and global failure. To achieve this, it is important to consider the role of each component within the overall structural setup. The analysis can typically be performed by considering the statics. Specifically, there is a hierarchy in load transfer, where some elements support others. For example, in Gerber supports, one element is carried by another. The type of support and its ability to function in both compression and tension, or only in compression, must be considered when analyzing bridge's robustness.

Depending on the arrangement of the elements and the typology of the bridge, some considerations on the overall robustness can be formulated. For statically determinate schemes, such as the typical viaduct with equal span beams shown in Figure 1(a), local damage cannot be tolerated. A hinge in the beam creates a mechanism that leads to the failure of the span, Figure 1(d). However, progressive collapse is prevented by the deck's inherent compartmentalization. In contrast, balanced systems are more prone to progressive collapse. Figure 1(b) shows a statically determinate system where cantilever beams on piles are connected by suspended decks, often using dapped-end beams. Failure of a component, such as the supports of the suspended deck, can cause unbalanced forces in the cantilever system, leading to failure and damage propagation, Figure 1(e). Surely, statically indeterminate structures present the more robust solution. For example, in continuous decks over supports of Figure 1(c), the formation of a hinge does not create a mechanism but can largely affect the distribution of the forces within the elements, causing the formation of additional hinges or other failures on other members, Figure 1(f). In general, if the system becomes a mechanism after a component fails, its robustness is null.

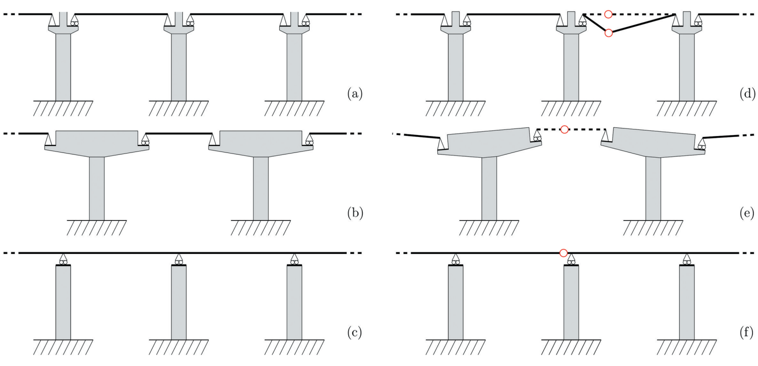

Figure 1. (a-c) Sketches of typical beam arrangements in existing concrete bridges and (d-f) effects of the formation of a hinge in the deck beams, from De Biagi et al. (2022).

2.2 *Collapse of masonry bridges*

Interesting considerations can be drawn for masonry arch bridges as well. In understanding the possible failure mechanisms, the first mechanical studies by Heymann (1982) on the collapse of vaulted structures in which he found that at least four hinges must form to generate a mechanism on the structure. Although this consideration proves that settlement in masonry bridge piers does not lead to the collapse of the structure as just three hinges form, see Figure 2, it must be noted that in shallow arches, the exceedance of compressive strength is the relevant failure mechanism (Drosopoulos et al., 2006).

Figure 2. Deba bridge, Spain. The settlement of the central pier was induced by shipworm infestation in the timber foundation piles, from Malena et al. (2021).

In multispan masonry arch bridges, the local failure of a structural component in one span may result in an unbalanced force that can cause the damage to propagate and the adjacent spans to fail, up to the complete bridge collapse, as occurred, for example, for the stone bridge over Tuojiang River, Fenghuang, China, that collapsed on 13 August 2007.

3 COLLAPSE-ORIENTED MONITORING STRATEGY

The bespoke monitoring strategy accounts for the potential failure modes of the system, and it can be structured as follows. For the sake of this work, we will focus on quasi-static measurements on the system (displacements, rotations, strains), in a hypothetical scenario with a set of transducers to be laid on the target infrastructure. Differently from the most conventional sensor layouts, which only focus on a very specific portion or, conversely, cover a longer tract in a homogeneous fashion, with spatially constant sensor density, we propose an inhomogeneous sensor layout, aiming at covering most of the infrastructure's whole length while using a variable sensor density. Taking advantage of engineering considerations on structural robustness, we want to propose a global sensor layout locally focused on the most-likely-to-fail-spans and only on the most-likely-to-plasticize tracts of those spans, rather than having a constantly spaced grid of displacement transducers as commonly done. Therefore, the bespoke grid of sensing devices will be coarser, far from the critical points and denser in the surroundings of what we suppose will be the most likely cross-sections for the formations of plastic hinges or support modification. The following steps are required to define a collapse-oriented monitoring strategy.

(1) The bridge components are identified. Examples of bridge components are beams, slabs, supports, piers, abutments, etc.
(2) The structural relationships between the components are drawn, focusing on the supporting-supported conditions, the directionality of the supports, unilaterality or bilaterality of the supports (i.e., if the support works both in tension and compression or not), the presence of constraints that are activated when specific kinematic conditions hold (e.g., excessive displacements, failure of the support, etc.).
(3) The possible failure mechanisms of the system are simulated, considering the minimum number of "damages" that must be imposed on the structure to cause its failure. Each damage consists in a reduction of the degrees of constraint of internal or external supports (like support removal, fixed to pinned connection, lack of bilaterality of the supports, etc.) or in a modification of the continuity of the component (like the formation of plastic hinges). As the failure corresponds to the formation of a mechanism, the rigid body hypothesis holds, making the process straightforward and allowing the possibility of exploring several collapse scenarios. The outputs of step 2. serve as a guide for understanding the potential failure modes. Insights can be obtained from the statistics provided by Zhang et al. (2022) or by

Deng et al. (2016) on the causes of bridge failures. The simulations are related to the rigid body mechanisms only, without considering the loads on the infrastructure.

(4) Study of the loading conditions and the effects on the components with the specific purpose of highlighting if any of the failure mechanisms listed in step 3. can be activated. A few questions can guide this step, such as: are there criticalities in the supports, say changes in force direction? Which are the cross-sections that experience larger forces? How are the loads redistributed on the system? How the continuity of the deck is relevant in the redistribution of the bending moments? This analysis can be done under the hypothesis of linear elasticity, considering code-based provisions in terms of ordinary traffic and oversized loads. In addition, the possibility of non-code-based exceptional loads on the structure (like impact against the piers, etc.) is assessed.

(5) The current condition of the infrastructure is assessed. The presence of deteriorated parts of the infrastructure, like corrosion in the supports, the corrosion in the beams/girders, the presence of foundations or abutment settlements, the lack of pre- or post-tension in tendons, corroded stirrups, missing mortar layers in masonry, or weathering of masonry/rock blocks, etc., are recorded and the resulting effects on the capacity of the components of the bridge are quantified.

(6) Based on the previous steps, the most likely failure mechanisms and the most relevant, e.g. in terms of activated mechanisms, are identified and the monitoring system that serves to identify the modifications in the structure that cause the formation of the mechanism is designed.

(7) Thresholds on the measured quantities (maximum displacements, rotations or stress/strains) are set to issue warning conditions for the operational activities on the structure. It should be considered that control of the loads acting on the infrastructure can provide better insights into the state of the system.

(8) Considering the construction material, quality and tolerances, and typical loading imposed on the infrastructure, random variations in the parameters related to the load resistance of the infrastructure can be defined in probabilistic terms. These statistics can then be used to establish the structural reliability of the infrastructure in its as-is condition. This reliability may then be considered to a minimum benchmark value to establish if risk associated with the structure is acceptable.

(9) Based on the existing and predicted deterioration of the infrastructure, an approximation of the transient reliability index can be established. This would facilitate the triaging of future retrofitting requirements between other infrastructures, as well as that for SHM implementation.

4 AN EXAMPLE OF APPLICATION

An example of application of the proposed monitoring strategy is presented in this section. For the purposes of the paper, a prestressed concrete multi-span bridge located in North Italy is considered. The Lambro viaduct is located at km 11.796 of the A1 motorway, between Milan and Bologna. The bridge, operative since 1959, is composed of 5 spans of separate length: 29.4 m, 56 m, 29 m, 15.4 m and 15.8 m. The top sketch of Figure 3 schematizes the bridge. From a static point of view, the main span (span no. 2) is characterized by a cantilever scheme with dapped-ends beams and central girders. The shorter beams are simply supported over the piers and the abutment. The cantilever scheme is interesting as it makes the supports work in tension: when the load is in the centre of the largest span, the left support tends to raise. For this reason, the designer included concrete pendulums with additional steel bars to absorb the uplift force, while keeping the rotational and translational degrees of freedom. The uplift force on the opposite of the cantilever is contrasted by the simply supported span no.4. The first sketch of Figure 3 illustrates the bridge in its actual support conditions.

Recalling the procedure previously described, the bridge components and their structural relationships have been identified. The possible damages are related to the ineffectiveness of the supports or the formation of internal joints and are depicted in Figure 3. Mechanism #1 refers to the failure of the uplift bars on the left abutment (*a*). The beam I rotates around the pin *b*, causing the rotation of girder II. Mechanism #2 refers to the formation of a hinge on support *b*, causing the rotation of the right part of beam I and the rotation of girder II (a symmetrical situation occurs if the hinge is formed on support *e*). The third mechanism is the formation of a hinge on the supported girder, which has effects on this component, only. A similar consideration can be drawn for Mechanism #4 on beam IV (the same problem can occur on beam V). Mechanism #5 refers to the formation of an internal joint (due to shear failure) on the left side of beam IV, causing the unloading of the support *f*, with consequent rotation of the cantilever beam III over the support *e* and, as a side effect, the rotation of beam II. It must be noted that the same joint on the right side would have caused a completely different mechanism as the support f would not have been unloaded. Mechanism #6 refers to the formation of the joint on the left of the support *f*, with consequences on beams III and II.

Referring to the loading conditions on the system, the strongest bending moments are recorded when the midspan of beam II is loaded, while the largest shears occur when the load is located close to supports *b* or *e*. It must be noted that the cantilever beams have variable cross section, taller on the supports *b* and *e*, hence with enhanced capacity with respect to the shear. The maximum shear on the beams II, IV and V occurs when the load is close to the ends, as they are simply supported beams. The scheme is statically determinate. Hence, a settlement of any pier or abutment would not cause extra forces in the elements, but a modification of the horizontality of the deck.

Considering no degradation of the structure, the most relevant mechanisms are selected. Based on the criterion that the worst mechanisms are those that activate the longest part of the bridge, it can be stated that Mechanism #1, which involves the full beam I and the girder II, and Mechanism #5, involving beams II, III and IV, represent the most significant scenarios. A monitoring system for such specific initial damages has to be chosen; strain sensors in the bars in support *a*, plus an LVDT transducer to check the crack opening on beam IV, are suggested. Obviously, planned inspections of the entire structure are necessary, as other failure mechanisms can also be activated.

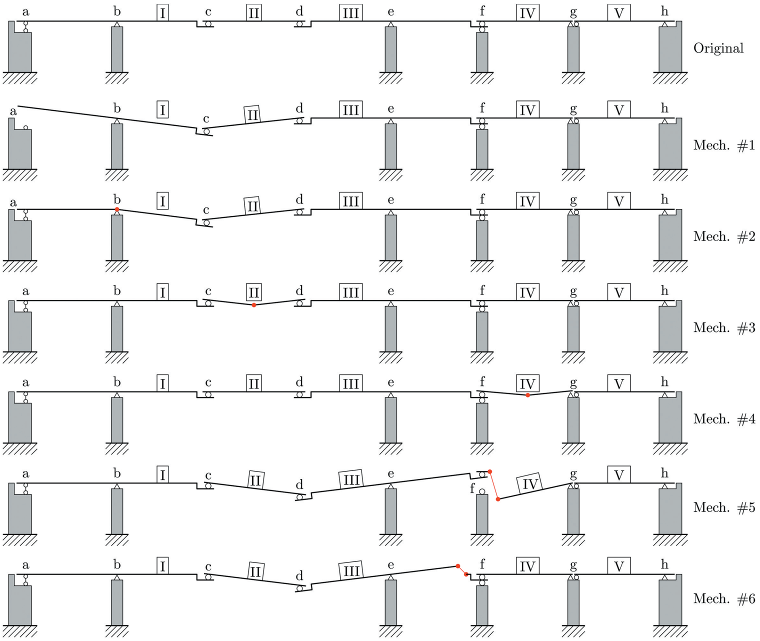

Figure 3. Static scheme of the Lambro viaduct and the five investigated mechanisms.

5 CONCLUSIONS

Optimal sensor placement is still an open question in structural health monitoring. Depending on the measured quantities and the type of structure to study, various techniques are available. Here, a method based on the selection of the worst damage scenarios is proposed. The approach is based on the study of the possible collapse mechanisms that can emerge on the infrastructure following a localized damage. Although the approach is general, each bridge has its own characteristics and, hence, the sensor setup is tailored to the specific infrastructure. An example of application on a prestressed concrete structure is proposed. Interesting insights into the collapse of arch structures, e.g. following the studies of Heyman (1982), make the approach also suitable for masonry bridges. The methodology preliminarily shown here is still in development and is currently being extended. In the example reported here, only simplified planar static schemes and previous engineering knowledge about the most likely failure mechanisms and scenarios were considered. Current works are extending this approach to actual 3D finite element models of real bridges and viaducts, with numerically modelled collapse-induced mechanisms.

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