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ABSTRACT: Bridges are among the most relevant structural engineering works in transport and mobility infrastructure. Depending on a wide range of needs and constraints, various types of structures are found: simply supported beams on piers, box girders, Gerber decks, arches, balanced systems, etc. European infrastructural heritage has now more than 50 years of working life, with increasing traffic loads and continuous ageing needs maintenance. Recent cases of existing bridge failures have opened the problem of the robustness of such systems. To this aim, a multilevel framework is formulated. This approach is needed for studying the propagation of damage from the element level to the whole structure. In the proposed multilevel approach each single part is studied and its damage tolerance is assessed. The effects of the damage on the single part on the overall bridge structural scheme are then assessed. This multilevel analysis allows to define a member consequence factor, i.e., a measure of the overall effects of the local damage. The proposed methodology is applied to case studies.

1 INTRODUCTION

Bridges are among the most important structural engineering works in the transportation and mobility infrastructure, allowing high-speed and regular tracks to be built in densely populated places or in topographically difficult areas. Various types of structures are found depending on a wide variety of purposes and constraints: simply supported beams on piers, box girders, Gerber decks, arches, balanced systems, and so on (Giannetti 2018). European road and railway infrastructure stretches back to the 1960s. With growing traffic loads and constant ageing, the infrastructure legacy has now been in use for more than 50 years and requires repair (Chiaia & De Biagi 2020). Because the failure of one element might lead to the bridge progressive collapse, inspections to determine the extent of damage and its impact on the member's capability must be scheduled. Recent bridge disasters have raised concerns about the damage tolerance of such systems (Morgese et al. 2020).

Although robustness is a key aspect in assessing the safety of the structures subjected to threads, the large part of the studies focuses on specific typologies of existing bridges, rather than on general approaches to quantify the robustness for a wide set of structures. A multi-scale approach is herein proposed to address this goal. A focus on structural robustness is proposed, first.

1.1 *Structural robustness*

The idea of robustness is widely diffused in technical and non-technical disciplines. Briefly, with reference to a general system, its robustness consists in the ability to maintain function even if changes in the internal structure or in the external environment occur (Callaway et al. 2000). This concept is turned in the structural engineering discipline with different facets. For example, the ISO 2394 (1998) refer to robustness as 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*", pointing out the origin of the damage. Other scholars propose a definition that is related to the disproportion between the initial damage and the consequences (Agarwal & England 2008), or to the disproportion between the causes of the initial damage and the consequences (Biondini et al. 2008).

The structural robustness has not be associated with the idea of redundancy. Although the former is related to a property of the system, the redundancy is somehow considered in the arrangement of the elements, for example in frame structures. Besides, compartmentalization, which is inherently the opposite of the redundancy, is one of the strategies to provide robustness to a structure (Starossek 2018). In a similar manner, the robustness has not to be confused with resilience. The former is related to the structure, the latter denotes the ability of the system (that is, for example, a building with the activities performed) to be recovered after the damage.

The absence of a unique definition of robustness is reflected by the absence of a unique metric for quantifying it. As highlighted by Starossek and Haberland (2011), although a quantitative metric is useful, so far none has emerged as preferable.

The variety of the definitions is reflected in a multitude of metrics for quantifying the robustness of a structure (Kiakojouri et al. 2020; Kiakojouri et al. 2021). In a simplified treatise, the existing metrics can be either considered as stiffness-, damage- or energy- based measures. The stiffness-based approaches consist in a comparison between specific properties of the structural system in the damaged and undamaged configuration (Frangopol & Curley 1987; Biondini et al. 2008; Starossek and Haberland 2011). Recently Chiaia et al. (2019) proposed an evaluation based on kinematic matrix. The damage-based measures monitor the performance of the system in term of general risk, fragility or vulnerability. For example, Starossek and Haberland (2011) proposed a metric R_d that is based on the complement of the dimensionless total damage:

$$R_d = 1 - \frac{\xi_{d_{in}}}{d_{acc}} \tag{1}$$

where ξ_{din} is the maximum total damage resulting from the initial damage d_{in} and d_{acc} is the acceptable total damage. Note that damage progression plays a relevant role in the metrics, since ξ_{din} is generally larger than d_{in}. Energy-based measures intend to compare the energy released during an initial failure and the energy required for failure to progress (Starossek & Haberland 2011). Metrics merging different approaches are found. For example, De Biagi (2016) suggested the normalized structural complexity index (De Biagi & Chiaia 2013) as a measure of the robustness of the structure.

2 A MULTI-SCALE APPROACH FOR BRIDGE ROBUSTNESS ASSESSMENT

The metrics proposed in the literature and briefly discussed in the previous section well fit for large structures, such as frames. To define a profitable approach to quantify the robustness of bridges, although they present different static schemes, basic properties should be first reported.

First, (i) a statically determinate structure is not robust since every possible damage can have consequences. Every structure is designed to transfer loads. The bridge is designed to transfer loads from the deck to the foundations. (ii) Load transfer is achieved through specific paths and it is governed by the ways the elements are arranged and the stiffnesses are distributed across the structure (De Biagi & Chiaia 2013). (iii) Each element of the structure has its own robustness (intrinsic robustness). For example, there are cases of elements that are oversized, there are redundant components, there is a redistribution of stresses over each cross-section. (iv) The failure of a single element has an effect on the whole structure. Elements arrangement and single-component properties (e.g., ductility) influence collapse propagation.

The previously reported concepts should be kept in mind when formulating a method for assessing the robustness of existing bridges. Differently from new constructions, where the project information is sufficient to draw considerations on the geometry of the system, the weights and the load distribution, the capacity of the single elements and their ductility, in existing constructions hypotheses should be made. Although the geometry of the structure can be easily determined with a survey, the actual material properties (e.g., compressive strength of concrete), the actual arrangement of the resisting elements in the cross section, the effects of degradation and ageing on the components make the evaluation of the robustness trivial and difficult. Meanwhile, the existing bridges exhibit different structural conceptions, depending on where they are located, who designed them, when they have been designed. In the Sixties, large span arch bridges were built, while nowadays viaducts are preferred.

To this aim, the proposed multi-scale approach, based on a sort of hierarchy in load transfer, herein proposed intends to highlight a framework for assessment of the robustness of such a variable structural item. Essentially, the robustness is the cross-result of two separate evaluations: the robustness of each component of the bridge and the robustness of the static scheme of the bridge, as detailed in the following.

2.1 *Robustness of the single component*

Each component of the bridge is made of various elements. For example, a concrete deck might consist in a grillage of main beams connected by transverse beams over which a slab lays. Similarly, bridge substructure is composed of a cab beam and the piles. The foundations are usually made of separate piles connected in the top by a slab or a beam. Other examples can be traced, considering that the technologies in bridge design and construction are various and sometimes tailored to specific site constraints (material, geotechnical problems, construction phases, etc.).

Although a large variety of components can be traced, it should be noted that a certain amount of robustness can be associated to each. For example, considering prestressed beams, the number of tendons is usually larger than one, with the possibility of redistributing the forces among the remaining parts if degradation phenomena, like corrosion, act on one of the tendons. This allows a certain amount of robustness with respect to environmental phenomena and degradation. Similarly, in ordinary concrete beams (without prestressing) the usual amount of reinforcement is larger than the required quantity to support the external loads and can provide additional capacity when one of the elements is damaged. Considering a concrete bridge deck, the arrangement of the elements foster the robustness of the component. In this sense, although is difficult to correctly quantify the contribution, the slab redistribution transfers the loads from the elements that might reduce their capacity (due to a damage) to the elements that are still "safe". Beam grillage acts in the same way. Although transverse beams are designed for creating a transfer of force, their overstrength can enhance the robustness of the system when one of the beams would fail. Another example follows from concrete box beams where there is an inherent redundancy within the cross section in which redistribution can act between the elements. Similar considerations can be traced for the piles: usually, extra reinforcement is put to contrast undesired phenomena (for example, during the curing phase).

It results that, in general, a certain degree of robustness exist withing each component of the bridge. This results in a sort of extra-capacity for providing alternative load paths and redistribution.

2.2 *Robustness of the components' arrangements*

Depending on the arrangement of the elements, a general theory on the robustness of the bridge can be traced. This serves for understanding how a damage on an element can progress into a local or total collapse of the structure (Kiakojouri et al. 2020; Kiakojouri et al. 2021). The large variety of static schemes that are present in bridges implicitly requires a general approach for dealing with progressive damage and global failure. To this aim, there are points that must be considered for understanding the role of each component in the general structural setup. The analysis can be generally performed considering the statics. In detail, there is a sort of hierarchy in the load transfer, with elements that are carried by others. This is the case, for example, in Gerber support, with an element that is carried by another one. The typology of the support, the possibility of working both in compression and in traction (Fig. 1), or in compression, only, must be considered in the analysis of the robustness of the bridge.

Figure 1. Slider support of a bridge with compression and tension reaction forces.

Depending on the arrangement of the elements, the typology of bridge, some considerations on the overall robustness can be formulated. Statically determinate schemes, such as the one reported in Figure 2.(a), which represents a typical viaduct with equal span beams, cannot tolerate local damage, since a hinge in the beam produces a mechanism with the consequent failure of the span, as sketched in Figure 3.(a). Meanwhile, progressive collapse is prevented by the inherent compartmentalization of the deck. Balanced systems, on the contrary, are prone to progressive collapse. Figure 2.(b) depicts a statically determinate system in which cantilever beams on the piles are connected the ones to the others by a suspended decks. Usually, dapped-end beams are adopted in such configurations. The failure of one of the components, for example, the supports of the suspended, deck could cause unbalanced forces in the cantilever system with consequent failure and damage propagation, as sketched in Figure 3.(b).

Finally, the arrangement of components that presents the larger robustness is the one in which statically indeterminacy holds. For example, in continuous decks over supports, see Figure 2.(c), the formation of a hinge would not cause a mechanism to be formed (Fig. 3.(c)).

To generalize, the use of statics allows to understand the potential effects of a variation in the static scheme of the bridge. If the system is turned into a mechanism after the failure of the component, the robustness is null.

3 EXAMPLES

This section intends to present some of the concepts previously mentioned in order to further explain the ideas behind the multi-scale approach.

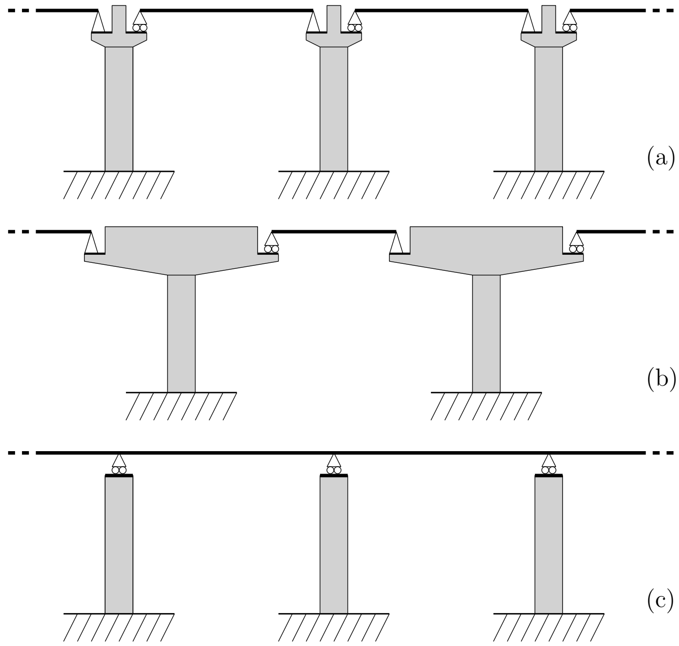

Figure 2. Sketch of typical beam arrangements in existing concrete bridges.

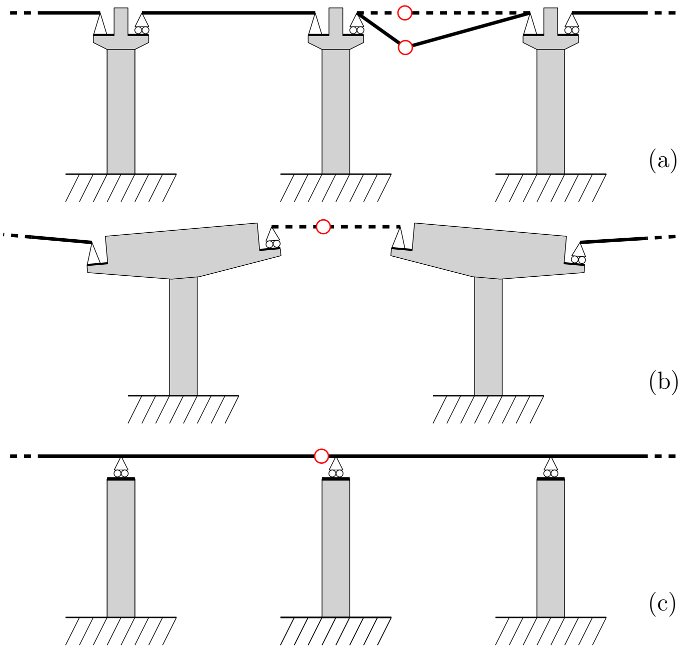

Figure 3. Effects of the formation of a hinge in the deck beams. The damage does not propagate only in the statically indeterminate continuous beam.

3.1 *Lesson learnt from the failure of an existing bridge: the case of the bridge over the river Magra*

The bridge over the river Magra, which connected Caprigliola and Albiano (Italy), built in 1949, had five arches (Fig. 4). It was built over a pre-existing bridge, demolished by the German Army during WWII. The span of the arches was 51.15 m, the width of the roadway was 6.5 m plus two cantilever slabs of about 83 cm. The slab was separated for each arch. Three-hinged statically determined arches with a Maillart cellular scheme were used to eliminate stresses caused by temperature variations and shrinkage, as well as to avoid the effects of possible foundation settlements and stone masonry of the piers (which had been subjected to the effects of mine deflagration). Top and base hinges were made with crossed ø30 reinforcement bars. Displacement monitoring was performed over the bridge. One of the two abutments experienced small lateral displacements due to a slow-moving landslide (Chiaia & Piana 2021).

The viaduct collapsed on April 8, 2020, causing only two injuries (Fig. 5). Although forensic investigations are still ongoing, the causes of the failure are attributed to the relict landslide which caused an anomalous displacement on the abutment that, by consequence, blocked the rotational capacity of the hinge and induced undesired stresses in the arch. The concrete failed and a new hinge formed in a three-hinge arch causing a mechanism. Thus, the span collapsed and the piles, being simply supported over the foundations, were not able to sustain the horizontal forces due to the lateral arches and start rotating, causing the failure to laterally propagate in a “domino” manner.

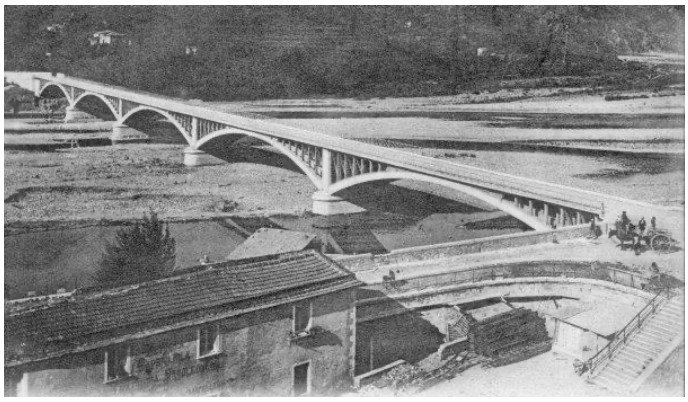

Figure 4. View of the Magra bridge between Caprigliola and Albiano (Italy), source Wikipedia.

Figure 5. View of one of the piles of the bridge after the collapse.

The capacity of the cross-section to support an extra (unexpected) bending moment would prevent the mechanism to be activated. The key aspect in the failure of the bridge over the river Magra is the fundamental contribution of equilibrium in the structure. As already mentioned, the knowledge of the path of the forces constitutes a key information for quantifying the effects of a local damage and, by consequence, the robustness of the bridge.

3.2 *Poggettone e Pecora Vecchia viaduct*

"Poggettone e Pecora Vecchia" viaduct is located on the Italian Apennines along the A1 highway between Bologna and Florence. The viaduct, which is 460 m long, was opened to the traffic in 1960. It consists in eight 42 m span arches with frame structure to support the deck. Each arch is physically separated from the others. All the structure is in ordinary reinforced concrete (Fig. 6).

Figure 6. View of Poggettone e Pecora Vecchia viaduct on the A1 Italian highway.

The main components of the bridge are the deck, the girders, the vertical columns, the arches and the foundations. Each component has a precise structural role in the bridge and a local failure (or, simply, a damage) can cause localized to total collapse. Referring to the girders, the presence of transverse beams foster load transfer. Similarly, vertical elements allow redistribution of forces in case of failure. On the contrary, arches, which static role is fundamental, are the key parts of the bridge because: (i) there are separate arches and, thus, no redistribution occurs; (ii) they are designed to transfer axial forces with a limited bending. In the case in which one of the arches would fail, the compartmentalization of the system will guarantee that the collapse would be limited to a single span, rather than to the whole bridge. Although simple, the hierarchical analysis allows to qualitatively define the robustness of the bridge, based on evaluation of the possible failure mechanisms and their effects on the system.

3.3 *Lambro viaduct*

Lambro viaduct is located in the South of Milan along the A1 Italian highway between Milan and Bologna. The bridge is composed of 5 spans of separate length: 29.4 m, 56 m, 29 m, 15.4 m and 15.8 m. Figure 7 shows a sketch of the static scheme of the bridge: four beams are present over 8 supports. Some supports work both in tension and in compression (details of the support named "a" in Figure 7 is illustrated in Figure 1). The central span consists in a suspended deck with dapped-end beams. It is interesting to note that failure of some components results in the failure of the total bridge. The removal of support "f" will result in an unbalanced system and parts "II" and "III" will create a mechanism.
A similar consideration holds for the support "a". The failure of the ends of the suspended deck will cause a local failure of the system. The robustness of the system is thus strictly related to the ability of the supports to properly work as they are designed.

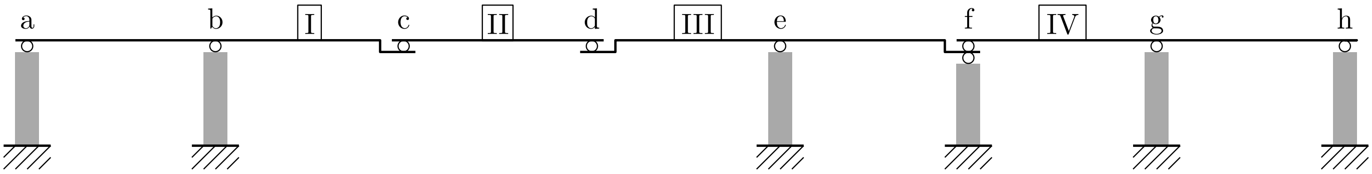

Figure 7. Static scheme of the Lambro viaduct.

4 CONCLUSIONS

The present paper details an approach for defining the robustness of existing bridges. The method accounts for the mutual dependence between the single components and their arrangement. Although the approach is still at a preliminary, it contains all the ingredients to develop a more detailed framework. Differently from common approaches that tend to define a threat and, then, to compute the outcomes on the structure, the present approach deals with a multi-stage analysis, focusing on the mutual interaction between each part of the structure. Although simple, this method can be adopted in any sort of bridge since a hierarchy can always be traced. Future developments will account for the quantification of the robustness.

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