A QUANTITATIVE RISK-BASED METHOD FOR PRIORITY ASSESSMENT OF EXISTING BRIDGES TO SEISMIC AND TRAFFIC HAZARDS

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Abstract: *Bridges are key infrastructure of road networks and their closure due to miss-function or collapse could result in significant economic and societal losses. Many of the existing bridges in Italy, as well as in other European countries, are now older than 50 years and there have been many reports of bridge failures recently. Due to ageing, deterioration, existing damages, and inadequate maintenance, bridge structures may experience changes in condition, with respect to that at the time of construction. To address this concern, in Italy, multi-level and multi-hazard qualitative guidelines for risk evaluation of large-scale bridge portfolios were published in 2020. However, management entities are unable to create fine-grained priority ranking of bridges within a network due to the qualitative nature of the assessment approach. On the other hand, the majority of quantitative approaches that are available in the literature estimate the amount of risk in a variety of ways, exclusively taking into account either the data on seismic hazard or the assessment of the defects/damage condition alone. This study proposes a method for condition and risk evaluation of bridges considering general structural robustness and the presence of defects, simultaneously. The proposed approach uses numerical expressions to define risk and, thus, the priority of a bridge within a stock considering hazard, exposure and vulnerability, and is applied to a case study of thirty real bridges in northern Italy, considering earthquakes and traffic loads as hazards. The findings are discussed from various perspectives, including the impact of defects on bridge vulnerability and priority ranking, according to two different defect state quantification strategies (average and critical). Finally, the results are compared with the current Italian bridge management guidelines.*

1. Introduction

Over the past few decades, ageing bridge structures have gained international attention followed by several bridge failures worldwide, making the bridge operating agencies look for new methodologies to manage these structures. Such methodologies should be primarily efficient and simple to use for risk condition evaluation of bridges. The most common risk assessment methods rate the bridges in a stock according to their importance; some recent examples of such methods are introduced in the following briefly described works. Zizi et al. (2023) presented an empirical risk assessment method based on seismic hazard to create a priority rank for bridges to perform damage inspections and applied the method to a case study of bridges in the Italian province of Caserta. Meoni et al. (2023) proposed a priority ranking method for bridges taking into account the risk assessment and the visual inspection costs with the aim of providing a visual inspection plan. Ivanković et al. (2021) developed an approach for prioritisation of bridges for repair purposes, using data from damage inspections and bridge performance indicators at component, system and network levels. The Federal Highway Administration of the United States (FHWA, 2022) has also issued instructions for condition assessment of highway bridges in order to ensure their safety. As summarized in FHWA (2016), more other bridge health indices are currently available and used in several countries around the world, as well as very recent optimal prioritisation methodologies proposed by various researchers, such as the works of D'Apuzzo et al. (2022), Abarca et al. (2023), and Saler et al. (2023).

The number of bridges in Italy is estimated to be about 120,000 (Santarsiero et al., 2021) and the majority of them were built between the 1950s and 1970s (Pinto and Franchin, 2010). It is expected that most of these bridges lack sufficient durability requirements, since their construction dates back prior to introduction of modern design regulations, such as those for seismic design issued in 2008 (Masi et al., 2021) and those for updated construction regulations (NTC 2018). Moreover, older bridges may not be able to withstand the present traffic loads, since such demand levels were not foreseen in their design (Bencivenga et al., 2022). In addition to their age, usually inadequate maintenance has also made the risk condition of many bridges worsen. The failure of the Annone overpass in Lecco in 2016 (di Prisco et al., 2018), the Morandi bridge in Genoa in 2018 (Calvi et al., 2019) and the multi-span arch bridge of Caprigliola in 2020 (Scattarreggia et al., 2022) are a few examples of recent bridge failures reported in Italy, showing their critical current condition.

In response to the aforementioned situation, the Italian Higher Council of Public Works published regulations for the risk assessment and management of existing bridges (ITA-Guidelines) in 2020, in order to provide a uniform management approach for bridge stakeholders. The ITA-Guidelines provide a multi-level and multi-hazard risk evaluation approach, featuring a preliminary classification of the bridges in five Classes of Attention (CoA), namely High (H), Medium-High (M-H), Medium (M), Medium-Low (M-L), and Low (L), indicating the level of attention that must be given to a bridge and, where applicable, the need for more refined analyses. The main drawback of the ITA-Guidelines, given such a qualitative definition of risk, is their inability to differentiate the priority of bridges within the same CoA. The application, strengths and shortcomings of the ITA-Guidelines have been a recent subject for several researchers (e.g., Cosenza and Losanno, 2021; Santarsiero et al., 2021; De Matteis et al., 2022; Fattorini et al., 2023; Fox et al., 2023).

In this study, a quantitative approach is developed to rate the priority of bridges based on a simplified description of risk, which helps to overcome the constraints of qualitative methods, such as those prescribed in the ITA-Guidelines (Hamidpour et al., 2023a). The method proposes closed-form expressions for vulnerability, exposure, and hazard as three main constituent parameters of risk assessment using the ITA-Guidelines instructions, as well as recently proposed methodologies (e.g. Zizi et al., 2023). The vulnerability parameter consists of two components linked to structural features (according to the ITA-Guidelines) and the presence of defects/damages in the bridge elements (using the United Kingdom Bridge Condition Index, BCI_{UK}, 2007). The exposure parameter is derived by estimating the potential impacts of a bridge collapse in the network context. The commercial vehicle traffic and the anticipated Peak Ground Acceleration (PGA) of an event with a 475-year return period at the bridge site are used to characterize the sources of hazard. Finally, the priority ranking is calculated as the weighted average of the three constituent parameters and presented in absolute and normalized ways. The priority ranking results of the proposed method are compared to the CoA of bridges acquired from the ITA-Guidelines, considering a case-study of 30 real bridges in northern Italy.

2. Overview of the proposed risk-based priority ranking method

In order to understand the risk susceptibility condition of a bridge, assessments based on a variety of influencing factors are performed. Generally, to decide about the required measure to be taken, a priority list of the bridges in a stock can be informative and helpful. The risk-based assessment methodology developed in this study considers three main parameters, namely, vulnerability (V), exposure (E) and hazard (H), evaluated through equations proposed in what follows. The risk-based priority ranking (PR) is quantified as the weighted combination of the three mentioned parameters, according to Eq. (1).

$$PR = 0.4V + 0.4E + 0.2H \tag{1}$$

In this formulation, while the vulnerability and exposure are assigned a greater weight of 0.4, a lower weight of 0.2 is given to the hazard. This unequal weighing approach originates from past bridge failure incidents in Italy that revealed the highest importance covered by vulnerability and exposure. Indeed, observed failures were mainly triggered by the critical structural condition and inability to carry loads, while associated socio-economic consequences resulted to be of great importance. However, according to a sensitivity analysis on the weight ratios as a part of this research, which is not presented for brevity reasons, the assigned weights do not change the final ranking result much.

The priority ranking obtained from Eq. (1) provides an absolute score (for the Italian territory) for every bridge. Thus, for comparative assessment of bridges in a specific stock, a normalized priority ranking (NPR) is introduced in Eq. (2). It provides a relative priority rank for a bridge among others in a given inventory. PR_{max} and PR_{min} represent the highest and the lowest priority ranks acquired for bridges in a bridge set.

$$NPR = \frac{PR - PR_{min}}{PR_{max} - PR_{min}} \tag{2}$$

2.1. Vulnerability

The vulnerability parameter (V) in this study is quantified by Eq. (3), which consists of two main components representing the vulnerability due to structural characteristics (V_{Str}) and the vulnerability due to damages and defects condition of the bridge elements (V_{Def}). V_{Str} is derived mainly based on the provisions of the ITA-Guidelines, while V_{Def} is determined using the aforementioned UK method for the bridge condition index (BCI_{UK}). According to the UK method, there are two defect conditions for every bridge including the average (Avg. Def.) and the critical defects (Crit. Def.) conditions. The average defects represent the bridge overall condition based on all damaged and undamaged elements. On the contrary, the critical defects condition shows the criticality of the bridge when accounting for the extremely poor condition of one of the elements, which has the most importance in the overall integrity of the structure. Using Eq. (3), the total vulnerability of a bridge is calculated as the root mean square of the two previously described components with three different combination assumptions including "*Str. & No Def.*", "*Str. & Avg. Def.*" and "*Str. & Crit. Def.*", which correspond to the structural vulnerability while considering no defects, average defects and critical defects, respectively.

$$V = \sqrt{\frac{V_{Str}^2 + V_{Def}^2}{2}} \tag{3}$$

Vulnerability due to structural characteristics (V_{Str})

The vulnerability due to structural characteristics mainly accounts for geometric and physical specifications of the bridge. In this study, it is determined according to Eq. (4), which includes five subcomponents namely V_{CY}, V_{SS}, V_{LS}, V_{NS}, and V_{DM}, representing vulnerability due to age (construction year), static scheme, largest span length, number of spans, and deck material, respectively.

$$V_{Str} = 0.25(V_{CY} + V_{SS}) + 0.2V_{LS} + 0.15(V_{NS} + V_{DM}) \tag{4}$$

Each subcomponent of the structural vulnerability in Eq. (4) takes a value according to Table 1, which is defined mostly in accordance with the ITA-Guidelines with some modification according to recent researches (e.g., Zizi et al., 2023). The weights assigned to each subcomponent in Eq. (4) were based on the hierarchical logic model of the ITA-Guidelines to assess the bridge vulnerability. According to the Table 1 specifications, bridges featuring greater age, simply supported decks, more and larger spans, and less resilient material are naturally affected by higher vulnerability.

Table 1. Structural vulnerability subcomponents (V_{Str})

Construction year	V_{CY}	**Static scheme**	V_{SS}	**Largest span length (m)**	V_{LS}
CY≤1945	1.00	Simply supported beams/slab	1.00	LS<5	0.10
1945<CY≤1980	0.75			5≤LS<15	0.30
1980<CY≤2003	0.50	Continuous beams/slab	0.90	15≤LS<25	0.70
2003<CY≤2018	0.25			LS≥25	1.00
CY>2018	0	Arches	0.80		
Number of spans	V_{NS}	**Deck material**	V_{DM}		
NS=1	0.10	Steel and reinforced concrete	0.80		
NS=2-4	0.30				
NS=5-7	0.60	Prestressed concrete	0.90		
NS=8-10	0.90	Reinforced concrete	0.95		
NS>10	1.00	Masonry	1.00		

Vulnerability due to damage and defects (V_{Def})

The UK bridge condition index (BCI_{UK}) approach is used to estimate the component of the bridge vulnerability associated with the defects condition of the bridge (V_{Def}) that can be represented by two terms including average and critical defects indices. The BCI is calculated based on the severity and extent of the damages in the bridge elements reported from visual inspections. Since a higher BCI_{UK} score implies better condition of the bridge, Eq. (5) is used in this study to estimate the vulnerability due to defects, in a way that a higher BCI_{UK} represents a lower vulnerability. More details about the UK bridge condition index procedure can be found in, e.g., Hamidpour et al. (2023b).

$$V_{Def} = 1 - \frac{BCI_{UK}}{100} \tag{5}$$

2.2. Exposure

Exposure describes the potential, in terms of value, for losses due to a bridge malfunction, which stem from service interruption because of the bridge damage or collapse. In this research, the exposure parameter of a bridge (E) is determined according to Eq. (6), where, E_{DT}, E_{DL}, E_{MS}, E_{EB}, and E_{RC} represent average daily traffic in the entire roadway, detour length in case of bridge closure, mean span length, entity bypassed by the bridge, and road category, respectively.

$$E = 0.3E_{DT} + 0.2(E_{DL} + E_{MS} + E_{EB}) + 0.1E_{RC} \tag{6}$$

The weights assigned to the exposure subcomponents were chosen according to the hierarchical logic model of the ITA-Guidelines with some modifications, such as including the road category and the detour length parameters, which were not originally foreseen. The numerical values of the subcomponents can be determined using Table 2. According to this table, greater traffic volume, detour length and mean span length, as well as the higher importance of the entity bypassed by the bridge and the road category, increase the exposure of the bridge.

Table 2. Exposure subcomponents (E)

Average daily traffic (vehicle/day)	E_{DT}	**Detour length (km)**	E_{DL}	**Mean span length (m)**	E_{ML}
DT≤10,000	0.80	DL≤1	0	MS<5	0.10
		1<DL≤10	0.25	5≤MS<15	0.30
10,000<DT<25,000	0.90	10<DL≤20	0.50	15≤MS<25	0.70
DT≥25,000	1.00	20<DL≤40	0.75	MS≥25	1.00
		DL>40	1.00		

Entity bypassed	E_{EB}	**Road category**	E_{RC}
The entity body use involves essential social/public effects (railways, main roads, constructed areas)	1.00	Highway or railway	1.00
		Main suburban road	0.90
The entity body use is without essential social/public effects (secondary roads, waterways and water bodies)	0.70	Secondary suburban road	0.80
		Urban road	0.70
Without social/public effects (Natural grounds and areas)	0.20	Local road	0.60

2.3. Hazard

Seismic and traffic loads were considered as two potential sources of hazard in this study. As shown in Table 3, the frequency of commercial vehicles per lane (H_T) and the Peak Ground Acceleration (PGA) at the bridge site (H_S) are taken into account for determining the hazard component. The intensity of the traffic hazard is quantified according to the discretization levels for commercial vehicle traffic provided by the ITA-Guidelines. Similarly, the seismic hazard is calculated as the ratio between the PGA for a return period of 475 years at the bridge site over the corresponding one in the Italian territory (i.e., 0.35g).

Table 3. Hazard parameters (H)

Traffic hazard (commercial vehicle/day)	H_T	Seismic hazard	H_S
CV≤300	0.50	PGA of event with 475-year return period	PGA(g)/ 0.35
300<CV<700	0.75		
CV≥700	1.00		

3. Bridge stock case-study

In this study, 30 highway viaducts and overpasses located in the Lombardy region in northern Italy were selected for the risk evaluation. Most of these bridges were built between the 1960s and 1990s and have a simply supported deck system consisting of steel girders and concrete slab. The bridges are situated along primary roadways that in average carry a traffic of more than 25,000 vehicles per day. Table 4 provides a summary of the main characteristics of the bridges. The collected data concerning damages and defects and their statistical representation in different bridge elements can be found in Figure 1. It is observed that corroded bars in piers, abutments and RC girders, and corrosion in steel girders are the most common damage types in the studied bridges. The structural and geometric characteristics of the bridges, as well as the defects and damage data, were collected through visual inspections. To those must be added the data about geotechnical properties and the potential hazards at the bridges' site, which were all gathered by expert teams according to the risk assessment specifications of the ITA-Guidelines.

Table 4. The main properties of the studied bridges

Bridge No.	Daily traffic per course (vehicle/day)	Commercial traffic per lane (vehicle/day)	Construction year	Number of spans	Largest span length (m)	Deck material
1	32,042	10,680	1960	4	14	PRC[1]
2	63,185	12,556	2000	3	33.9	S-RC[2]
3	31,615	15,807	1968	1	38	S-RC
4	26,511	26,511	1972	1	31.15	RC[3]
5	52,123	10,503	1967	2	27.8	S-RC
6	55,746	11,092	1967	3	27.8	S-RC
7	55,746	11,092	1967	2	15	PRC
8	55,746	11,092	1967	3	25.7	S-RC
9	55,746	11,092	1967	1	25	S-RC
10	28,229	5,595	1969	2	39	S-RC
11	28,229	5,595	1967	3	37.5	S-RC
12	55,746	11,092	1967	4	38	S-RC
13	55,746	11,092	1967	1	36.7	S-RC
14	58,992	11,874	1968	3	50	S-RC
15	63,185	12,556	1968	3	50	S-RC
16	63,185	12,556	1968	1	31.15	S-RC
17	35,559	4,373	1967	2	15.55	RC
18	34,322	4,261	1970	2	15.55	RC
19	34,322	4,261	1972	2	16.44	PRC

Bridge No.	Daily traffic per course (vehicle/day)	Commercial traffic per lane (vehicle/day)	Construction year	Number of spans	Largest span length (m)	Deck material
20	26,572	26,572	1971	1	24	PRC
21	12,000	6,000	1973	3	36.9	S-RC
22	12,000	6,000	1978	2	30	S-RC
23	10,000	300	1992	3	33.9	S-RC
24	10,000	300	1992	3	33.9	S-RC
25	14,561	2,097	1974	1	15	PRC
26	13,659	1,953	1974	1	15	PRC
27	10,000	300	1992	3	33.9	S-RC
28	10,000	300	1981	2	24	PRC
29	10,000	300	1992	3	33.9	S-RC
30	10,000	300	1958	1	27.2	RC

[1] Prestressed Reinforced Concrete, [2] Steel and Reinforced Concrete, [3] Reinforced Concrete

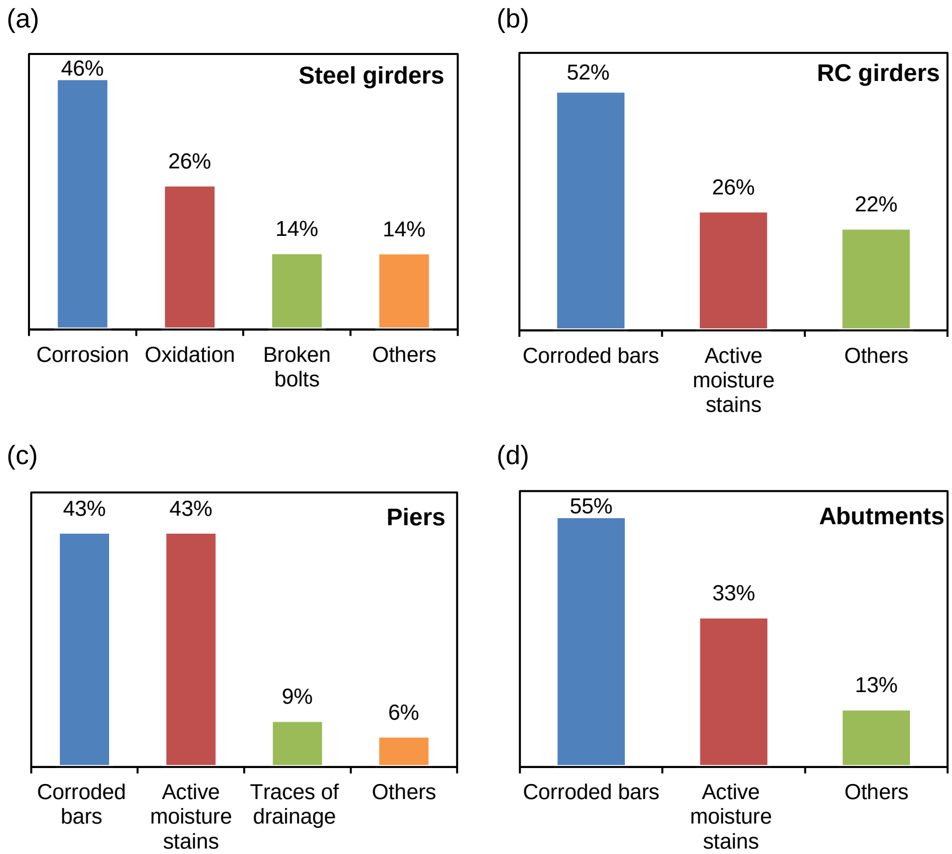

Figure 1. Statistical representation of common damages/defects of the case-study bridges in: (a) steel girders, (b) RC girders, (c) piers, and (d) abutments.

4. Application of the proposed method

4.1. Determination of vulnerability and its components

Figure 2 shows the vulnerability values for the studied bridges when three different combinations of structural features (according to Eq. 4), and average and critical states of defects (according to Eq. 5) are taken into account as described in Section 2.1. The results illustrate how almost all of the bridges have the same vulnerability level with regard to the structural features when there are no defects present (*Str. & No Def.*), which can be attributed to the similar age, geometry, design and material of the studied bridges. Furthermore, it is observed that majority of the bridges has a higher vulnerability when considering the "*Str. & Crit. Def.*"

condition rather than "*Str. & Avg. Def.*" condition. This observation suggests that the vulnerability in the "*Str. & Avg. Def.*" term represents the general wellness of the whole bridge, regardless of whether any particular member is damaged or not, whereas the vulnerability in "*Str. & Crit. Def.*" highlights the most serious state of health of those elements, which are most crucial for the overall bridge integrity.

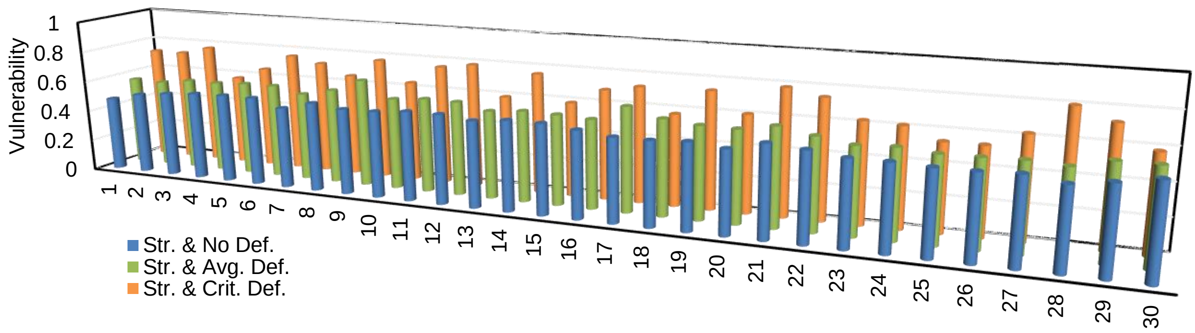

Figure 2. Vulnerability of the case-study bridges in three combination forms according to Eq. (3): "Str. & No Def.", "Str. & Avg. Def." and "Str. & Crit. Def.".

The vulnerability components associated with the structural features (V_{Str}) and the defects (V_{Def}) were investigated to understand to what extent they contribute to the total vulnerability of the bridges, as proposed in Eq. (3). Figure 3 shows that the greater contribution to the total vulnerability belongs to the structural features rather than the defects condition for all of the studied bridges. The structural component is involved in the total vulnerability with the average contribution of 73% and 57%, when considering the defects in average (Figure 3a) and critical states (Figure 3b), respectively. These findings are consistent with the proposed methodology and the specifications of the bridge inventory analysed. Nonetheless, the presence of defects plays a relevant role in the final vulnerability of such bridges that are intrinsically highly vulnerable due to their as-designed structural characteristics.

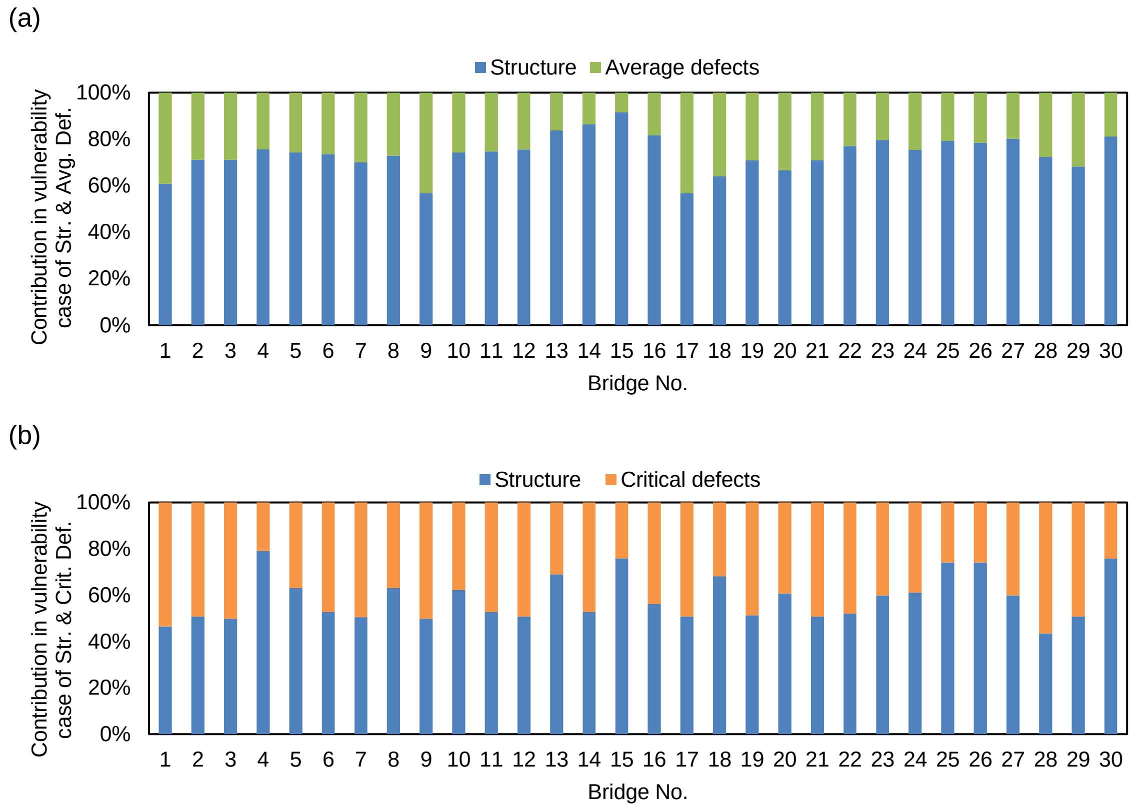

Figure 3. Contribution of structural and defects associated vulnerability in total vulnerability considering: (a) average defects and (b) critical defects states.

4.2. Priority and normalized priority rankings of bridges

Figure 4 (a) and (b) show the absolute priority ranking (PR) of the bridges applying Eq. (1) for both traffic and seismic hazards. Furthermore, the plots display the rankings considering the aforementioned method of defining the vulnerability parameter. Indeed, the results show how the priority rank of a bridge is affected (increased) by taking the defects and damages of the bridge elements into account as appears from "*Str. & Avg. Def.*" and "*Str. & Crit. Def.*" curves, when compared to the one without defects (titled "*Str. & No Def.*"). Such a difference is more pronounced when considering the case of "*Str. & Crit. Def.*", which is also comparable to the higher vulnerability value that this case produced, as discussed in the previous section. It is also observed that the priority rank of a given bridge can be different when accounting for two hazard types, showing generally higher ranks for the traffic hazard. This also suggests that, since vulnerability and exposure are constant parameters regardless of the involved hazard, the traffic hazard assessment produced higher priority rankings because the case-study bridges are situated in a region with low seismicity levels, but with heavy daily commercial traffic.

Since the values of the PR indicator turned out to be almost similar and with small dispersion for all of the case-study bridges, they were normalized using Eq. (2) to increase the resolution of the relative priority within the analysed bridge stock. Figure 4 (c) and (d) display the normalized priority ranking (NPR) result of the bridges representing the ranking scores, varying in a wider range, between zero and one.

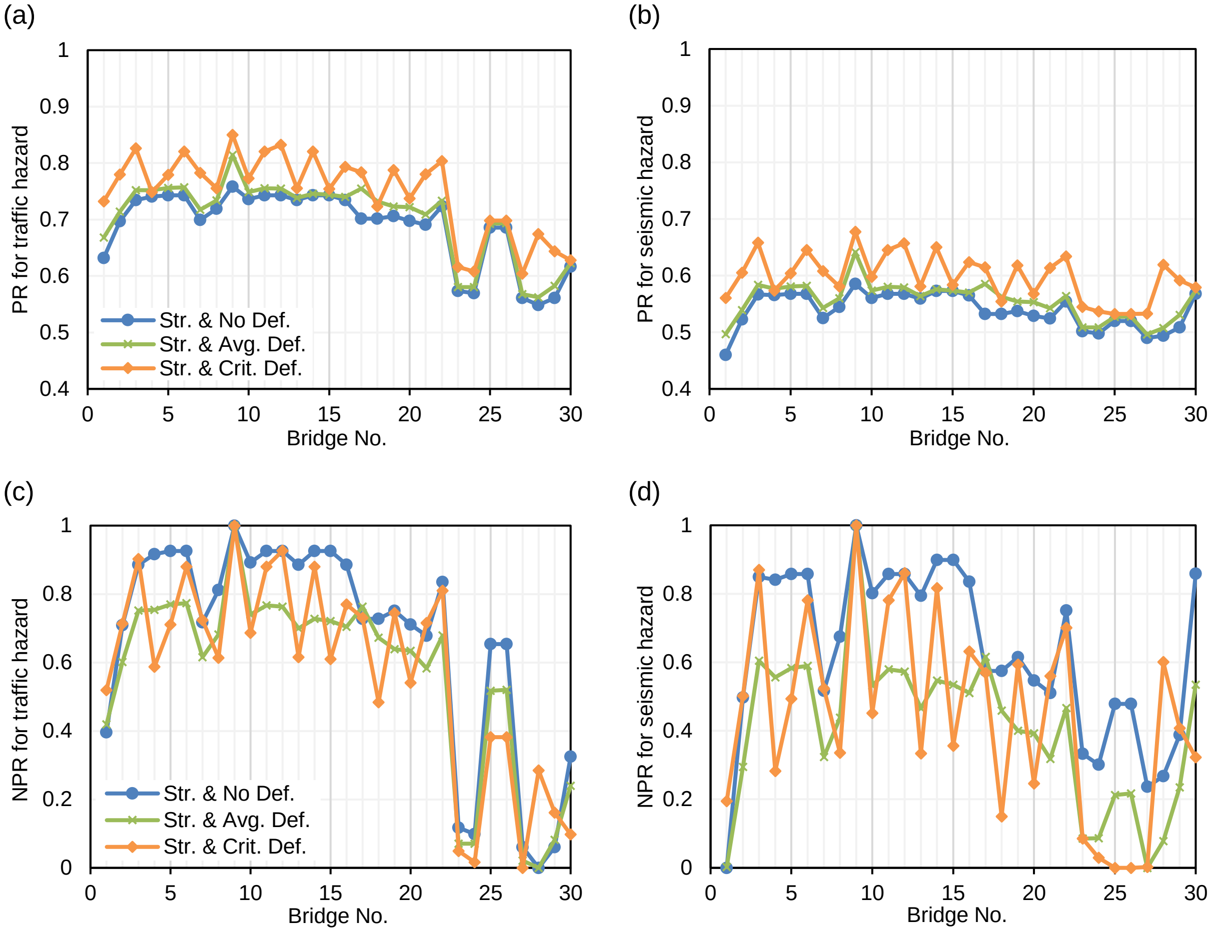

Figure 4. Risk assessment results of the case-study bridges under traffic and seismic hazards: (a) and (b) priority ranking, PR, and (c) and (d) normalized priority ranking, NPR.

Figure 5 shows the obtained PR and NPR results of the bridges arranged in five subranges at 0.2-unit uniform intervals. Considering the PR results in Figure 5 (a) and (b), most of the bridges are ranked in the subrange of 0.6-0.8 for the traffic and the subrange of 0.4-0.6 for the seismic hazard. However, the NPR results, displayed in Figure 5 (c) and (d), show a wider distribution for the ranking of bridges in all subranges and enable a more distinguished identification of the relative priority of the bridges. In addition, considering the case of "*Str. & Crit. Def.*" in the proposed method, it is observed that more bridges are classified in higher categories rather than the case of "*Str. & Avg. Def.*" for both hazards. For the case of seismic hazard in Figure 5 (b), for instance, it is observed that 15 bridges are classified in the subrange of 0.6-0.8 when considering the critical defects condition, while only one bridge belonged to this subrange when considering the average defects condition.

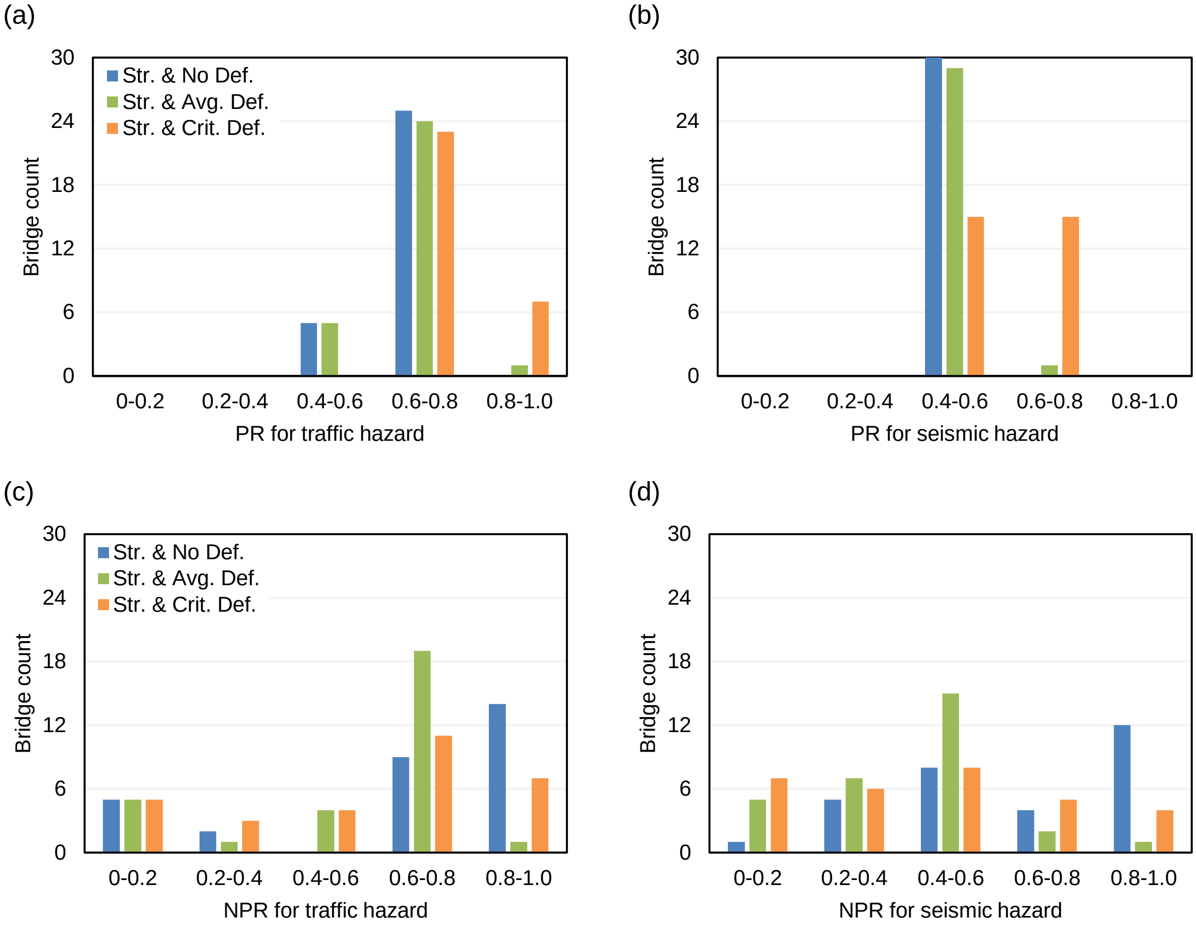

Figure 5. Classification of risk assessment results of the case-study bridges under traffic and seismic hazards based on: (a) and (b) priority ranking, PR, and (c) and (d) normalized priority ranking, NPR.

4.3. Comparison between the proposed method and the ITA-Guidelines

By rearranging the PR values into five smaller subranges as presented in Figure 5, it is possible to create a comparison with the five classes of attention foreseen by the ITA-Guidelines. In this way, the subranges of 0.0–0.2, 0.2–0.4, 0.4–0.6, 0.6–0.8, and 0.8–1.0 are assumed equivalent to Low, Medium-Low, Medium, Medium–High, and High CoAs of the ITA-Guidelines, respectively. Applying the ITA-Guidelines approach for the risk classification of the studied bridges, the obtained CoA for the bridges were compared with the PR results of the proposed method. As presented in Figure 6 (a) for traffic and (b) for seismic hazard, the ITA-Guidelines classify most of the bridges in a higher priority class in comparison with the proposed method. For instance, for traffic hazard, 28 bridges are classified in "H" category according to the ITA-Guidelines, while only one and seven bridges are classified in this category when using the proposed method considering "*Str. & Avg. Def.*" and "*Str. & Crit. Def.*" conditions, respectively. Similar findings were obtained for the seismic hazard. This observation implies that the ITA-Guidelines are more conservative in risk assessment of the bridges and prescribe higher risk classes compared to the proposed method in this research.

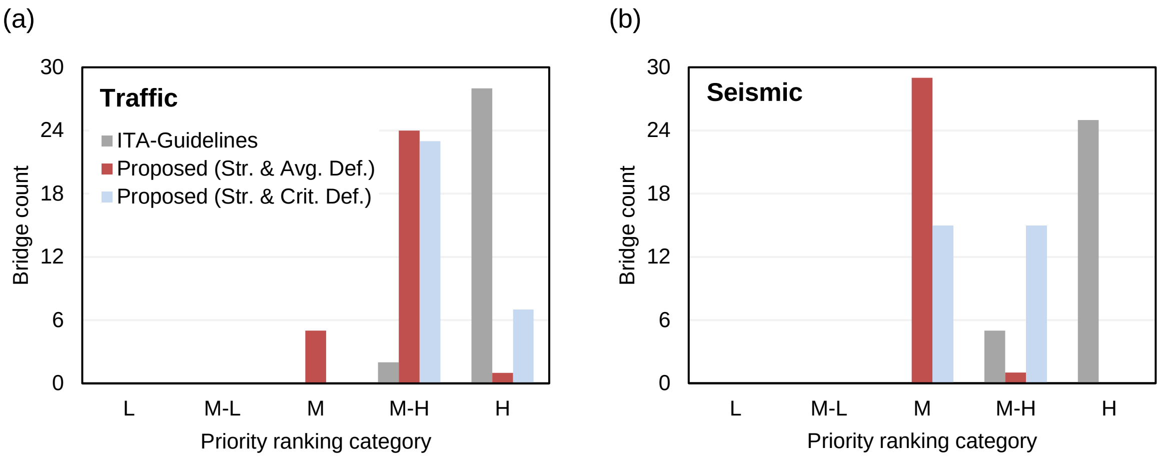

Figure 6. Comparison of the priority ranking category of the case-study bridges obtained from the proposed method and the ITA-Guidelines for: (a) traffic and (b) seismic hazard.

5. Conclusions

In this study, a quantitative method for risk-based priority ranking of existing bridges based on their structural robustness and damages/defects condition is proposed. The method provides equations to estimate vulnerability, exposure and hazard as the three primary risk assessment factors. Vulnerability is defined considering two main components including vulnerability due to structural characteristics and that due to defects condition of the bridge elements. While the former component is defined primarily in accordance with the recently issued Italian Guidelines (ITA-Guidelines), the latter is defined using the BCI_{UK}, which provides an index for the bridge condition based on the presence of damage/defects. The exposure parameter is calculated according to the characteristics of the bridge and the road, thus considering the potential outcomes of a bridge failure. The effect of the seismic and the traffic loads on the bridges is included in the definition of the hazard parameter.

The proposed methodology was applied to thirty real bridges in the Lombardy region in northern Italy. The majority of these bridges were older than 50 years and their structural and physical properties were quite similar. It was shown that when considering the impact of defects in addition to the structural features, bridges gained a higher vulnerability and priority. Additionally, almost all of the bridges were given a higher priority rank when subjected to traffic rather than seismic hazard. According to the observations, while the absolute priority ranking of the bridges was spread in a narrow range, normalizing the priority ranking (NPR) provided results with higher priority resolution in the studied bridge stock.

Finally, a comparison of results was carried out between the proposed method and the Class of Attention (CoA) of bridges using the ITA-Guidelines, which showed that the latter produced more conservative risk classification for the bridges. Nonetheless, the proposed method due to its quantitative calculation approach could be employed to rank bridges belonging to the same CoA, thus refining their relatively priority.

6. References

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