A preliminary methodology for multi-hazard risk assessment of large bridge portfolios using quantitative indicators

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ABSTRACT: In the last years, several catastrophic collapses of existing bridges have raised growing awareness to the need for structural assessment, health monitoring, and retrofitting by public institutions and infrastructure management entities. Several issues, such as limited knowledge of existing bridge structures, exposure to multiple hazards, or deterioration, make risk assessment and decision-making on existing bridges a challenging task, especially when qualitative approaches are used for risk prioritization. This study proposes a methodology for quantitative risk assessment of existing bridges, considering the large-scale analysis of bridge portfolios under natural and anthropic hazards, and the impact of their out-of-service/collapse on the road network. Specifically, a rational risk-based ranking of large bridge portfolios is obtained to identify the most critical ones, which are subject of further detailed analysis. Four available methods in the literature are used to assess the structural condition and the seismic, fire, and impact risks for a stock of twenty bridges located in northern Italy. The individual risk indicators are then combined to obtain a total multi-hazard risk indicator (I_{MH}), while studying different combination approaches being compared one each other. Finally, the obtained results are compared with those obtained according to the Italian guidelines, which rely upon more qualitative approaches that are not so easily usable for risk prioritization from management entities.

1. INTRODUCTION

Bridges are a key component of any infrastructure system and their collapse, in addition to life losses, can cause serious economic losses in combination with traffic disruption; recently observed failures worldwide also highlighted their critical condition. In Italy and many other countries, the backbone of existing road infrastructure has been built after the Second World War, which implies that many of the existing bridges are 50 years old or more. This in combination with the recently observed collapses, e.g., the Morandi bridge in Genoa (Calvi et al. 2019; Scattarreggia et al. 2022a), the multi-span arch bridge between Albiano Magra and Caprigliola (Scattarreggia et al. 2022b), have prompted the need for assessment and, if necessary, intervention. However, in a world where resources are limited, a rational approach to decide which bridges need to be further analyzed is required. Detailed safety checks of bridges can be carried out according to current code-based approaches, eventually identifying the need for structural strengthening or replacement. This context has thus highlighted the necessity to look for methods that can assist in the assessment of large-scale bridge portfolios. To this end, many recent efforts have been made to implement practical risk assessment methods, which may help to rank the opportunity of such actions (e.g., Abarca et al. 2023) following similar studies conducted in the last decades (e.g., Castorani et al. 2011). As such, while there has been substantial progress in the evaluation of bridges, especially in the assessment of damage and deterioration conditions in many countries, in Italy, only recently the promotion of guidelines (MIT 2020) for a unified and effective solution to the management of existing bridges has taken place. Still, these guidelines are in contrast with the own procedures of the main bridge managing entities (e.g., ANAS, RFI), which are now called to adopt the official ones. The procedure of the Italian guidelines is based on a multi-level multi-hazard approach for risk assessment of existing bridges, considering the presence of various hazards (structural/foundational, seismic, landslide, and flood), which leads to the attribution of an overall class of attention (CoA). The result is a qualitative assessment and categorization into five main classes. Consequently, the main drawback of these guidelines is the qualitative basis of the provided classes of attention for bridges, according to which ranking of bridges falling in the same CoA turns out to be a complex task, as opposed to quantitative methods.

This study proposes a preliminary quantitative method for multi-hazard assessment of bridges, by taking advantage of quantitative methods already available in the literature for the definition of indicators about the structural condition, and the risk associated with seismic, fire, and impact hazards. Impact is one of the main causes of observed bridge failures, while fire is less common but the associated consequences can be dramatic. After each indicator is homogenized in terms of hazard, exposure, and vulnerability, they are appropriately combined, using various combination schemes, to obtain a multi-hazard-based risk indicator (I_{MH}) useful for bridge prioritization. A group of twenty real bridges located in northern Italy was selected with the aim to apply the proposed multi-hazard quantitative approach for bridge risk assessment/prioritization. The results are compared, first with each other, considering the various adopted combinations, and then with the Italian guidelines on bridges.

2. QUANTITATIVE SINGLE-HAZARD METHODOLOGIES

2.1. Structural condition assessment: the United Kingdom approach (UK BCI)

The United Kingdom condition performance indicator (2007) is a measure to represent the structural condition of the highway structures stock, including bridges. A Bridge Condition Indicator (BCI) is defined, describing the condition of a bridge based on its damage and deterioration state. The overall process is summarized as follows:

- Step 1 – For each element, the Element Condition Score (ECS) is defined based on its condition data acquired from inspections. ECS is a numerical value that is assigned based on the combination of the damage extent scale – from A (non-significant) to E (>50% of area/length affected) – and the severity scale – from 1 (best) to 5 (worst).
- Step 2 – The Element Importance Factor (EIF) is assigned to reflect the importance of the element to the overall functionality of the structure, such as load carrying capacity, durability, and public safety, ranked as Very High, High, Medium, or Low. Then, ECS and EIF are used to determine the Element Condition Factor (ECF), which is used to weigh ECS in terms of its contribution to the overall structural condition.
- Step 3 – ECS (from step 1) is combined with ECF (from step 2) to produce the Element Condition Index (ECI), which represents the condition of the element on a scale of 1 (best) to 5 (worst).
- Step 4 – Steps 1 to 3 are applied to all elements or element groups in a bridge, leading to the Bridge Condition Score (BCS). The following

variants of BCS are evaluated: (i) BCS(Avg) as the weighted average of all the ECI values for the bridge's elements; and (ii) BCS(Crit) as the maximum ECI value for the elements classified with "Very High" importance. The consideration of the two scores provides a better indication of the health condition of the structure. Indeed, BCS(Avg) provides an overall picture of the bridge condition, indicating how widespread the deterioration is. Besides, BCS(Crit) measures the criticality of the structure due to the very poor condition of one of the critical elements.

- Step 5 – The BCS values are converted to the corresponding Bridge Condition Index (BCI) on a scale from 0 (worst) to 100 (best).

2.2. Seismic risk assessment: the FHWA2006 approach

US guidelines, issued by the Federal Highway Administration (FHWA 2006) provide a performance-based approach for seismic retrofitting of highway bridges. The same provisions also contain a screening process to identify and prioritize existing bridges, which can be summarized as follows:

- Step 1 – Determine the bridge importance class as essential or standard.
- Step 2 – Estimate the anticipated service life (ASL) to determine the bridge's residual service life and subsequently a retrofit category. Three such categories are used in this manual including ASL 1 to 3 representing anticipated service life of 0–15, 16–50, and >50 years, respectively.
- Step 3 – Determine the earthquake ground motion levels and obtain the spectral ordinates. Two levels of earthquake intensity levels are considered: Lower Level (LL) and Upper Level (UL) which correspond to a 50% probability of exceedance in 75 years (return period of 100 years) and a 7% probability of exceedance in 75 years (return period of 1000 years), respectively. The spectral acceleration values at short and long periods (S_s and S_l) are obtained as spectral ordinates.
- Step 4 – Determine the expected performance level based on the different seismic intensity levels and ASL, namely from PL0 (no minimum performance) to PL3 (fully operational).
- Step 5 – Determine the bridge vulnerability rating (V) based on two main components that are assumed to be more vulnerable to seismic damage, including: (a) vulnerability of connections, bearings, and seats (support length) and (b) vulnerability of columns, abutments, and liquefaction. The maximum score between (a) and (b) is assumed as the bridge vulnerability ranging from 0 (very low vulnerability) to 10 (high vulnerability).
- Step 6 – Determine the seismic hazard rating (H), which considers both the seismicity and geotechnical conditions of the site. S_{D1} is used for this purpose, which is the spectral acceleration at 1.0 s modified by the site amplification factor. The parameter E is scaled to 10 to have the same weight as V.
- Step 7 – Calculate the bridge rank (R) on a scale of 0 (best) to 100 (worst), based on the seismic hazard rating (H) and the vulnerability rating (V) by multiplying these two scores.

2.3. Impact priority index assessment

The method by Kim et al. (2020) proposes a priority index based on the vulnerability (V) and hazard (H) components. For the definition of the hazard, the following parameters are considered: the type of lower road, the existence of bridge columns within 9 m of the road verge, the distance from industrial sites, and truck accessibility to the road. In turn, the definition of the vulnerability accounts for the service years, the current safety level, the number of columns, the minimum diameter of the column(s), the slenderness ratio, and the design load. However, only bridges that can be actually exposed to such kind of hazard, i.e., pass the so-called "preliminary risk analysis", are further analyzed in terms of vulnerability according to the proposed "simplified risk analysis". For instance, bridges without columns are not analyzed, as well as wall-section piers, because their probability of failure under vehicle impact is negligible. Both hazard and vulnerability are defined as the sum of weighting factors (from 1 (best) to 3 (worst)) assigned to each parameter, according to the definition of sub-parameters. With reference exclusively to the quantitative parameters (e.g., number of columns, slenderness ratio, and distances), the scale that defines the attribution of the weighting factor is evaluated using the method of standard deviation (SDI Method). After the value of the sub-parameter (x_i) is known for all analyzed bridges, the mean (μ) and the standard deviation (σ) are evaluated, and the weighting factor is assigned. After the SRA is conducted, the risk index (I) for each bridge is given by the sum of the hazard (I_h) and vulnerability (I_v) indicators: $I = (I_v+I_h)/2$. Both I_v and I_h are evaluated individually by normalizing the sum of the weighting factors attributed to each sub-parameter, with respect to the sum of the maximum value that the weighting factor can have for each sub-parameter. Although it is beyond the scope of the present study, the proposed method goes ahead with a third phase called “detailed risk analysis” in which all high risk bridges are numerically analyzed.

2.4. Fire risk assessment

Kodur and Noser (2013) proposed a methodology for identifying, within a transport network, the most critical bridges to the effect of fire, through the determination of an Importance Factor (IF). In a simplified manner, the method accounts for vulnerability, hazard and exposure. Specifically, five classes are evaluated, each of them composed of parameters that in turn include sub-parameters:

- Class I (ψ_g): Geometrical features, material properties, and design characteristics. The sub-parameters are the number of lanes, age, current standard rating in terms of functionality, and the additional presence of service features.
- Class II (ψ_h): Hazard (fire) likelihood. The sub-parameters are the response time in terms of necessary time before actions, architectural/historical importance, threat perception according to historical fires close to the bridge, and probable fire scenario in terms of consequences.
- Class III (ψ_t): Traffic demand. The sub-parameters are the average daily traffic and location of nearby facilities.
- Class IV (ψ_e): Economic impact. The sub-parameters are the presence of alternative routes, time and cost expected for repair.
- Class V (ψ_f): Expected fire losses. The sub-parameters are life and property losses, and environmental damage.

Each sub-parameter is assigned a weighting factor ($\varphi_{g,x}$), mostly between 1 (best) and 5 (worst). The maximum factor ($\varphi_{g,x(max)}$) corresponds to the highest weight that the sub-parameters can assume for each parameter. The class weight (ψ_x) and class coefficient (Δ_x), from which the overall class coefficient (λ) derives, are given by:

$$\psi_x=\sum \frac{\varphi_x(max)}{\varphi_{total}} \quad (1); \quad \Delta_x=\sum \frac{\varphi_{i,x}}{\varphi_x(max)} \quad (2);$$

$$\lambda= \sum \Delta_x \, \psi_x \quad (3).$$

Although λ describes implicitly the bridge importance, the method proposes to assign an arbitrary IF (from 0.2 to 1.5) to qualitatively describe the risk grade from “low” to “critical”.

3. CASE STUDY

A group of twenty real bridges located in primary roads of the Lombardy region in northern Italy was selected for the present study. Their main characteristics are given in Hamidpour et al. (2023). The bridges are viaducts and overpasses that were mainly built from 1967 to 1972 as shown in Figure 1(a), implying that many of them are at least 50 years old. A statistical distribution of these bridges in terms of number of spans and length of the largest span (Figure 1(b)), structural scheme (Figure 1(c)), and main deck material (Figure 1(d)) is also presented. The examined bridges are mainly either single-span or few-span (2 or 3) structures and most bridges have the largest span length of over 25 m, with simply supported decks. In simply supported beam systems, single or multi-span bridges deck consist of parallel beams with simple supports at the extremities. They span between the abutments by crossing continuously over the central piers when they are continuous. In continuous slab bridges, a cast-in-place slab extends all over the spans. Finally, all bridges feature either multi-column or single-wall RC piers.

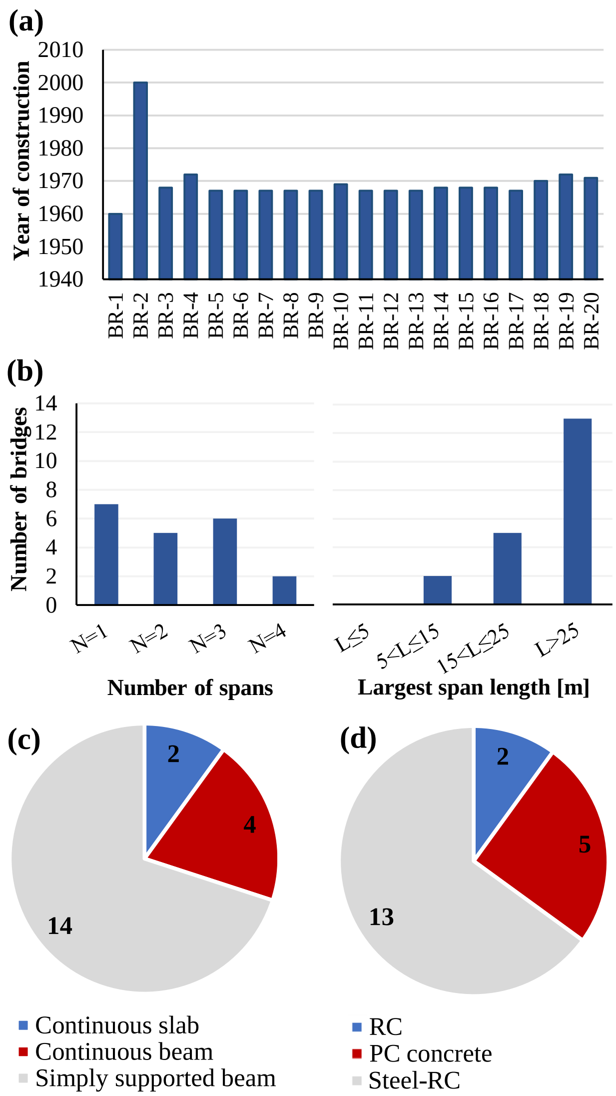

Figure 1: (a) Year of construction, (b) number of spans and the largest span length, (c) static scheme, and (d) deck material of the analyzed bridges.

4. MULTI-HAZARD ASSESSMENT

4.1. The Italian guidelines qualitative approach

The Italian guidelines (MIT 2020) propose a multi-level multi-hazard approach to manage the safety of existing bridges. Risk classification of bridges is based on CoA via simple census and multi-hazard safety checks. The results of the verification and classification provide useful information for a subsequent assessment of the bridge, as well as the resilience analysis of the network. They are articulated on six levels of assessments, with increasing complexity and accuracy. Level 2 analysis is related to the definition of the CoA based on the information collected in Levels 0 and 1 (see MIT 2020) about the, e.g., location, road use, year of construction, geometrical characteristics and defects (based on visual inspections), as well as potential risks associated with landslide and flood.

CoA is determined as a function of hazard, vulnerability, and exposure, resulting into High (H), Medium-High (M-H), Medium (M), Medium-Low (M-L), and Low (L). After CoA is identified for each hazard, a logic tree is used to combine all hazards. The structural/foundational-related CoA assumes the highest importance and governs over all hazards. Consequent actions corresponding to the assigned CoA include immediate accurate assessments for High CoA and preliminary assessments for Medium-High and Medium CoA.

4.2. Proposal of simplified quantitative approach

Although the Italian guidelines propose a multi-level multi-hazard approach, their qualitative nature does not allow them to rank bridges within the same CoA, as opposed to quantitative methods. Furthermore, while the Italian guidelines rely on the consideration of four hazard types, namely gravity loads, landslide, flood, and earthquake, the method herein proposed aims to account also for two additional important anthropic hazards, namely vehicle impact and fire. The above-introduced quantitative methods are herein customized and applied to the analyzed bridges, combining the single-hazard risk indicators to assess multi-hazard bridge risk. Accordingly, the individual risk indicators, i.e., structural/gravity load (I_G), seismic (I_E), fire (I_F), and impact (I_I), were computed. All methods were integrated with the exposure component as proposed by Kodur et Noser (2013), thus assuming uniform exposure, similarly to the Italian guidelines. In addition to that, I_G (based on the BCI) has been also integrated with the hazard component, herein assumed to be the highest for all bridges, considering they all have average commercial daily traffic ≥ 700 vehicles/day per driving lane (threshold given by the Italian guidelines). This way, all the considered methods account for the three typical components of risk, namely hazard, vulnerability, and exposure, even if in a simplified manner. Thus, Figure 2 shows the risk indicators for each hazard type.. Although the structural risk (I_G) was evaluated by analyzing the conservation state of the structure, it could be roughly estimated according to the main features of the bridge (e.g., static scheme, material, and design code adopted), if information on damages/defects is not be available, including a proper measure of epistemic uncertainty. In general terms, the risk of a bridge structure with a damage/defect level equal to k_{Hi} when subjected to a specific hazard (H_i) can be estimated as $I_{Hi} = H_{Hi}\, V_{Hi}\, E_{Hi}\, k_{Hi}$. The factor k_{Hi} accounts for the conservation state of the bridge according to the relative importance of each defect/damage in a specific element on the global bridge vulnerability when subjected to the considered hazard (H_i).

In this study, different combinations of individual risk estimates are tested for the computation of the total multi-hazard risk indicator (I_{MH}): (i) a quadratic combination of individual risk indicators, normalized with respect to the number of considered hazards (N_H) (Eq. 4); (ii) a summation of individual risk indicators, again normalized with respect to N_H (Eq. 5), but considering the possibility of using weighting factors (C_{Hi}) that can be applied to each risk according to, e.g., the level of knowledge of input required. Weighing factors can also be applied to the risk components (i.e., H, V, and E).

$$I_{MH_i} = \sqrt{\frac{\sum_i {I_{H_i}}^2}{N_H}} \tag{4}$$

$$I_{MH_iC_i} = \frac{\sum_i C_{Hi} I_{Hi}}{\sum_i C_{Hi}} \tag{5}$$

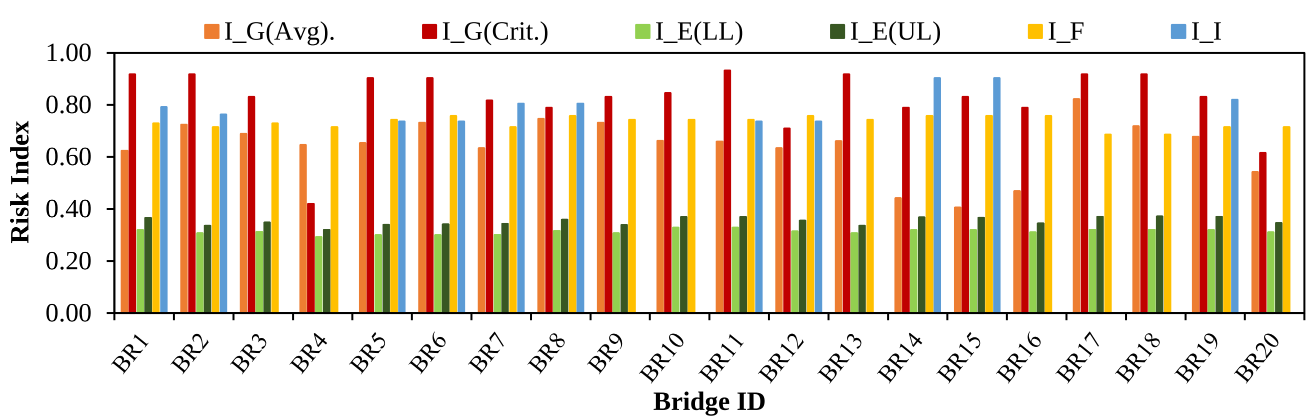

Figure 2: Risk indicators for structural (I_G), seismic (I_E), fire (I_F), and impact (I_I) hazards for the analyzed bridges.

Assuming $I_{G(Avg)}$ as structural indicator and considering both the lower $I_{E(LL)}$ and the higher $I_{E(UL)}$ levels of seismic action, two multi-hazard risk indicators I_{MH1} and I_{MH2} can be calculated using Eq. 4, respectively. Similarly, Eq. 4 can be used to compute another indicator I_{MH3} by combining $I_{G(Crit)}$, $I_{E(UL)}$, I_F, and I_I. An additional combination is carried out using Eq. 5, based on various weighting factors assigned to the different risks. For instance, considering the relatively low probability of occurrence (when computable) of the fire and impact hazards, C_F and C_I, respectively, were taken as 0.25. On the other hand, the highest weight was assigned to the structural risk indicator, i.e., C_G = 1, considering its higher likelihood with respect to the other risks (a rationale also adopted by the Italian guidelines). The earthquake-related weight was assumed as C_E = 0.5. As a result, Figure 3 shows the total multi-hazard risk indicators (I_{MH}) obtained for the four combinations considered. The comparison between I_{MH3} and I_{MH4} highlights the importance of the BCI approach employed for the assessment of the structural condition. Indeed, when $I_{G(Crit)}$ – i.e., BCI(Crit) – is considered, high risk is obtained using $I_{G(Avg)}$, i.e., BCI(Avg). On the other hand, the comparison between I_{MH1} and I_{MH3} indicates that the intensity level of the seismic action would not have played a relevant role in the definition of the total risk. Finally, I_{MH4} points out bridges that are more vulnerable to structural and seismic actions, given that both fire and impact were weighted minorly. The bridge ranking in Figure 3 from high risk to low risk (from the left to the right) is produced according to the results obtained with the indicators I_{MH4}.

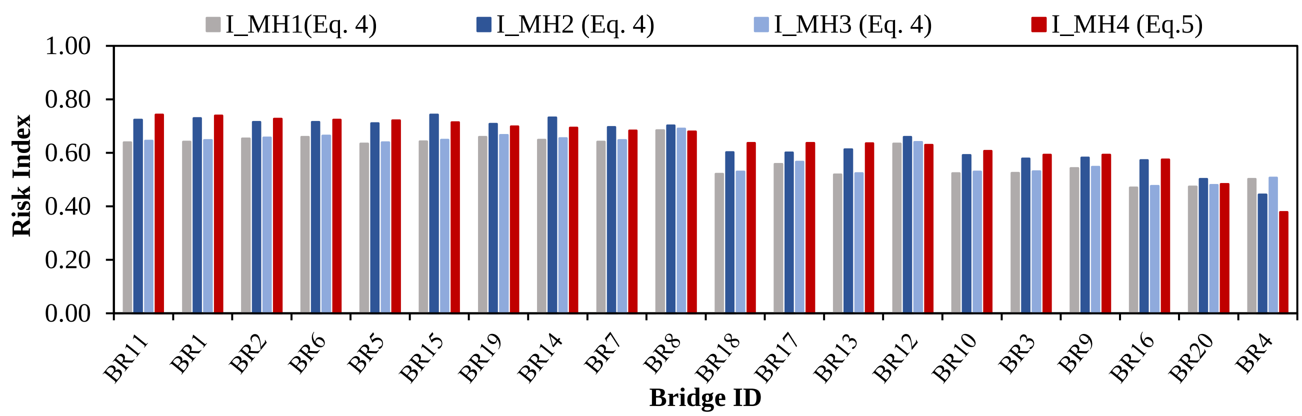

Figure 3: Total multi-hazard risk indicators according to the proposed combinations for the analyzed bridges.

4.3. Comparison between Italian guidelines and the proposed quantitative approach

According to the Italian guidelines, all the analyzed bridges fall in the "High" CoA (see Hamidpour et al. 2023), based on the dominance of structural and seismic risk (fire and impact are not considered by these guidelines). As a result, a managing entity would not be able to prioritize interventions on the selected bridge stock, as opposed to the ranking obtained in Section 4.2 with the proposed multi-hazard quantitative approach. Assuming a correspondence between High (H) to Low (L) risk condition ranges of the Italian guidelines via the equivalent scale given in Table 1, the proposed method allows bridges to be grouped as illustrated in Figure 4. The comparison is conducted as follows: (i) using Eq. 4 and Eq. 5 considering only the structural indicator $I_{G(Crit)}$, and the seismic indicator $I_{E(UL)}$; (ii) using only the structural indicator $I_{G(\mathrm{Crit})}$. $I_{G(Crit)}$ was preferred over $I_{G(Avg)}$ considering the observations in Hamidpour et al. (2023), who found a good agreement between BCI(Crit) and structural CoA.

Table 1: Equivalence adopted between Italian guidelines CoA and multi-hazard indicators (I_{MH}).

ITA CoA	Proposed I_{MH}
High	0.60-1.00
Medium-High	0.35-0.60
Medium	0.20-0.35
Medium-Low	0.10-0.20
Low	0.00-0.10

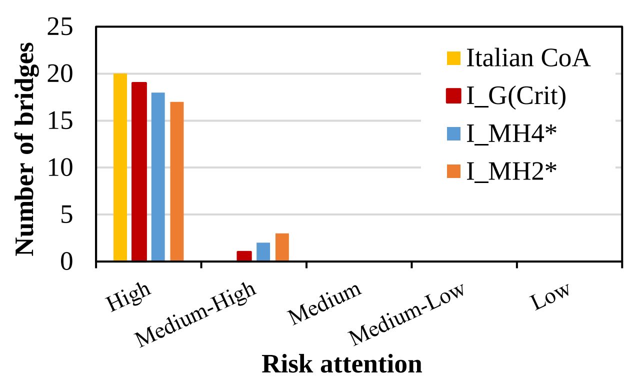

Figure 4: Comparison between Italian CoA and equivalent representation of the proposed multi-hazard risk indicators.

The comparison in Figure 4 leads to similar observations, i.e., $I_{G(Crit)}$ produces the closest results to the Italian CoA. On the other hand, when both the structural and seismic indicators are combined according to Eq. 3 and Eq. 4, i.e., I_{MH2*} and I_{MH4*}, respectively, the differences slightly increase.

5. CONCLUSIONS

This study has presented a preliminary multi-hazard risk analysis method for large bridge portfolios by calculating quantitative indicators (I_{MHi}), combining individual risk estimates (I_{Hi}) derived from available methods in the literature. The structural, seismic, fire, and impact risks are considered for the computation of the total multi-hazard risk indicators (I_{MHi}). The goal was to propose a quantitative multi-level multi-hazard as opposed to the qualitative approach of the Italian guidelines, according to which ranking bridges belonging to the same class of attention is not an easy task. To this end, for prioritization purposes, the efforts in increasing the resolution of the Italian guidelines could be their integration with more quantitative parameters, which may also permit the inclusion of extreme hazards (such as the herein considered fire and impact). Notwithstanding the promising results that were obtained with this preliminary version, future studies should aim to propose a more comprehensive multi-hazard quantitative method, e.g., accounting for the structural robustness (vulnerability component), the load intensity (hazard component), and consequences (exposure component).

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