Evaluation of prioritization schemes for bridge stock assessment

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The important role of bridges in transportation network resiliency has made the management of the existing bridge stock an essential task. In order to implement and prioritize the activities to secure the proper performance of large numbers of existing bridges, it is necessary to go through a complex process of condition assessment and decision-making for identifying the relative priority of the bridges within a network. The prioritization of bridges serves the decision-making agencies to understand and compare the current structural condition and expected performance of a bridge for objectives such as monitoring, maintenance, retrofitting, or even replacement. In this sense, the methods used for bridge prioritization typically identify, weigh and analyse a variety of parameters to quantify the vulnerability of a bridge, referring to service loads, seismic, hydraulic, and geotechnical actions, as well as structural condition in terms of deficiencies and material degradation. In this paper, three available methods employed by different standards and regulations in different countries are compared and discussed for bridge prioritization taking advantage of their application to twenty real bridges located in northern Italy. The approaches are reviewed in terms of required input data, condition evaluation procedure, computational method, and corresponding strengths and weaknesses. The outcome of such a review enables one to understand better the pros and cons of quantitative methods with respect the qualitative counterpart for bridge prioritization while giving insight into the potential of their combination, if required.

Keywords: Bridge, prioritization, condition assessment, vulnerability.

1 INTRODUCTION

Road networks play a fundamental role in supporting the social and economic systems in societies. Bridges are critical components of transport networks facilitating links between locations and their collapse may cause serious economic and life losses in combination with traffic disruption. In the last decades, the structural deterioration of aging bridges has become an important issue worldwide. In Italy, a relatively large number of local and global bridge failures has been recently reported, e.g. the collapse of the Annone overpass in Lecco in 2016 (di Prisco et al. 2018), the Morandi bridge in Genoa in 2018 (Calvi et al. 2019) or the multi-span arch bridge of Caprigliola in 2020 (Scattarreggia et al. 2022), indicating that the situation is quite alarming and highlighting the need for an urgent assessment and rehabilitation of road infrastructures. However, in a world where resources are limited, a rational approach to decide which bridges need strengthening (or replacement) and which ones can be left without intervention is required. To this end, many recent efforts have been made to introduce practical risk assessment methods, which may help to rank the necessity of such interventions (e.g. Abarca et al. 2023). In this regard, there has been substantial progress in the evaluation of bridges, especially in the assessment of damage and deterioration conditions in many countries. For instance, in 2020 the Italian High Council of Public Works (HCPW) issued guidelines for the management and assessment of existing bridges. Likewise, nowadays, different approaches have been proposed based on simplified methods that can be distinguished as quantitative or qualitative approaches. Particularly, quantitative approaches (e.g. FHWA 2006) assess the condition of a bridge using a numerical rating scale and mainly include ratio-based, weighted average and the worst condition element methods (FHWA 2016). On the other hand, qualitative approaches (e.g. the above-mentioned Italian Guidelines) assess the bridge's condition with descriptive indicators spanning from low to high risk or, similarly, from poor to good condition.

In this study, a group of twenty real bridges located in northern Italy has been selected with the aim to compare the qualitative approach given by the Italian guidelines with alternative existing methods for bridges risk assessment/prioritization. In addition to Italian guidelines, two other approaches, adopted in the United Kingdom and the United States, were selected to assess the bridge's structural and seismic condition. Recently, (Fox et al. 2022), (Cosenza and Losanno 2021), and (Santasiero et al. 2021) have commented on the reference Italian guidelines, by applying them to various case studies, i.e. a prestressed concrete bridge, a reinforced concrete overpass and a stock of 48 bridges in southern Italy, respectively. In turn, in the study herein, two quantitative methods in addition to the qualitative one used by the current Italian guidelines are employed for the risk assessment of a selected case-study of bridges. More specifically, the method used in the United Kingdom for bridge prioritization based on the damage condition assessment and the one used in the United States, proposed by the Federal High Way Administration (FHWA 2006) for seismic risk assessment, have been employed. These approaches use quantitative (United Kingdom and FHWA2006) and qualitative (Italian Guideline) ratings as the condition measures to show how vulnerable the bridges might be in service situations (under static conditions) or when subjected to seismic hazard, with a view to defining bridge prioritization. The required input data to apply the selected methods were obtained from on-site inspections of the bridges. In what follows, first, an overview of each evaluation method is given, and then the main features of the selected bridges are illustrated. Finally, once the results of each method are obtained, they are compared for the structural condition and the seismic risk assessment being useful for bridges prioritization.

2 APPROACHES AND METHODOLOGIES

2.1 Italian guidelines approach (ITA Guidelines): qualitative and multi-hazard assessment

The ITA Guidelines (2020) outlines a multi-level multi-hazard approach for managing the safety of existing bridges. It indicates the risk classification of a bridge in terms of the class of attention (CoA) which is determined based on simple census and multi-hazard safety checks of the bridge stock. The results of the verification and classification provide useful information for a probable subsequent assessment of the bridge, as well as the resilience analysis of the network. The approach of ITA Guidelines is developed on six levels of assessments, with increasing complexity and depth as described below:

Level 0 - Simple census of all bridges in the stock is provided focusing on the general information and main characteristics including location, geometry, type and material of structure, year of construction, design documents availability, road use classification and site morphology.

Level 1 – The extended information on the geometrical and structural characteristics of the bridges based on visual inspection and survey of the structure is gathered. This level aims to identify the decay and degradation state on a time basis as well as the potential risks associated with landslide and hydraulic actions.

Level 2 – The decision on the class of attention of the bridges is made based on the information acquired from the two previous levels. CoA is determined as a function of three factors, namely hazard, vulnerability and exposure according to which bridges are classified, in a qualitative manner, into High (H), Medium-High (M-H), Medium (M), Medium-Low (M-L) and Low (L) CoA. According to the determined CoA, one of the following levels might be followed.

Level 3 – This level includes the execution of a preliminary assessment to understand better the condition of degradations and deficiencies detected in Level 1 inspections, and to see if further investigations of Level 4 are necessary.

Level 4 – Execution of detailed and accurate assessment based on the requirements of current technical standards for construction is covered.

Level 5 – This level is not explicitly covered by the guidelines but applies to bridges of significant importance within the network for which sophisticated analyses such as resilience studies of the network might be required.

The consequent actions corresponding to the assigned CoA might include immediate accurate assessments for High CoA and preliminary assessments for Medium-High and Medium CoA. Ordinary periodic inspections and, if necessary, continuous monitoring systems might be considered for all the mentioned CoAs as well. For Medium-Low and Low CoA, no further assessment is required but periodic inspections might be performed.

2.2 United Kingdom approach (UK BCI): quantitative, for condition assessment

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

Step 1 – Select the element and evaluate the Element Condition Score (ECS). One element of the bridge is selected and, based on the element's condition data acquired from inspections, the ECS is determined. The ECS is a numerical value assigned based on the combination of the extent scale of A (non-significant) to E (>50% of area or length affected) and the severity scale of 1 (best) to 5 (worst).

Step 2 – Select the Element Importance Factor (EIF) and determine the Element Condition Factor (ECF). The EIF reflects the importance of the element to the overall functionality of the structure such as load carrying capacity, durability and public safety classified as Very High, High, Medium or Low. Then ECS and EIF are used to determine ECF. The ECF is used to weigh the ECS by enabling the direct comparison of the element condition in terms of its contribution to the overall structural condition.

Step 3 – Produce the Element Condition Index (ECI). The ECS (from step 1) and ECF (from step 2) are combined to produce the Element Condition Index (ECI) which represents the condition of the element on a scale of 1 (best) to 5 (worst). Steps 1 to 3 are applied for all elements or element groups in a bridge.

Step 4 – Evaluate the Bridge Condition Score (BCS). The BCS is evaluated as two different scores including $BCS_{(Avg)}$ as the weighted average of all the ECI values for the bridge's elements and $BCS_{(Crit)}$ as the maximum ECI value for the elements classified with "Very High" importance. The two scores together provide a better indication of the health condition of the structure since the $BCS_{(Avg)}$ provides an overall picture of the bridge condition indicating how widespread the deterioration is, while the $BCS_{(Crit)}$ provides an indication of the criticality of the structure due to the very poor condition of one of the critical elements.

Step 5 – Evaluate individual Bridge Condition Index (BCI). The BCS values are converted to the corresponding condition indices (BCI) on a scale of 0 (worst) to 100 (best). Steps 1 to 5 are repeated for all bridges in the bridge stock to produce the BCI for every individual bridge.

2.3 FHWA2006 approach: quantitative, for seismic risk assessment

FHWA2006 manual provides a performance-based approach for the seismic retrofitting of highway bridges. It contains a screening process to identify and prioritize bridges and a methodology to quantitatively evaluate the seismic capacity of a bridge and finally retrofit approaches and the corresponding techniques for enhancing the seismic resistance of existing bridges. The procedure can be summarized in the following steps:

Step 1 – Determine the bridge importance class as essential or standard. Essential bridges are those expected to function or that cross routes that are expected to remain open immediately after an earthquake. All other bridges are classified as standard.

Step 2 – Estimate the anticipated service life (ASL). ASL is estimated for determining the bridge's remaining service life and subsequently a retrofit category. Three such categories are used in this manual including ASL 1-3 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. This manual considers two levels of earthquake: 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_1) for two seismic levels are obtained as the spectral coordinates.

Step 4 – Determine the expected performance level based on the different levels of earthquake and ASL which are defined as four performance levels including 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 connection, bearings and seats (support length) and (b) vulnerability of columns, abutments, and liquefaction. The maximum of (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 (E), 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 second modified by the site amplification factor. The coefficient E is scaled to 10 to have the same weight as V.

Step 7 – Calculate the bridge rank (R) based on the seismic hazard rating (E) and the vulnerability rating (V) by multiplying these two scores. The bridge seismic rank (R) is on the scale of 0 (best) to 100 (worst).

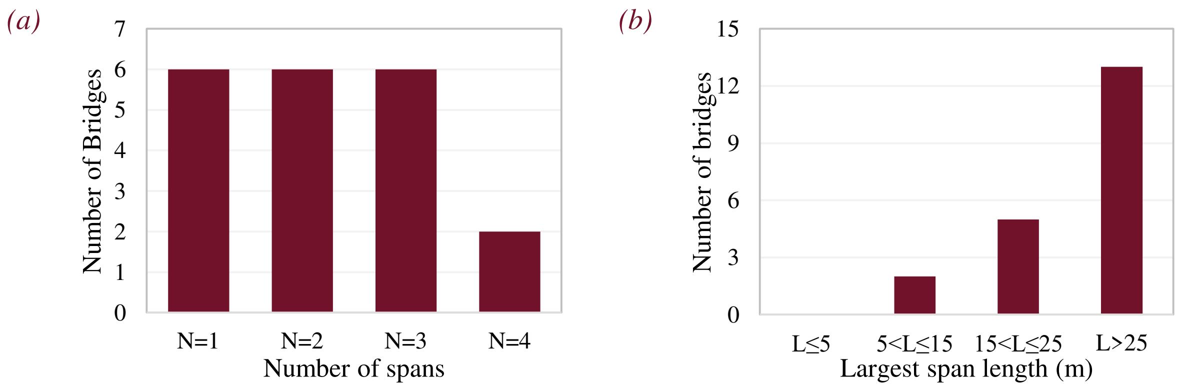
3 CASE STUDY BRIDGES

The three approaches introduced above were applied to a group of twenty real bridges belonging to primary roads of the Lombardy region in northern Italy, with the aim to classify them in terms of damage and seismic conditions. The bridges are viaducts and overpasses with a total length between 24 to 126 m with single or multi-span structural schemes, and most of them were built from 1967 to 1972. A summary of their main characteristics is provided in Table 1, while a statistical distribution of these bridges in terms of the number of spans, the largest span length, the construction material and the structural scheme is given in Figure 1.

Table 1: Summary of the main characteristics of 20 studied bridges.

Bridge ID	Year of construction	Number of spans	Bridge total length (m)	Largest span length (m)	Bridge width (m)	Avg. traffic (vehicle/day)
BR-1	1960	4	70	14	33	32042
BR-2	2000	3	51.9	33.9	26.08	63185
BR-3	1968	1	38	38	10.44	31615
BR-4	1972	1	31.15	31.15	10	26511
BR-5	1967	2	55.6	27.8	20.9	52123
BR-6	1967	3	72	27.8	20.9	55746
BR-7	1967	2	30	15	32	55746
BR-8	1967	3	49.7	25.7	42	55746
BR-9	1967	1	25	25	42	55746
BR-10	1969	2	78	39	10.44	28229
BR-11	1967	3	100	37.5	15.5	28229
BR-12	1967	4	126.5	38	20.9	55746
BR-13	1967	1	36.7	36.7	42	55746
BR-14	1968	3	110	50	16	58992
BR-15	1968	3	110	50	16	63185
BR-16	1968	1	31.15	31.15	41.8	63185
BR-17	1967	2	31.1	15.55	20.5	35559
BR-18	1970	2	31.1	15.55	16.52	34322
BR-19	1972	2	32.86	16.44	13	34322
BR-20	1971	1	24	24	13.5	26572

According to Figure 1 (a, b), most bridges have more than one span and the largest span length over 25 m (13 out of 20 bridges), while, as shown in Figure 1 (c), they mainly consist of simply supported beams. Figure 1 (d) groups the bridges in terms of the bridge deck material. In simply supported beams systems, single or multi-span bridges deck consists of several parallel beams with simple supports at the ends. Whilst in the continuous beam bridges deck, the beams span between the abutments by crossing continuously over the central piers. Finally, in the continuous slab bridges, a cast-in-place slab extends all over the spans forming a continuous slab deck. It is also worth mentioning that the largest multi-span bridges under assessment consist of steel beams with reinforced concrete slabs supported by reinforced concrete columns as the central piers.



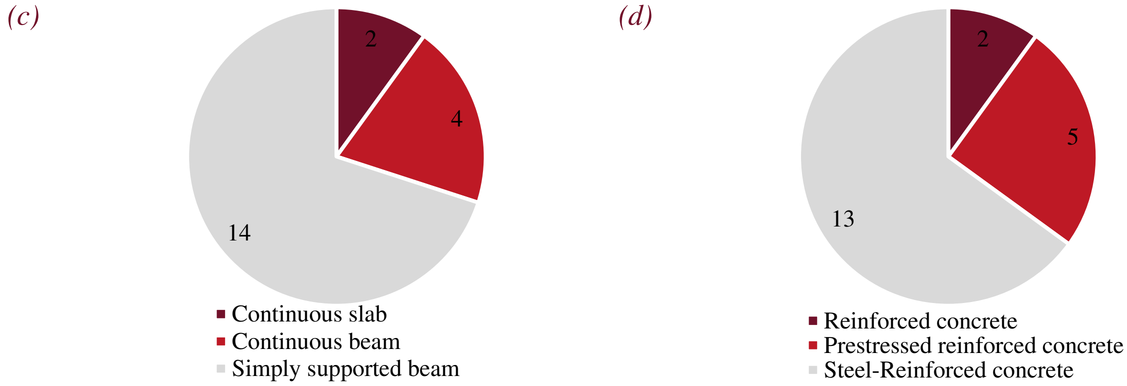


Figure 1: Statistical distribution of twenty selected bridges in terms of (a) number of spans, (b) largest span length, (c) structural scheme and (d) main deck material.

4 CONDITION ASSESSMENT AND RATING OF BRIDGES

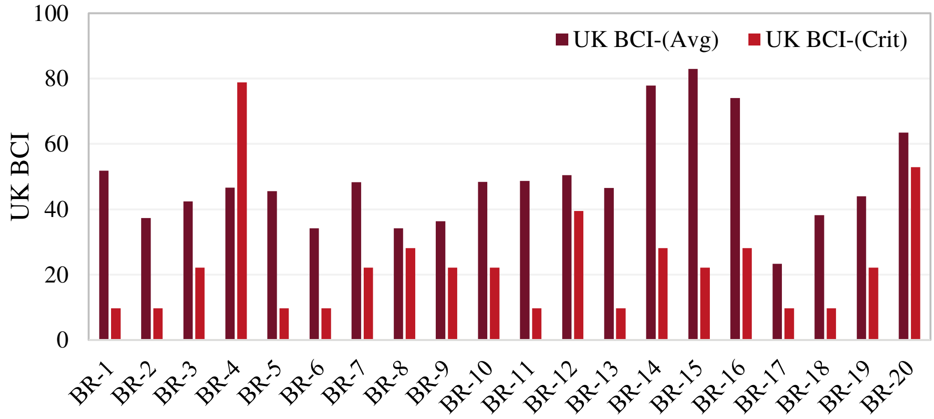
Following the description of the three approaches given in Section 2, the damages and seismic conditions of twenty selected bridges were assessed. The field data collection has been done according to the ITA Guidelines by visual inspections and expert teams in 2022. The bridge data included geometric, geotechnical and structural characteristics, site hazards and the damages and defects description and severity. As previously discussed, the ITA Guidelines account for both damage and seismic conditions in the risk assessment, while the UK BCI provides the damage condition rating and the FHWA approach provides the seismic condition rank for the bridges.

Using the ITA Guidelines, the defects CoA for 17 bridges out of 20 results as “High”. To this end, it must be noted that, in these guidelines, if the defects CoA is High, the final vulnerability of the bridge, regardless of the other influencing parameters, will always be High. Moreover, if a bridge is classified with High vulnerability, regardless of the hazard level and the bridge exposure level to that hazard, it will always be classified with a CoA of High to the corresponding hazard. The structural CoA for all bridges and the seismic CoA for all bridges excluding only three were High. Since in the ITA Guidelines the greatest weight and importance has been given to the structural CoA when combining the CoA of all hazards, all twenty bridges were classified with a total CoA of High. In this study, floods and landslides were not considered in the analysed bridges since they were not exposed to such hazards.

The rankings produced by the application of the UK and FHWA methods for damage and seismic conditions are shown in Figure 2. The UK BCI was estimated as two indices including $BCI_{(Avg)}$ and $BCI_{(Crit)}$. While the average index is calculated by weighing the damage condition of all elements based on their importance to the bridge stability (for gravity loads), the critical index represents the worst damage condition among the elements with a very high importance factor. Figure 2 (a) shows that wherever the $BCI_{(Avg)}$ had a larger value, the $BCI_{(Crit)}$ was not necessarily a larger value as well for the same bridge in comparison to the others and vice versa. Therefore, a bridge might be in a good overall condition by averaging the damage condition of all elements (larger $BCI_{(Avg)}$), while it might be in a very poor condition just accounting for the criticality of a single element damage condition (smaller $BCI_{(Crit)}$) e.g. BR14 and BR15. In other words, a bridge is considered to be in a good (e.g. BR20) or in a poor (e.g. BR17) condition from both overall condition and critical element condition perspectives, when both indices have large or small values simultaneously, respectively.

The ranking produced by the FHWA2006 method is shown in Figure 2 (b). The bridges ranks account for the structural vulnerability and site seismic hazard, thus the results represent the expected damage for a given earthquake level. Considering that in the FHWA rating scale, the larger rank indicates more vulnerability, the obtained results seem to indicate that all bridges have a very low seismic risk (maximum rank of about 12 for BR17-19 in upper level (UL) motion), which may be consistent with the low seismic risk of the Lombardy region (where the bridges are located). Indeed, the average peak ground acceleration (PGA) on bridge sites was 0.031g and 0.058g for LL and UL motions, respectively. In addition to that, the similarity of the seismic risk indicator among all bridges may be associated with their repetitive structural characteristics. The vulnerability of most of those bridges mainly resulted from the level of vulnerability of columns since their construction dates back to the late 60s and early 70s, which suggests that they were not adequately designed and detailed according to appropriate seismic requirements. Results showed that among the evaluated case studies, single-span bridges (e.g. BR4, 9, 13 and 16) are less vulnerable (smaller rank) when compared to the multi-span ones.

(a)



(b)

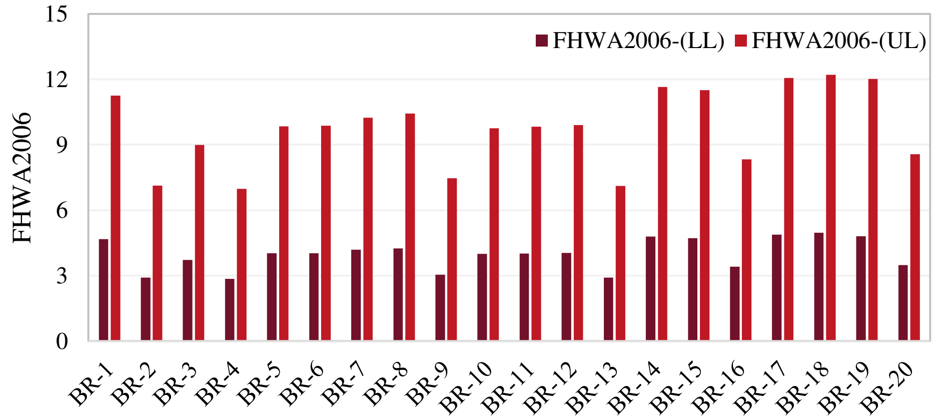


Figure 2: Numerical rating results of (a) UK BCI and (b) FHWA2006 methods for twenty studied bridges.

Figure 3 displays the risk assessment ratings obtained from the UK and FHWA methods compared to the corresponding classes of attention (CoA) of bridges according to the ITA Guidelines. The classification is presented in High (H) to Low (L) risk condition ranges using an equivalent scale between the UK and FHWA methods with the ITA Guidelines according to Table 2. As shown in Figure 3 (a), considering the UK $BCI_{(Crit)}$, the statistical distribution of the bridges in terms of the damage and deterioration condition was very similar to the results obtained with the ITA Guidelines for the defects CoA. The reason for this observation can be explained by the fact that both methods follow the same logic to define the overall defects condition of the bridge, which is based on the worst damage condition in a critical element. As previously mentioned in determining the total CoA of the bridges in the ITA Guidelines, the greatest dominance is given to the structural CoA, which in turn is mainly a function of the defects condition, hence in Figure 3 (b) almost the same results as (a) are observed. According to Figure 3 (c), the damage and deterioration condition obtained as UK $BCI_{(Avg)}$ and the ITA Guidelines defects CoA do not match much. This may be because the UK $BCI_{(Avg)}$ represents the overall condition of the bridge based on the damages of all elements, while the ITA Guidelines consider the worst damage case in critical elements to represent the defects condition of the bridge. Finally, the comparison given in Figure 3 (d) shows that the ITA Guidelines lead to very different seismic condition categories with respect to the FHWA method. In this regard, the ITA Guidelines seem to be more conservative, considering that many additional parameters are included e.g. lack of seismic design criteria, strategic importance, or alternative routes. In addition, the ITA Guidelines account for defects, type of structural scheme, and materials for the seismic vulnerability assessment as well. On the other hand, the FHWA method mainly focuses on the vulnerability of connections, bearings and seats as well as that of columns, abutments and probability of liquefaction.

Table 2: The considered equivalent ranges for bridges condition rating in different methods

ITA CoA-Defects		UK BCI	ITA CoA-Seismic		FHWA2006
High		Very poor (0-40)	High		80-100
Medium-High		Poor (40-65)	Medium-High		60-80
Medium	≈	Fair (65-80)	Medium	≈	40-60
Medium-Low		Good (80-90)	Medium-Low		20-40
Low		Very good (90-100)	Low		0-20

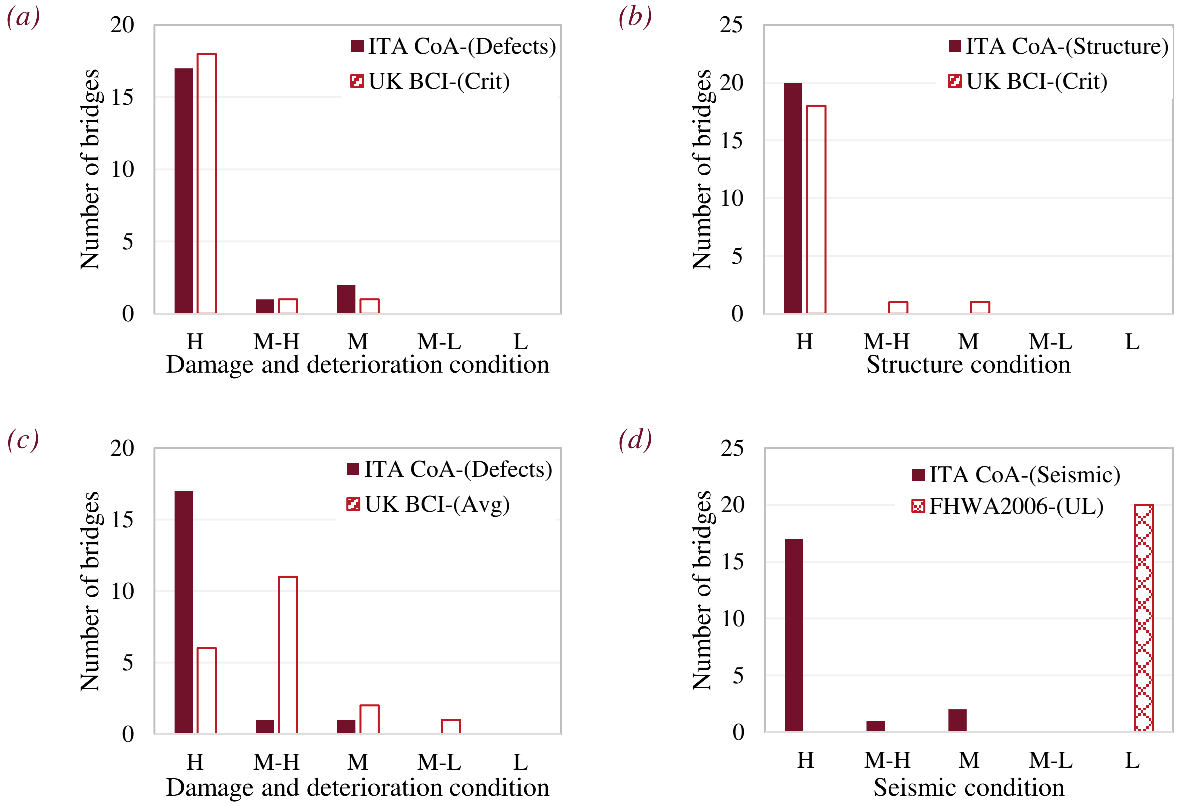


Figure 3: The comparison of twenty studied bridges classification using ITA Guideline, UK BCI and FHWA2006.

5 CONCLUSIONS

This paper presented a comparative assessment of prioritization scheme evaluations considering a stock of twenty bridges located in the Lombardy region in northern Italy. The assessment was performed according to three different approaches: The Italian Guidelines, the United Kingdom method and the FHWA2006 (USA) method, with the aim to assess the bridges in terms of the structural deterioration and seismic condition. The

United Kingdom and FHWA2006 methods provide quantitative indices for bridges condition rating, while the ITA Guidelines represent the bridge condition on a qualitative basis. The findings of this study showed that the ITA Guidelines seem to be more conservative when compared to the other two approaches. Nevertheless, these guidelines involve a wider variability of bridge characteristics as input parameters including the bridges geometric, structural and static characteristics as well as the bridge age, deterioration speed, hyperstatic or isostatic schemes, and the adopted design regulations at the time of construction. To all those mentioned above must be added the traffic flow, the strategic importance, the body bypassed and the existence of alternative routes, which affect the exposure class of the bridge to existing seismic hazards. The main drawback of the ITA Guidelines is the qualitative basis of the provided classes of attention (CoA) for the bridges according to which it is not easy to classify the bridges of the same CoA in relative priority order, as opposed to the UK and FHWA methods. For this reason, for prioritisation purposes, the near future efforts in increasing the resolution of the ITA Guidelines could be their integration with more quantitative parameters. This should enable a distinction between bridges that are assigned the same CoA, i.e. enable decision-making agencies to use simplified quantitative methods for bridges within specific classes of attention to produce rankings. Overall, according to the findings of this study, a balance can be found between the different approaches regarding the objectives of the decision-making agencies from performing the risk assessments, which might affect the maintenance, rehabilitation or replacement decisions of the bridges. For the further development of this study, more standards from other countries including the New Zealand guidelines were under evaluation at the time of writing this paper, the findings of which are expected to be available in the near future.

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