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Characterisation of an urban bridge portfolio and multi-risk prioritisation accounting for deterioration and seismic vulnerability

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ABSTRACT

This contribution proposes a procedure to prioritise retrofit interventions on stocks of bridges according to their seismic vulnerability. The procedure also combines a previously presented approach to evaluate deterioration effects on bridges at a territorial scale. Thereby, the combination of the two approaches provides a multi-risk classification method for bridge stocks. This method also allows refined prioritisation within each class, based on the proposed quantitative indices and on multicriteria decision-making methods. The method was applied to the bridge stock managed by the municipality of Padova, in North-East Italy. First, an extensive characterisation of the analysed stock is provided, according to typological, geometric, and structural parameters. Then, the application of the combined approach is presented, highlighting which bridge types resulted more vulnerable to either seismic actions or deterioration effects.

1. Introduction

The safety and operativity of bridges are key aspects to ensure functionality of roadway networks, which are vital for economic and social life of communities, as well as for emergency management, to reach impacted areas. Bridge safety is therefore of paramount importance to guarantee that roadway and railways networks remain operational.

Bridge can be affected by various hazard, which can be classified into two broad categories: natural hazards (e.g., flood, scour, earthquake, and landslide) and human factors (e.g., design imperfection, construction deficiencies, collision, and lack of maintenance) [1]. Thus, procedures to prioritise detailed verifications and, subsequently, restoration and retrofit interventions are required by administrations in charge of managing bridge stocks with limited human resources and funds.

A growing part of the literature has investigated the above-mentioned aspects, generally focusing on a single risk. These studies proposed tools to support decision-making, to devise and address mitigation strategies, and to enhance reliability and resilience of

Abbreviations: **DM**, Masonry deck; **DC**, Reinforced concrete deck; **DPC**, Prestressed reinforced concrete deck; **DS**, Steel deck; **DCS**, Composite steel deck; **ARCH**, Arch; **SIM**, Simply supported; **GER**, Multi-span Gerber scheme; **CONT**, Continuous span; **RET_SIM**, Reticular – simply supported; **CBL**, Cable bridge; **PC**, Reinforced concrete pier; **PM**, Masonry pier; **PS**, Steel pier; **PSC**, Single column pier; **PW**, Wall pier; **PF2**, Double frame pier; **PFM**, Multi-frame pier; **SR**, Solid rectangular section; **SC**, Solid circular section; **HS**, Hollow simply connected section; **HM**, Hollow multiply connected section; **AC**, Reinforced concrete abutment; **AM**, Masonry abutment; **AST**, Stone abutment; **KL**, Knowledge level.

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networks. Among the others, these tools include bridge management systems (BMS), prioritisation procedures, and vulnerability assessment towards natural risks. A presentation of the literature relevant for our work is presented in section 2.

Evaluations of stocks of structures, at a large scale, might be affected by paucity of information, which retrieval would require time-consuming on-site surveys and documentation research, and may be hindered by the territorial extension of the same stock. In this framework, investigation and analysis of datasets of structures, in this case bridges, can be useful to define a thorough taxonomy, by identifying typological and structural characteristics.

Oliveira et al. [2] analysed more than 4700 bridges managed by the Brazilian Federal Department of Transport Infrastructure (almost 80% of total infrastructure asset), to collect data aimed at predicting degradation evolution, improving the adopted BMS. A quite extensive statistical description of U.S. bridge inventory was also presented in the literature [3].

Some Italian bridge stocks were briefly presented by Pinto and Franchin (2010) [4], Borzi et al. (2015) [5], and De Matteis et al. (2019) [6], while extensive discussions of stocks are difficult to find, despite the wide interest, due to the lack of informative resources and difficulty to carry out time consuming on-site surveys. An example of extensive analysis of a bridge inventory was presented by Tecchio [7], with specific reference to reinforced concrete (r.c.) bridges.

For these reasons, after providing a review of the available literature regarding either single-risk or multi-risk analyses of bridge stocks, this paper proposes a novel priority ranking procedure to sort bridge according to their seismic vulnerability. The procedure is consistent with prioritisation approaches proposed in the literature to analyse the level of deterioration of bridges. The combination of both outcomes (i.e., regarding degradation and seismic evaluations) to obtain a multi-risk classification is also provided. Interclass prioritisation is also defined through a well-established multi-criteria decision-making (MCDM) method (i.e., Weighted Aggregated Sum Product Assessment, namely WASPAS [8,9]). Therefore, the proposed approach attempts to fill the gap between the Italian Guidelines for existing bridges [10], which have been recently issued and which define a procedure for grouping bridges of a stock within four attention classes, and the needs of the administrations in charge of the bridge stock management, which require a quantitative rating for bridges falling within the same attention class, in order to prioritise interventions.

The work was carried out on a bridge stock at an urban scale, accounting for more than 160 bridges of various macro-classes. An extensive on-site visual inspection campaign was carried out on the urban stock, as well as data collection by retrieving original project documentation. The fulfilled knowledge process, which required significant burden in terms of work and time, provided detailed data about typological, geometric, and structural characteristics of masonry, reinforced concrete (r.c.), and steel bridges part of the inventory, here presented by means of aggregated information.

The analysed stock refers to the urban area of the Municipality of Padova, in North-East Italy, whose specific features are described in the paper. Information regarding the characterisation of the stock may be useful to build up web platforms of infrastructures (e.g., Faravelli et al. (2018) [11]), as well as the Italian public infrastructures dataset, called AINOP [12].

Lastly, findings resulting from the application of the procedure to the analysed urban stock are discussed in Section 5, highlighting which types of bridges are suggested to be more susceptible to degradation and seismic damage.

2. Review of available bridge management and assessment approaches

An overview of bridge management systems (BMS), bridge prioritisation approaches and methodologies to evaluate the seismic vulnerability of bridges is given in this section, without claiming to be exhaustive. Some of the mentioned approaches consider multiple hazards and risks, given the growing scientific interest on this topic.

2.1. Bridge management systems

Research in the field of BMS has been a topic of great interest since it has provided scientific-based tools to manage large stocks of bridges and to support decision-making for the administrations.

One of the pioneer administrations in this area was the U.S. Federal Highway Administration (FHWA). Starting from the early 90s the FHWA have developed the software package PONTIS, which adopted an optimisation model. A multi-year simulation, accounting for both maintenance and retrofit, allows intervention strategies to be optimised through benefit/cost analyses within budget constraints [13]. In the same context, in the framework of the U.S. National Cooperative Highway Research Project (NCHRP) a BMS software for transportation agencies was developed, named BRIDGIT. It can be run in parallel to PONTIS, providing further analyses on the bridge stock, based on life-cycle costing. It also provides the optimal timing for actions, evaluating their ideal delay to enhance cost-effectiveness [14]. Both PONTIS and BRIDGIT are based on similar mathematical procedures to optimise the bridge network efficiency from an economic point of view. Indeed, deterioration and performance concerns are expressed in economic terms, as reported by Frangopol et al. (2001) [15], who highlighted the main limitations of these procedures and proposed a reliability-based BMS in order to consider the uncertainties related to the bridge management.

Six European highway research laboratories (of United Kingdom, France, Germany, Norway, Slovenia, and Spain) took part to the EU project BRIME (i.e., Bridge Management in Europe) [16]. The goal of the project was to develop a BMS taking into account: condition state, load bearing capacity, rate of deterioration, effect on traffic, life of repairs, and residual life of the structure. A multi-level approach was proposed, identifying five assessment stages of increasing detail. In this framework, bridges with an acceptable safety level can be assessed with limited effort, while more refined analyses are carried out for structures with inadequate capacity. This multi-level approach has become a crucial reference, being proposed in several management tools developed in the following years. This approach contemplates seismic risk in terms of special inspections to be carried out in the aftermath of an earthquake, and seismic hazard can be considered in a simplified manner, through a factor increasing the index expressing the importance of bridges and networks.

The Italian Railway Network (RFI) administration adopted a BMS based on the DOMUS procedure [17], which consists in the following main modules: bridge inventory, computer-aided visual inspection, automated defect catalogue and priority-ranking procedure. A probabilistic framework for priority evaluation was calibrated for various classes of bridges by using Monte Carlo simulations.

Zonta et al. (2007) [18] presented the BMS developed for the Autonomous Province of Trento. This web-tool includes condition state evaluation by means of visual inspection, as well as possible connection to real-time permanent monitoring systems. A specific section was provided for formal reliability assessment, which is not directly derived from the condition state section. The reliability assessment provides five stages of increasing complexity in order to rationalise the assessment procedure, as recommended by BRIME [16].

Starting from the early 2000s, reliability-based BMS have been object of broad research interest due to the possibility to deal with uncertainties [15]. Liu and Frangopol (2004) [19] provided a tool for bridge maintenance planning, accounting for uncertainties associated with deterioration processes, considering whether maintenance actions are implemented. A numerical procedure, based on a multi-objective genetic algorithm, evaluates the best possible maintenance planning solution, referring to three objective functions: condition index, safety index, and cumulative life-cycle maintenance cost. Kim et al. (2020) [20] introduced a probabilistic approach to determine the optimum target reliability, as reference for maintenance planning, of a single bridge at network level. The following objective functions were taken into account: maximizing the reliability and the redundancy of the bridge network while minimizing expected costs of maintenance and for users.

Together, these studies, which represent the major examples of BMS, focused on aging and deterioration effects on bridges and networks to plan maintenance. However, an efficient planning of interventions (including maintenance) cannot leave aside retrofit towards natural risks affecting the area. Hence, BMSs should be integrated with evaluations of natural risks to devise mitigation strategies at territorial scale. Therefore, this research aims to propose a methodology for the seismic assessment of bridge assets consistent with that of the deterioration level. The combination of both evaluations thus represents a useful tool for managing stocks of bridges, enabling the planning of both maintenance and retrofit interventions.

2.2. Approaches for risk classification and prioritisation of bridge stocks

The definition of priorities for interventions on networks is strongly required to define efficient maintenance programs based on knowledge acquisition and standardised techniques. Not only this need is found in developing countries, whose networks are often degraded, but it is also common in developed countries which neglected for long time the maintenance of infrastructures, and then must put in place extensive repair and rehabilitation plans for their stocks [16]. Several prioritisation approaches are available in the literature. Many of them take into account deterioration effects on bridges as the main cause of risk and are based on visual inspections and various types of rating, although some methods also consider other risks, such as seismic, hydraulic and hydrogeologic.

Sathananthan et al. (2010) [21] proposed a risk ranking procedure for a preliminary definition of inspection priority, through a qualitative score, to support administrations in charge with large stocks and networks to plan on-site surveys. Structural characteristics, type of environment, consequences of failure, survey accessibility, and deterioration information were all included in the evaluation. This procedure must be followed by inspections and deeper evaluations, to define intervention priorities.

The prioritisation scheme proposed by Montepara et al. (2008) [22] consists of two levels: decay affecting structures (project level) and the importance of each structure in the network (network level). The procedure requires on-site visual surveys of the deterioration state. Each defect type is numerically described by discrete values associated to predefined thresholds, considering severity, frequency, extension, and rapidity of evolution of surveyed defects. The overall structure state is then assessed exclusively according to the most critical element of the bridge. The importance of bridges in the network is estimated through a coefficient defined as a function of three discrete parameters: road network classification, traffic entity, and strategic viability. This method focused on deterioration, while the vulnerability of structures and networks towards other natural hazards is not included.

Another procedure based on the level of deterioration only was developed by Pellegrino et al. (2011) [23], and it was implemented as part of the application presented in this paper. Deterioration effects on each bridge are evaluated through visual inspections, by assigning a condition value (*CV*), to each element of the observed bridge, related to its functional condition. Ratings are then calculated at both element and bridge level. Both element and total ratings are corrected by coefficients accounting for the bridge's importance within the network and for the structure age.

More recently, Yang et al. (2018) [24] proposed a prioritisation procedure for bridge maintenance, focusing on deterioration, based on risk at network level. The procedure provides an accurate estimation of failure probabilities for bridges and the consequent impact on the entire network.

Regarding multi-risk evaluations, Valenzuela et al. (2010) [25] proposed a multi-risk prioritisation index accounting for the bridge importance within the network, seismic and hydraulic risk, and deterioration. The prioritisation index is computed as sum of indices, each of which quantified the susceptibility of the bridge to one specific risk. Corrective coefficients were calibrated by the authors, based on expert elicitation on many randomised scenarios. The proposed method is fairly expeditious for most of the risks included in the evaluations, except for seismic risk, which requires the definition of numerical models to be assessed as proposed.

Focusing on the importance of each bridge within the network, Abarca et al. (2022) [26] proposed a simplified methodology for prioritisation in roadway networks. The proposal quantified the importance of bridges in terms of indirect losses (specifically, the delay experienced by a single user in case of collapse). This method could be integrated with evaluation of deterioration levels and susceptibility to natural risks to optimise mitigations strategies at network level.

Recently, in Italy, new Guidelines were issued for risk classification, safety evaluation and monitoring of existing bridges [10]. A new simplified and multi-level approach was proposed to evaluate bridges part of a stock, considering multiple risks (i.e., structural risk accounting for degradation, and seismic, hydraulic and hydrogeologic risks). The first assessment level, at a territorial scale, is based on visual inspections and it classifies bridges by assigning an "attention class" related to each of the above-mentioned risk. No quantitative rating is provided in this assessment level to prioritise bridges assigned to the same class. A multi-risk classification is also provided according to a combination matrix, based on attention classes obtained for each risk. Santarsiero et al. (2021) [27] presented the application of novel Italian Guidelines to a stock of 48 bridges located in the Basilicata region, in Southern Italy, highlighting that the methodology, as it is defined nowadays, provides conservative results. In this context, this paper makes an important contribution that overcomes one of the critical issues, after the application of the current Guidelines, by proposing an MCDM-based methodology for sorting bridges within the same multi-risk class, and thus support the decision-making process of the administrations in charge of the bridge stock management.

2.3. Rapid evaluation of seismic vulnerability at a territorial scale

During past seismic events, in regions of medium-high seismicity such as Italy, bridges showed a low susceptibility towards collapse [28]. However, retrofit interventions are generally required to prevent functionality loss during post-event emergency, as observed in the past [5]. In this context, fragility curves are an important tool for seismic risk assessment of large bridge stocks at a territorial scale, as they allow estimating seismic vulnerability by accounting for uncertainties. Moreover, bridge assets are particularly suitable for evaluation through fragility curve for macro-classes, due to structural repetitiveness, provided that a sufficient knowledge of exposed assets is fulfilled, to correctly assign taxonomy-based fragility curves to each bridge [29].

Muntasir and Shahria (2015) [30] presented a review of the available methods implemented for seismic fragility assessment of highway bridges, specifying limitations and fields of application.

Empirical fragility curves for bridges were developed based on the large amount of data from the 1994 Northridge and the 1995 Kobe earthquakes [31,32]. Empirically derived fragility functions are rather accurate; however, they are strongly related to the observed construction taxonomy and to eventual site-specific features of the occurred earthquake. In addition, empirically derived fragility depends on the inference of ground motion intensity at sites [33]. Spatial correlation of ground motion (g.m.) intensity was demonstrated to significantly impact fragility assessment [34,35], as well as loss estimation [36].

Analytical models allow the derivation of fragility curves for generalised taxonomies of bridges, also when post-event data are not available. Among these, the HAZUS earthquake model [37] represents one of the most widespread methods for vulnerability assessment. It provided analytical fragility curves for macro-classes of structures, calibrated for an extensive taxonomy specific of United States. With a consistent methodology, sets of fragility curves for the European context were derived in the framework of RISK-UE project [38].

The implementation of non-linear time history analyses (NLTHA) is one of the most applied analytical methods to derive fragility curves, also allowing evaluation of specific aspects. For instance, Ramanathan et al. (2012) investigated the influence of structural conceptualisation (either gravitational or seismic) on structural fragility [39], whilst fragility assessment for specific g.m. features was carried out by Kabir et al. (2019) [40]. By means of NLTHA, fragility curves were derived for specific bridge types, such as simply supported steel bridges [41], multi-frame bridges [42], and concrete arch bridges [43], since numerical analyses can overcome the lack of empirical data. Results from NLTHA strongly depend on the chosen ground motion set, as well as on selected demand parameters, discussed in the review by Muntasir and Shahria (2015) [30].

Bayesian approaches were exploited to estimate probabilistic seismic demand models for bridge columns [44,45] and for fragility evaluations [46].

A number of studies focused on fragility assessment for particular regions around the world to better catch the regional construction characteristics, for instance for North America regions [47,48], Greece [49], and Italy [5,7,50]. In particular, Borzi et al. (2015) [5] implemented a comprehensive database of existing bridges of the Italian infrastructure asset, accounting for about 17,000 bridges of heterogeneous level of knowledge. This database was used to develop seismic risk and scenario maps at national level. With this aim, the fragility assessment was implemented, only for r. c. girder bridges, through NLTHA.

The seismic capacity of masonry arch bridges was assessed through limit analysis in case of both multi-span [51] and single span [52] bridges proposing, for the latter, a fragility set for each collapse mechanism affecting these structures.

Furthermore, deterioration can affect the seismic performance of bridges. To date, only few studies have developed seismic fragility curves accounting for deterioration, mainly focusing on r. c. bridges. Some authors have mainly investigated the effect of corrosion on r. c. bridges [53–55], while one study by Sung and Sue (2011) [56] proposed time-dependent fragility curves accounting for carbonation. Very recently, fragility curves accounting for deterioration were derived for single-span masonry arch bridges [57].

In the last few years, research has focused also on multi-hazard risk assessment, considering the occurrence of cascading events or multi-hazard interactions. Gehl and D'Ayala (2018) [58] presented an integrated method for risk assessment of infrastructures exposed to earthquake and flood. The methodology considers the potential interaction between the two above-mentioned hazards by a time window, based on repair duration, in which the effects of one event may still affect bridges. Bayesian networks are used to propagate uncertainties and to compute joint probabilities. Li et al. (2020) [59] applied resilience assessment for bridges also in case of multiple independent natural hazards (i.e., earthquakes, hurricanes, and floods).

3. Typological and structural characterisation of the bridge inventory of Padova, Italy

In this work, the inventory of bridges managed by the municipality of Padova (as the local administration in charge for the road above or underneath the bridge) is presented. The stock was object, in the years 2016–2019, of an extensive on-site visual inspection campaign, and data collection through the retrieval of archival documentation. The carried-out knowledge process preceded the application of a combined priority ranking procedure, illustrated in the following sections, and allowed typological and geometrical characteristics to be collected, here presented as aggregated distributions.

The Padova bridge inventory counts 162 structures of various types, neglecting very short bridges (with a total length shorter than 3 m). Some examples of observed bridge types are illustrated in Fig. 1. Typological distributions are strongly affected by topography and urbanization of the municipality. Padova is indeed located in a flat area and its first urban settlement dates back to the XII century BC. As many European cities, it is surrounded by rivers and artificial canals, used in the past for both defence and transport functions. A significant number of buildings and structures from Roman and Medieval ages can be found in the Historical Centre (HC); among these, a certain number of bridges which are mostly operational. Although Padova is a medium city in the national contest, accounting for slightly less than 250.000 citizens, its metropolitan area, considering the nearby municipalities, is a large urban system of almost 500.000 inhabitants, including a beltway more than 40 km long and various connections to the railway and highway systems. Therefore, despite its flat topography, it is also possible to find long span bridges within the HC, particularly those overpassing the railway tracks close by the railway station, as also common in many European and Italian cities. Outside the HC, where the main obstacle to span is given by the roadway network, long span bridges can be mainly found in extra-urban interchanges.

Data related to bridges inside and outside the HC were grouped separately. In this way, peculiarities of each subset are highlighted hereinafter. Indeed, the partial inventory consisting of bridges outside the HC provides dataset information that are comparable to other general infrastructural networks, not including an ancient urban nucleus.

Fig. 2 shows the distributions of single typological and geometrical parameters for all bridges of the Padova inventory, whereas Fig. 3 shows the same parameters but analysed in a coupled manner (i.e., deck material versus type of bridge and static scheme subdivided considering year of construction and span length).

Most of the observed structures are road bridges, with also a significant number of pedestrian bridges. The age of the stock is quite heterogeneous. About 27% of the stock was built before 1920, mainly in the historical centre, including most of the masonry arch bridges. A second relevant number of bridges (23% of the stock) was built between 1960 and 1980, corresponding to the expansion of urbanized and productive areas outside the historical centre. Finally, the last relevant group of bridges (22%) was built very recently, after 2000. This peak was linked to the accomplishment of the main suburban beltway, carried out in the early 2000s, and to the design of safe pedestrian paths, including pedestrian bridges, to improve safety towards the increasing traffic volume. Most bridges in the historical centre have either masonry or reinforced concrete decks. Outside the historical centre, more than 60% of structures are reinforced concrete bridges (considering both ordinary and prestressed r. c.), percentage increasing up to almost 70% when only road bridges are considered. Although r. c. bridges represent the greater subset, other structural types are not negligible, as stated for highway (extra-urban) assets described in the literature [4,5]. Hence, heterogeneous stocks may be generally expected in urban networks, as the one here presented.

Bridges in the Padova inventory are mainly single-span structures, followed by bridges with two or three spans, whose amount in the inventory is still significant. Structures with a greater number of spans are uncommon, and almost entirely located outside the HC. With reference to the total length distribution, small (<20 m) to medium (20–40 m) bridges are mainly observed, as commonly perceived for cities with densely populated centres and flat topography. Out of the HC, longer structures are found, while almost all bridges within the HC are shorter than 60 m. Due to the prevalence of single-span bridges, the span length tends to be in the middle

Fig. 1. Examples of bridge types in Padova inventory: a) masonry arch; b) r. c. deck with Gerber scheme; c) composed steel-r. c. deck; and d) steel deck arch.

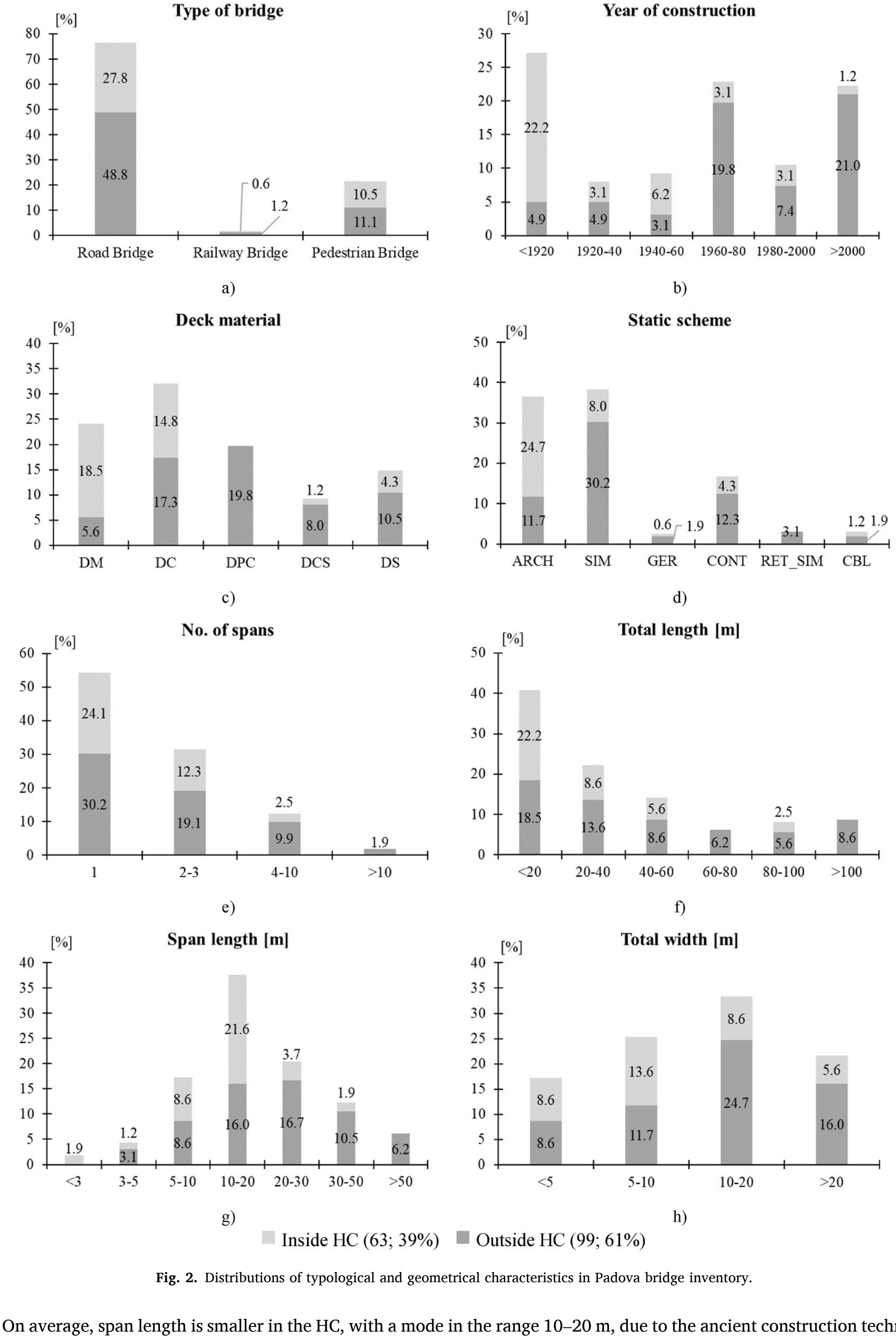


Fig. 2. Distributions of typological and geometrical characteristics in Padova bridge inventory.

ranges. On average, span length is smaller in the HC, with a mode in the range 10–20 m, due to the ancient construction technology of masonry arch bridges. The same span length is also found in a large part of r. c. bridges within the HC, which were built as enlargement of previous bridges. Outside the historical centre, the span length mode is in the range of 20–30 m, and longer bridges correspond to

Deck material vs type of bridge

Ouside HC 162 [%]		Road	Railway	Pedestrian
Deck Material	DM	16.7	0	7.4
	DC	27.2	1.2	3.7
	DPC	19.8	0	0
	DS	4.9	0	9.9
	DCS	8.0	0.6	0.6

Inside HC 63 [%]		Road	Railway	Pedestrian
Deck Material	DM	31.7	0	15.9
	DC	33.3	1.6	3.2
	DPC	0	0	0
	DS	3.2	0	7.9
	DCS	3.2	0	0

Ouside HC 99 [%]		Road	Railway	Pedestrian
Deck Material	DM	7.1	0	2.0
	DC	23.2	1.0	4.0
	DPC	32.3	0	0
	DS	6.1	0	11.1
	DCS	11.1	1.0	1.0

Static scheme vs year of construction

All 162 [%]		<1920	1920-40	1940-60	1960-80	1980-00	>2000
Static scheme	ARCH	25.3	4.9	1.2	0.6	0	4.3
	SIM	1.9	0.6	4.9	13.0	8.0	9.9
	GER	0	0.6	0	1.9	0	0
	CONT	0	0	2.5	6.8	1.9	5.6
	RET_SIM	0	1.9	0	0.6	0	0.6
	CBL	0	0	0.6	0	0.6	1.9

Inside HC 63 [%]		<1920	1920-40	1940-60	1960-80	1980-00	>2000
Static scheme	ARCH	52.4	6.3	3.2	1.6	0	0
	SIM	4.8	0	6.3	3.2	3.2	3.2
	GER	0	1.6	0	0	0	0
	CONT	0	0	4.8	3.2	3.2	0
	RET_SIM	0	0	0	0	0	0
	CBL	0	0	1.6	0	1.6	0

Ouside HC 99 [%]		<1920	1920-40	1940-60	1960-80	1980-00	>2000
Static scheme	ARCH	8.1	4.0	0	0	0	7.1
	SIM	0	1.0	4.0	19.2	11.1	14.1
	GER	0	0	0	3.0	0	0
	CONT	0	0	1.0	9.1	1.0	9.1
	RET_SIM	0	3.0	0	1.0	0	1.0
	CBL	0	0	0	0	0	3.0

Static scheme vs span length

All 162 [%]	Span length [m]	<3	3-5	5-10	10-20	20-30	30-50	>50
Static scheme	ARCH	0	1.2	8.6	15.4	4.3	3.7	3.1
	SIM	1.2	3.1	6.2	14.2	13.0	0.6	0
	GER	0	0	0	1.2	0.6	0.6	0
	CONT	0.6	0	2.5	5.6	1.9	5.6	0.6
	RET_SIM	0	0	0	0.6	0	0	2.5
	CBL	0	0	0	0.6	0.6	1.9	0

Inside HC 63 [%]	Span length [m]	<3	3-5	5-10	10-20	20-30	30-50	>50
Static scheme	ARCH	0	3.2	14.3	36.5	6.3	3.2	0
	SIM	3.2	0	6.3	11.1	0	0	0
	GER	0	0	0	1.6	0	0	0
	CONT	1.6	0	1.6	6.3	1.6	0	0
	RET_SIM	0	0	0	0	0	0	0
	CBL	0	0	0	0	1.6	1.6	0

Ouside HC 99 [%]	Span length [m]	<3	3-5	5-10	10-20	20-30	30-50	>50
Static scheme	ARCH	0	0	5.1	2.0	3.0	4.0	5.1
	SIM	0	5.1	6.1	16.2	21.2	1.0	0
	GER	0	0	0	1.0	1.0	1.0	0
	CONT	0	0	3.0	5.1	2.0	9.1	1.0
	RET_SIM	0	0	0	1.0	0	0	4.0
	CBL	0	0	0	1.0	0	2.0	0

5 % 5-15 % 15-30% 30-50% >50%

Fig. 3. Frequencies of coupled geometric and typological characteristics in Padova bridge inventory.

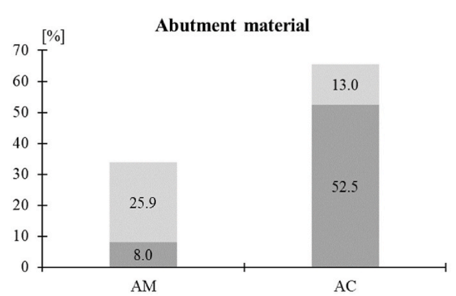
precast r. c. girders or steel decks. An exception, within the HC, is represented by bridges close to the railway station, which have a greater span length, up to 50 m, to overpass the rail tracks. The total transverse width distribution is quite heterogeneous, with a peak corresponding to the range 10–20 m (33%).

Distributions of coupled parameters showed a prevalence of road bridges for subsets of bridges having masonry, r. c. and composed steel-r. c. decks, whereas steel bridges were mainly used for pedestrian bridges. Almost all ancient bridges in the HC have arched static scheme.

Girder decks built after 1940 in the HC were often realized next to masonry arch bridges, to enlarge the roadway. Outside the HC, static schemes distribution through the years is more heterogeneous, with a pick corresponding to simply supported girder bridges in the period 1960–1980.

Fig. 4 shows the frequency distribution of the abutment material for the entire inventory, also subdivided according to the year of construction. These frequencies refer to 161 structures of the inventory, as one pedestrian bridge does not present typical abutments against soil. A clear evolution was observed during years. The most ancient structures have mainly masonry abutments, with a progressive increase over years in the use of r. c., which is overall most used (66%).

Figs. 5 and 6 refer only to multi-span bridges (24 structures within the HC, 50 outside the HC) displaying distributions of pier characteristics, also coupled with typological parameters. Reinforced concrete is the most used material for both piers. However, similarly to abutments, ancient bridges mostly have masonry piers. Frame piers, both double- and multi-column, are the most frequent pier type (53%). Obtained distributions suggested that the pier type is related to the total transverse width, as highlighted by the



All 161 [%]		<1920	1920-40	1940-60	1960-80	1980-00	>2000
Abutment material	AM	26.1	3.1	1.9	2.5	0.6	0
	AC	1.2	5.0	7.5	19.9	9.9	22.4

Inside HC 63 [%]		<1920	1920-40	1940-60	1960-80	1980-00	>2000
Abutment material	AM	54.0	3.2	4.8	4.8	0	0
	AC	3.2	4.8	11.1	3.2	7.9	3.2

Ouside HC 98 [%]		<1920	1920-40	1940-60	1960-80	1980-00	>2000
Abutment material	AM	8.2	3.1	0	1.0	1.0	0
	AC	0	5.1	5.1	30.6	11.2	34.7

Inside HC (63; 39%) Outside HC (98; 61%)

5 % 5-15 % 15-30% 30-50% >50%

Fig. 4. Distribution of abutment material in Padova bridge inventory.

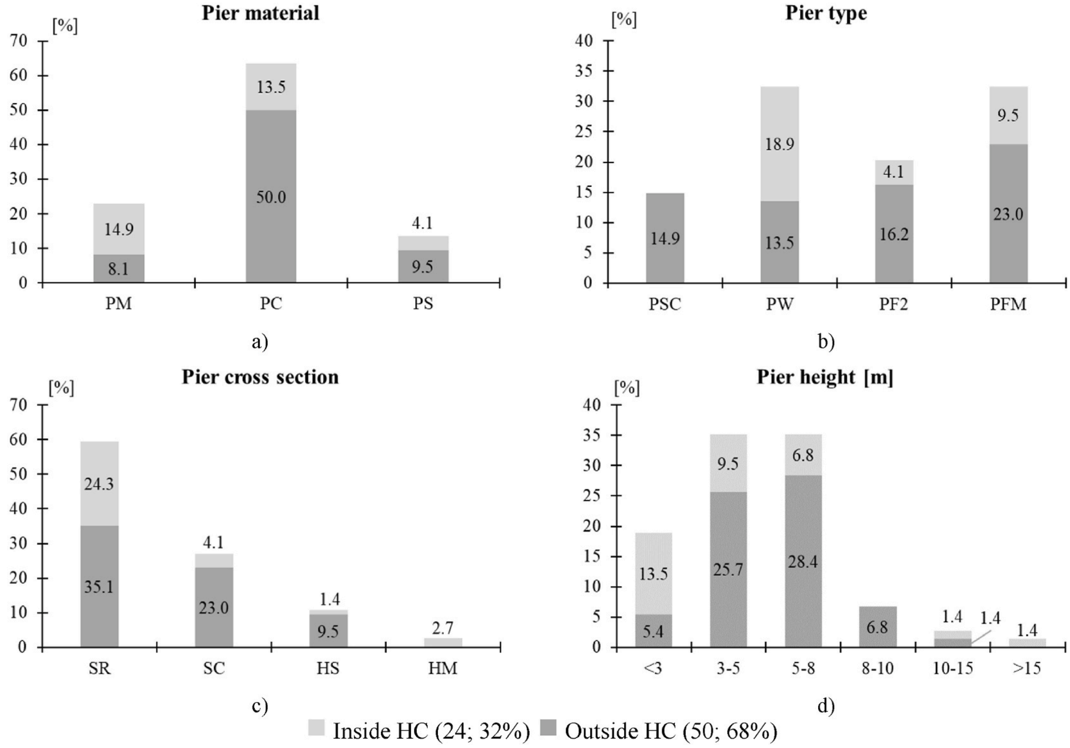


Fig. 5. Distributions of pier characteristics for multi-span bridges in Padova inventory.

Pier material vs year of construction

All 74 [%]		<1920	1920-40	1940-60	1960-80	1980-00	>2000
Pier material	PM	20.3	1.4	0	1.4	0	0
	PC	0	1.4	8.1	29.7	9.5	14.9
	PS	0	0	2.7	0	2.7	8.1

Inside HC 24 [%]		<1920	1920-40	1940-60	1960-80	1980-00	>2000
Pier material	PM	45.8	0	0	0	0	0
	PC	0	4.2	25.0	8.3	4.2	0
	PS	0	0	4.2	0	8.3	0

Ouside HC 50 [%]		<1920	1920-40	1940-60	1960-80	1980-00	>2000
Pier material	PM	8.0	2.0	0	2.0	0	0
	PC	0	0	0	40.0	12.0	22.0
	PS	0	0	2.0	0	0	12.0

Pier type vs total width

All 74 [%]		<5	5-10	10-20	>20
Pier type	PSC	8.1	4.1	2.7	0
	PW	4.1	12.2	10.8	4.1
	PF2	4.1	2.7	6.8	6.8
	PFM	0	5.4	14.9	13.5

Inside HC 24 [%]		<5	5-10	10-20	>20
Pier type	PSC	0	0	0	0
	PW	12.5	33.3	8.3	4.2
	PF2	8.3	0	4.2	0
	PFM	0	12.5	8.3	8.3

Ouside HC 50 [%]		<5	5-10	10-20	>20
Pier type	PSC	12.0	6.0	4.0	0
	PW	0	2.0	12.0	4.0
	PF2	2.0	4.0	8.0	10.0
	PFM	0	2.0	18.0	16.0

5 % 5-15 % 15-30% 30-50% >50%

Fig. 6. Frequencies of coupled typological and pier characteristics for multi-span bridges in Padova inventory.

prevalence of single piers for narrow structures, while both wall and frame piers are mainly found in bridges with larger decks. Due to the flat topography of the site, pier height mainly falls in a low range, up to 8 m. Hence, piers tend to be rather squat, in particular pier walls.

Focusing on masonry bridges (DM) (Fig. 7), the inventory is quite homogeneous, due to masonry construction technology. All of DM bridges have an arched static scheme and masonry abutment and, for multi-span bridges, masonry wall piers with solid rectangular sections. Most of them dated back before 1920, with only two structures built between 1920 and 1940. DM bridges are more frequently single-span (64%) and of small dimensions (56% shorter than 20 m).

The span length mode belongs to the range 10–20 m. Almost 70% of DM bridges are segmental, with a ratio of arch rise to span length (f/L) lower than 0.3. The ratio of the arch thickness to span length (s/L) falls mainly (77%) in the lower interval (<0.075). Multi-

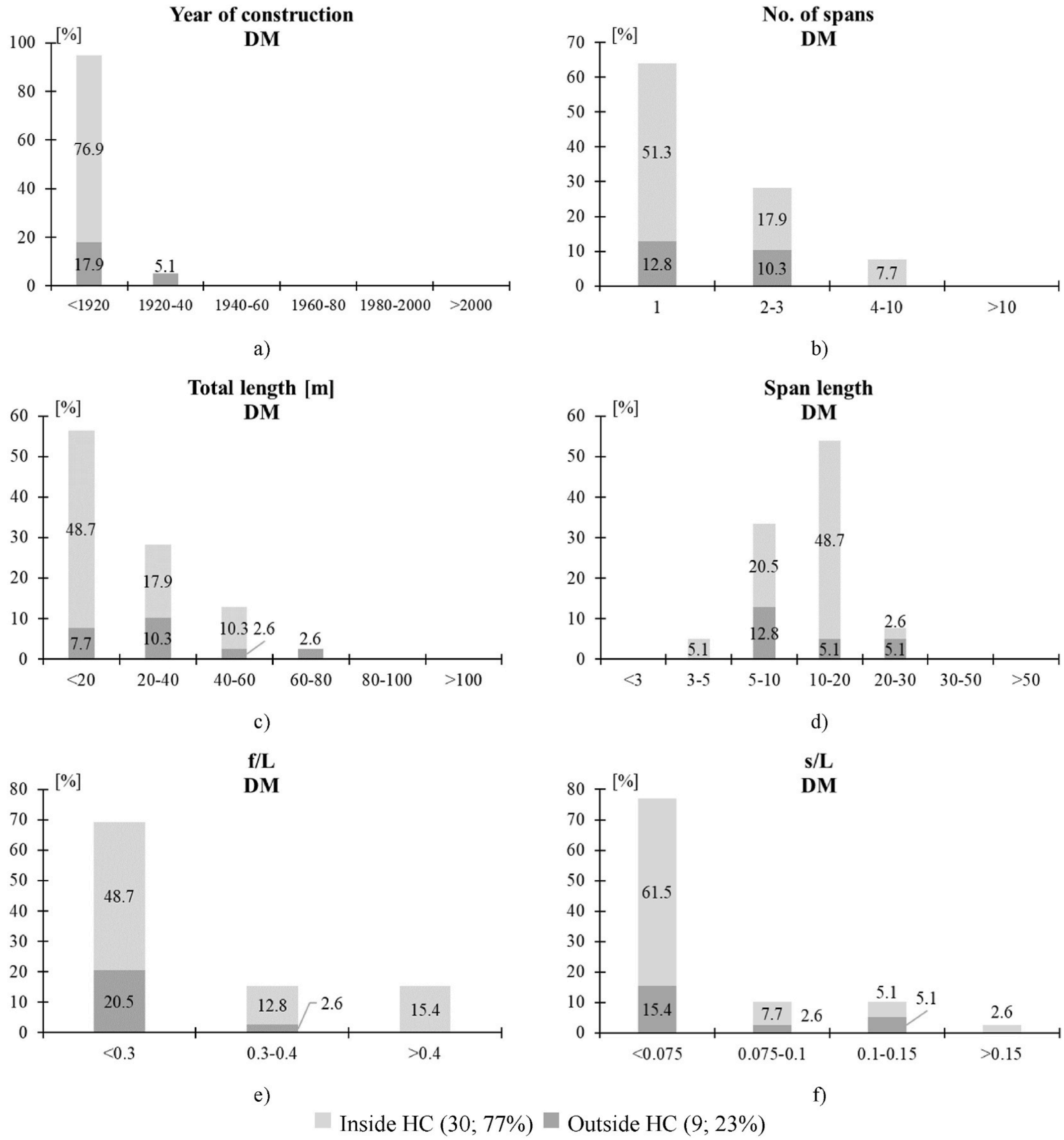


Fig. 7. Distributions of characteristics for masonry bridges in Padova inventory.

span masonry bridges commonly present short piers (71% shorter than 3 m), as displayed in Fig. 8.

Data distributions for r. c. deck bridges of the Padova inventory are presented in Fig. 9, putting together structures with both ordinary (DC) and prestressed (DPC) decks. More than 60% were built more than 40 years ago, with a mode in the range 1960–1980. Simply supported girder decks, either single or multi span, are the most used static scheme (67%). Both small and large structures, up to more than ten spans, or to a total length greater than 100 m, are found in the inventory, highlighting the adaptability of r. c. technology. Greater span lengths are reached with arched static scheme or post tensioned decks. However, reinforced concrete bridges have more frequently a single span (56%) overall shorter than 20 m (47%). Similarly to DM bridges, the span length mode (41%) belongs to the range 10–20 m, with also a significant portion (25%) in the range 20–30 m.

Fig. 10 shows distributions of pier characteristics for multi-span r. c. bridges in the inventory.

The vast majority of r. c. bridges also have r. c. piers; few cases, which represents the most ancient r. c. infrastructures, have masonry piers. Frame piers are largely the most common pier type, found in 73% of the subset. All piers present solid sections, mainly rectangular (65%). For almost half of the subset, pier height falls in the range 3–5 m.

Lastly, data about steel structures in Padova inventory, including mixed steel-r. c. girder bridges, are reported in Fig. 11.

In the inventory, there are examples of steel deck arch bridges dating back to the XIX century and reticular bridges built in the 1930s. Steel was used between 1940 and 2000; however, in this period, r. c. was preferred. In the last 20 years, steel has been chosen more frequently. Arched and continuous girder are the most diffuse static schemes. Most steel bridges have either one span (41%) or 2–3 spans (46%). Inside the HC, all of steel structures have less than three spans.

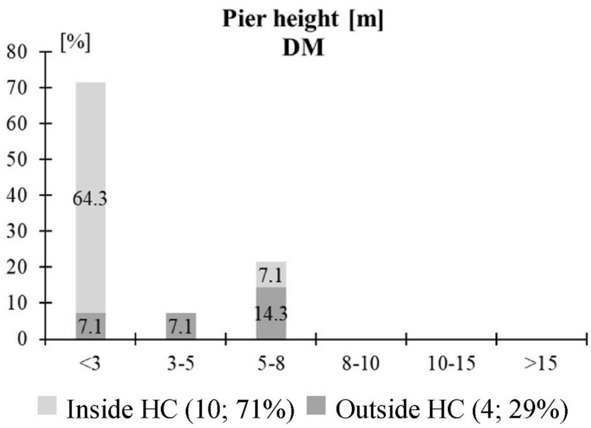


Fig. 8. Distributions of pier height for multi-span masonry bridges in Padova inventory.

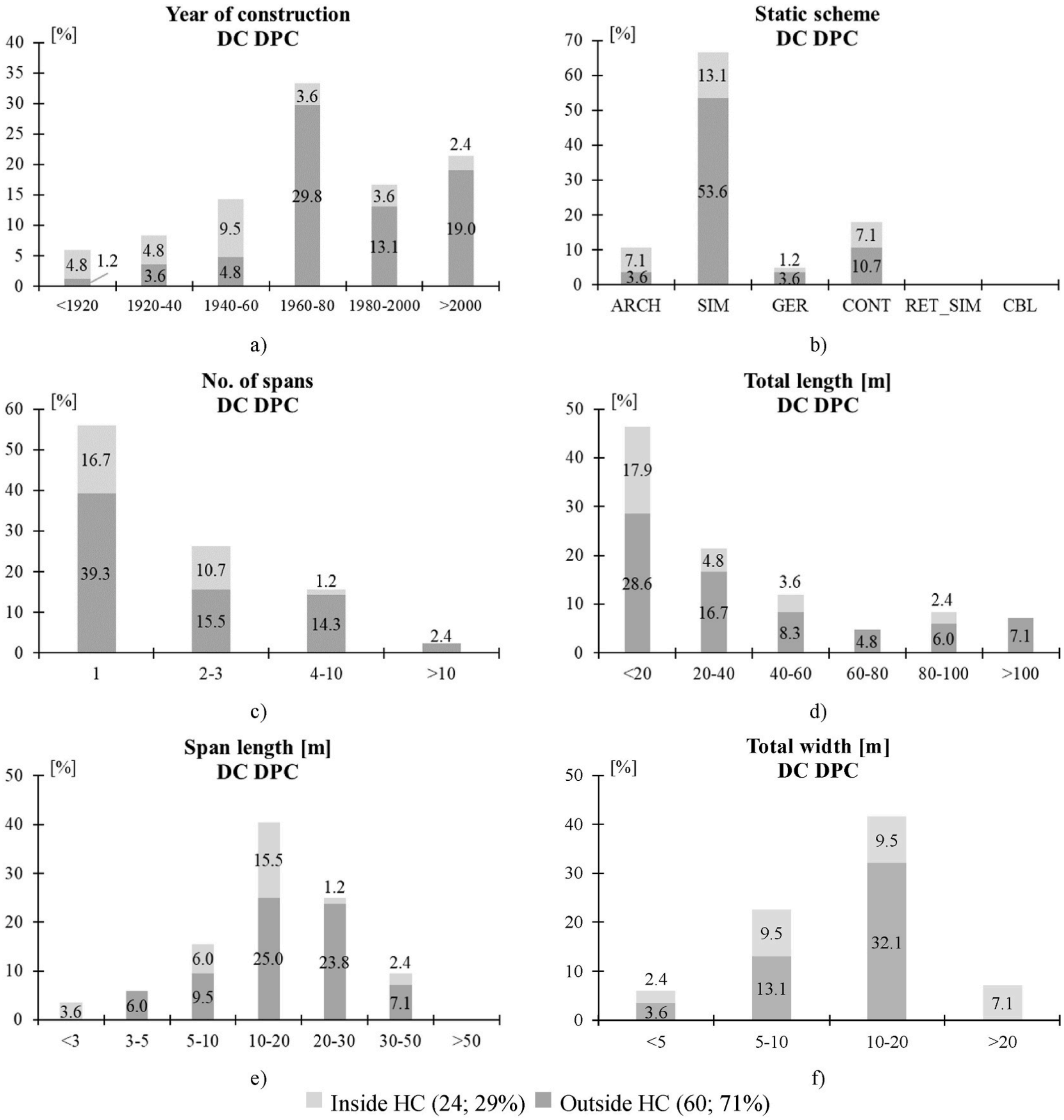


Fig. 9. Distributions of characteristics for r. c. bridges in Padova inventory.

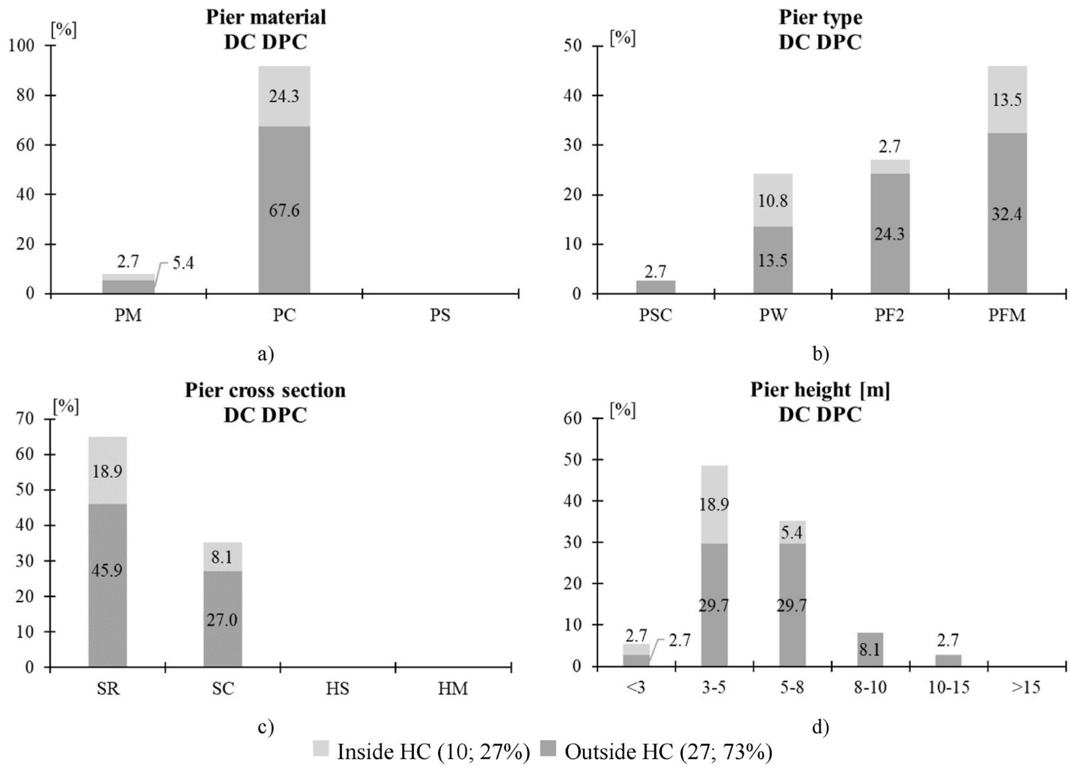


Fig. 10. Distributions of pier characteristics for multi-span r. c. bridges in Padova inventory.

The total length distribution covers quite evenly all the considered ranges. Span length tends to be, in average, greater than the length of masonry and r. c. spans, with almost 70% of steel bridges outside the HC having a span length greater than 30 m, while steel bridges within the HC mainly have a span length between 10 and 30 m. Due to the greater frequency of pedestrian bridges in this macro-class (Fig. 3), the total transverse width distribution presents a peak (44%) for the smallest range (<5 m), followed by a second peak (26%) for the range 10–20 m.

Fig. 12 shows the distribution of pier characteristics for multi-span steel bridges, which generally may be somewhat limited by the small sample of the subset (23 structures). Steel bridges present either r. c. piers, with solid cross sections, or steel piers, with hollow section. As previously mentioned, the pier type distribution appears to be linked to the total width of the bridge. Thus, the observed peak corresponding to single-column piers (44%), was likely related to the higher frequency of narrow bridges (<5 m wide). High (5–8 m), and thus reasonably slender, piers were mostly found.

Data about obstacles spanned by bridges within the Padova inventory were collected. These data are significant for hydraulic risk assessment, and they allowed some considerations to be drawn about the urban development in the past years. Bridges crossing a river, above all in case of piers or abutments in the riverbed, may be subjected to the risk of flooding [60,61] and scour [62]. Furthermore, underpasses are subjected to flooding, with a significant risk for users and loss of functionality in case of hydraulic emergency.

Within the Padova inventory, the most frequent crossed obstacle, both inside and outside HC, is represented by rivers and canals (46%), followed by roads (29%), underpasses (12%) and railways (11%). A rarely surveyed configuration, included in the figures, regards ancient masonry bridges with partially or totally buried arches. Examples of bridges crossing these types of obstacles are showed in Fig. 13, while frequency distributions are showed in Fig. 14.

Focusing on the evolution during decades, before 1960, rivers and artificial canal were the main obstacle to be overpassed, while in the following period, between 1960 and 1980, bridges were built to cross existing roads, suggesting an increasing density of road networks, where interchanges were preferred to at-grade intersections. The former are indeed characterised by higher throughput and safety [63], both requested due to increasing traffic volume. In the last 20 years, both bridges passing roads and underpasses were frequently realized, to increase the traffic safety and reduce the landscape impact. Distributions of crossed obstacles according to bridges' materials are showed in Fig. 15. Most (82%) of DM bridges span rivers or artificial canals, while r. c. bridges presented a more uniform distribution of the related obstacle, due to the versatility and continuous use of this material over years and urban development phases. Lastly, steel bridges mostly cross rivers and roadways.

4. Combined priority ranking procedure: condition state assessment and seismic fragility

The proposed approach aims to rank bridges part of a stock based on two scores, considering respectively the level of deterioration and seismic vulnerability. The methodology is represented in a flowchart in Fig. 16. It is structured in five phases.

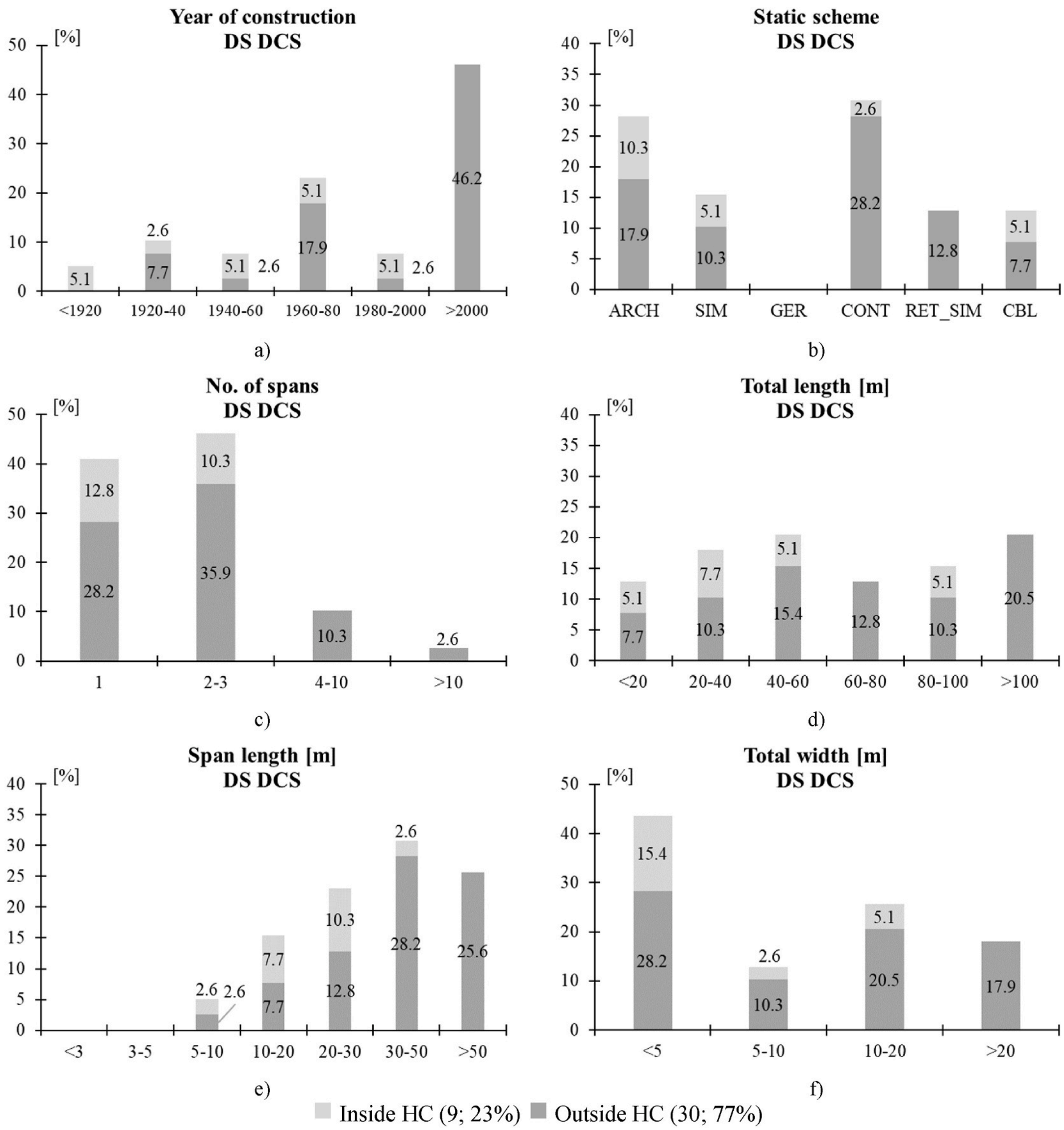


Fig. 11. Distributions of characteristics for steel bridges in Padova inventory.

1. Inventory of each bridge through satellite images and archive documentation;
2. Expeditious surveys and visual inspections of all structures, identifying the deterioration/condition state for each visible component of the bridge;
3. Calculation of deterioration rating;
4. Calculation of seismic rating;
5. Combination of results in a priority-ranking list.

In addition, a summary of retrieved information and results from both evaluations are suitable to be stored within geographic information system (GIS) models.

Both deterioration and seismic effects depends on bridge types. Indeed, decay differently acts on various materials. Moreover, some structural components are generally more affected by deterioration, for example due to stagnant water (e.g., Gerber saddles in r. c. bridges). In addition, expected seismic damage and collapse mechanisms are also strongly linked to structural components and construction details. The subclasses of bridges, identified based on structural material and static scheme and considered in the presented approach, are showed in Table 1.

4.1. Rating of bridge deterioration

To evaluate the effects of deterioration on bridges, the method proposed by Pellegrino et al. (2011) [23] was applied. It allows combining quite expeditious surveys with an overall rating of the condition of each bridge element (such as arch, longitudinal

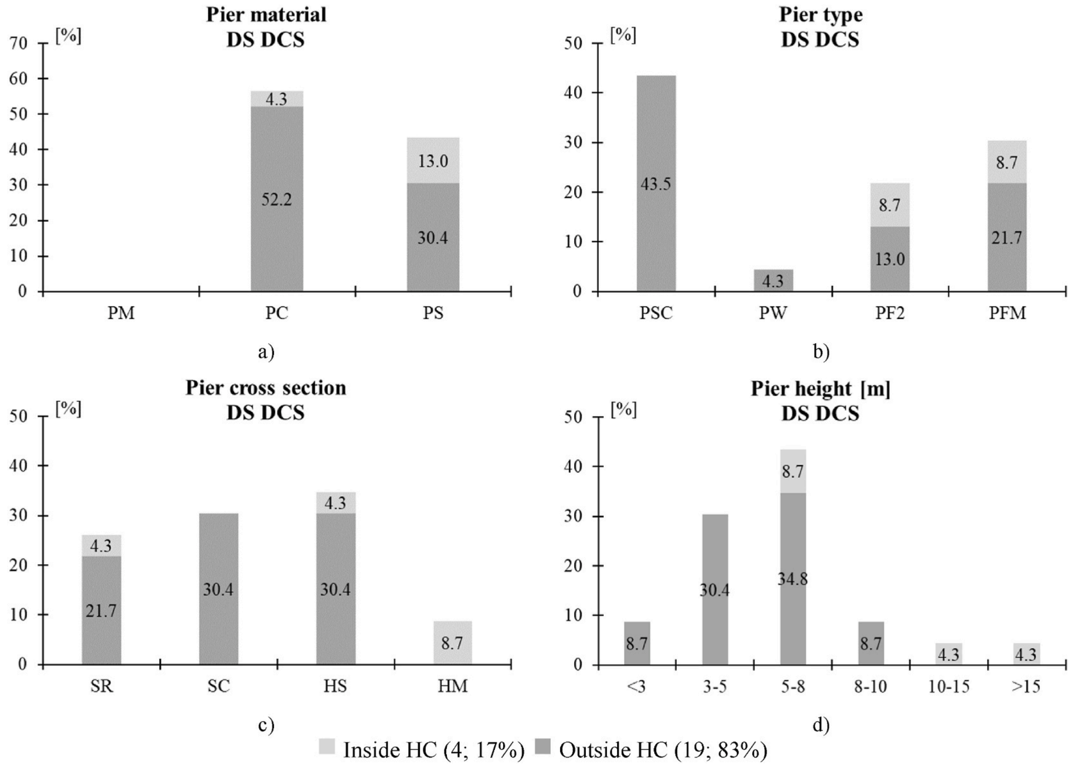


Fig. 12. Distributions of pier characteristics for multi-span steel bridges in Padova inventory.

Fig. 13. Examples of bridges spanning various types of obstacles, observed in Padova inventory.

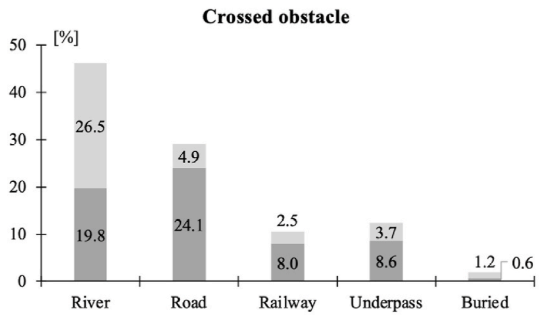
elements, transverse elements, slab, supports, abutments, piers, etc.), and include the possibility of overlooking a few, not easily reachable, elements (e.g., pier and abutments foundations, covered expansion joints, water drainage system). A flowchart specific for this phase of the procedure is displayed in Fig. 17.

Visual inspections allow the surveyor to assign a condition value (*CV*), ranging from 1 to 5, to each element of the observed bridge, describing its functional condition. Each value of *CV* is in turn associated with a discrete value of a condition factor (*CF*).

In addition, each evaluated element is associated to a weight (*W*), which describe its significance in the overall evaluation of deterioration effects, ranging from 5 (minimum importance) to 10 (maximum importance). Each weight value corresponds to a precise value of Location Factor (*LF*) [64,65]. Bridge elements for which the effects of deterioration/decay must be evaluated depend on the structure sub-class. The evaluation also includes further non-structural components, which are independent from bridge sub-types: waterproofing, road pavement, guard-rails, pavements, parapets, and pipelines.

Computed ratings are corrected by a penalty factor (*PF*) to include important aspects, which shall be considered in prioritisation of bridge stocks. *PF* is the product of four indices: *i*) the road type index (*RT*), according to the significance of roads carried and crossed by the analysed bridge; *ii*) the traffic index (*TI*), related to the average daily traffic volume; *iii*) the index of importance of the analysed bridge within roadway network (*NBI*), in terms of alternative ways, in case of bridge closure; and *iv*) the age factor (*AF*), which takes into account that old bridges rather than new structures might be affected by some deterioration, even though not manifest.

The element sufficiency rating (*ESR*) is calculated as product of *CF*, *LF* and *PF* for each component. A total sufficiency rating (*TSR*) is then calculated as the weighted average of the *CF* of the various elements, using the *W* weights, scaled by *PF*, also considering components which might not be observed during inspections being intrinsically hidden (e.g., foundations) or due to obstacles (e.g., tangled vegetation). A confidence factor (COF) allows the degree of completeness of the survey to be accounted in the computed TSR. Based on the value of this index, the analysed bridge is associated with one of the four efficiency classes established, named in this



All 162 [%]		Year of construction <1920	1920-40	1940-60	1960-80	1980-00	>2000
Crossed obstacle	River	22.2	6.8	6.2	4.9	1.9	4.3
	Road	1.9	0	0.6	15.4	3.7	7.4
	Railway	0.6	1.2	1.9	2.5	2.5	1.9
	Underpass	0.6	0	0.6	0	2.5	8.6
	Buried	1.9	0	0	0	0	0

Inside HC 63 [%]		Year of construction <1920	1920-40	1940-60	1960-80	1980-00	>2000
Crossed obstacle	River	46.0	7.9	9.5	3.2	1.6	0
	Road	4.8	0	1.6	4.8	1.6	0
	Railway	1.6	0	3.2	0	1.6	0
	Underpass	1.6	0	1.6	0	3.2	3.2
	Buried	3.2	0	0	0	0	0

Outside HC 99 [%]		Year of construction <1920	1920-40	1940-60	1960-80	1980-00	>2000
Crossed obstacle	River	7.1	6.1	4.0	6.1	2.0	7.1
	Road	0	0	0	22.2	5.1	12.1
	Railway	0	2.0	1.0	4.0	3.0	3.0
	Underpass	0	0	0	0	2.0	12.1
	Buried	1.0	0	0	0	0	0

Inside HC (63; 39%) Outside HC (99; 61%)

5 % 5-15 % 15-30% 30-50% >50%

Fig. 14. Distribution of obstacles crossed by bridges in Padova inventory.

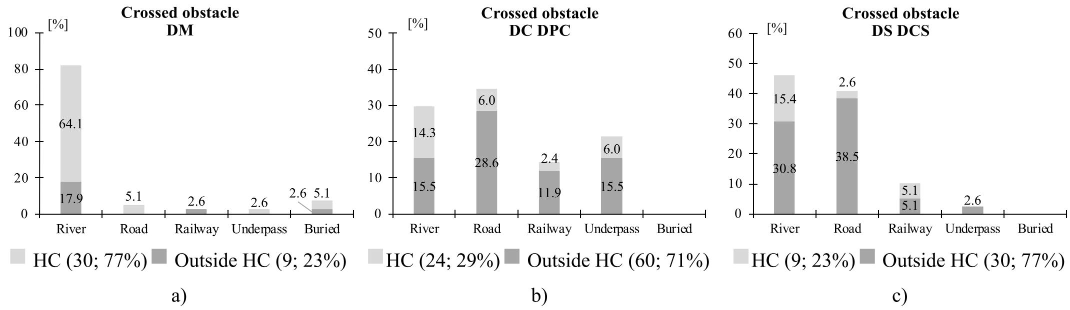


Fig. 15. Distributions of obstacles crossed by bridges in Padova inventory according to deck material.

study A_D, B_D, C_D, D_D (with the deterioration level increasing from A_D to D_D). For further details please refer to Pellegrino et al. (2011) [23].

4.2. Rating of bridge seismic vulnerability

Mechanics-based fragility curves were taken from previous studies of this research group, and derived by setting specific demand parameters for various structural element (i.e., bridge components), thus defining seismic fragility at the component level. Component-level seismic assessment was already effectively implemented by Perdomo et al. (2022) [66] to estimate direct losses related to individual structural elements (i.e., piers and abutments).

In this work, the major references for masonry bridges are da Porto et al. (2015) [51] and Tecchio et al. (2016) [52], whereas for r. c. substructures this study refers to Tecchio (2013) [7]. Both Life Safety Limit State (LSLS) and Damage Limit State (DLS) were included in the adopted fragility models. The mechanisms considered by the selected fragility models are showed in Table 2, for the analysed structural sub-classes.

It is also worth noting that the proposed approach is flexible regarding fragility models, as it is possible to select, on a case-by-case basis, the most suitable fragility sets for a given bridge portfolio, based on the specific structural information and the fragility studies available. Clearly, the more refined and representative the fragility models selected, the more reliable the result of the prioritisation procedure.

The steps of the seismic assessment are illustrated in Fig. 18.

For each potential mechanism, the probability of exceeding a given limit state (LS) was computed based on the expected peak ground acceleration (PGA) at the site. Then, for each structural element, the exceedance probability is calculated, by combining the mechanisms that concern it, as the maximum probability among those of all potential mechanisms associated to that component (Eq. (1)).

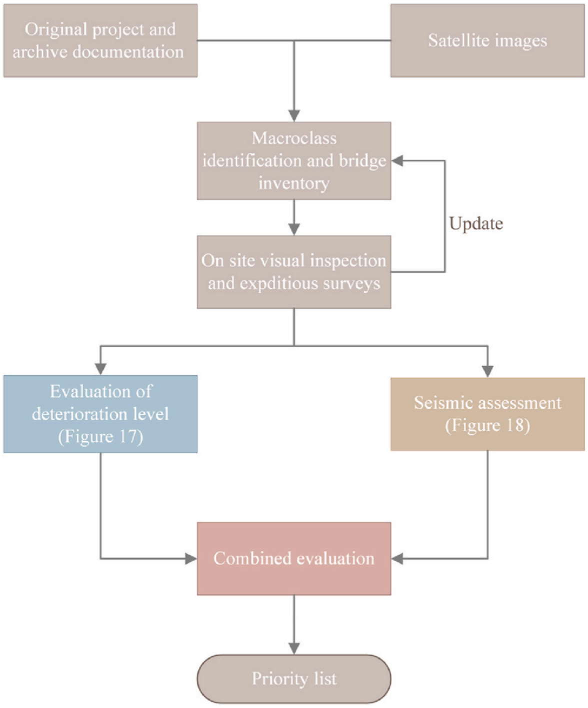


Fig. 16. Flowchart of the proposed combined ranking procedure.

Table 1
Subclasses of bridges based on structural material and static scheme.

	Arch	Girder	Gerber saddlers	Reticular	Cable-stayed	Suspended
Masonry	X					
R.c.	X	X	X			
Precast r.c.		X	X			
Steel	X	X		X	X	X

Then, the exceedance probability for the overall bridge is defined by combining those of its components. An upper-lower bound approach [47] was implemented to define a probability range (Eq. (2)), where the lower bound represents a system whose components are fully stochastically dependent, whereas the upper bound corresponds to statistically independent components. The lower bound provides an unconservative estimation of the overall bridge's exceedance probability, while the upper bound is conservative. Thus, for each LS, exceedance probability is cautiously evaluated by considering the upper bound.

$$P(F_i) = \max\left[P\left(F_{mech,i}\right)\right] \quad (1)$$

$$\max_{i=1}^{m}[P(F_i)] \leq P\left(F_{sys}\right) \leq 1 - \prod_{i=1}^{m}[1 - P(F_i)] \quad (2)$$

Then, for each LS, a Condition Factor (*CF*) is associated, based on the computed exceedance probability (Table 3). Probability thresholds were defined according to Tecchio (2013) [7]; these values were effectively applied and validated in a national project, funded by the Italian Railway Network (RFI) authority, aimed at seismic vulnerability assessment of railway bridges [67,68].

Consistently with condition state assessment presented in section 4.1, a penalty factor (*PF*) was introduced that take into account the importance of each analysed bridge within the network and structure age. For each limit state, the seismic Total Sufficiency rating (TSR_{S_LS}) is then calculated as in Eq. (3). *TSR* value is a natural number between 1 and 100, which assumes lower values for higher vulnerability.

$$TSR_{LS} = 10 \bullet PF \bullet CF_{LS} \quad (3)$$

Finally, TSR_S for each analysed bridge is evaluated by considering the minimum rating obtained for DLS and LSLS, representing the bridge score for prioritisation. This assumption is consistent with the Seismic Classification for buildings in force in Italy [69], which assigns the worst seismic class between that resulting from an estimation of expected annual loss, evidently influenced by damage [70], and the seismic class related to the ratio of capacity to demand at the Life Safety Limit State. Moreover, functionality loss of bridges can

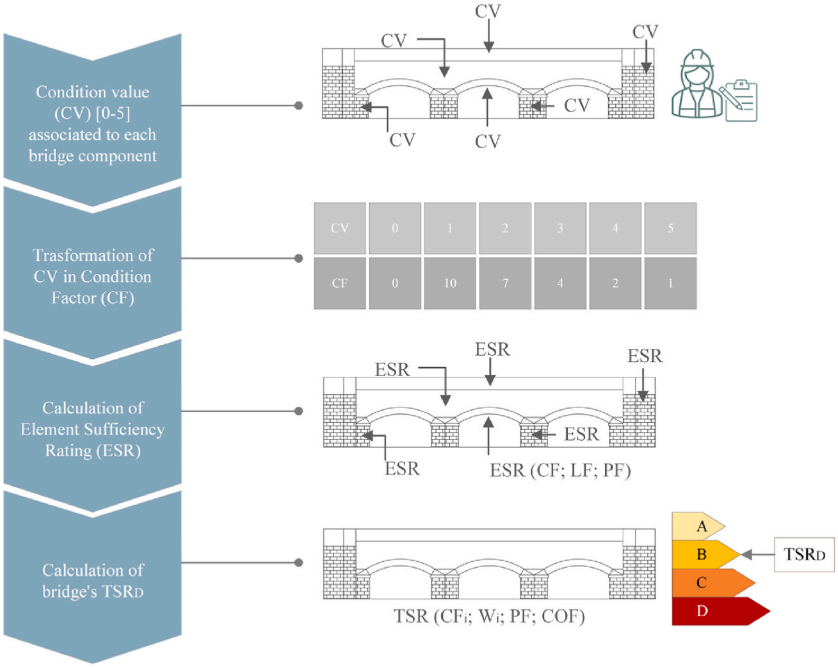


Fig. 17. Flowchart of the evaluation of deterioration levels.

Table 2
Seismic collapse mechanisms and related elements.

Structural element	Mechanism	Single-span masonry arch	Multi-span masonry arch	Single span r.c./steel bridge	Multi span r.c./steel bridge	R.c. arch
Arch	*Longitudinal*	X				X
Arch-pier	*Longitudinal*		X			
	Transverse		X			
Spandrel walls	*Spandrel wall overturning*	X	X			
Supports	*Support failure*			X	X	X
	Deck loss of support			X	X	X
Abutment	*Shear/sliding*			X	X	X
	Flexure			X	X	X
Pier	*Shear or flexure*				X	

interfere with post-event emergency phases and rescue operations [71]. Exceeding DLS in bridges might cause interruptions of the transportation network, and thereby represent a significant source of losses and a threat for human life.

In the current procedure, a seismic class is then assigned to each analysed bridge, according to four TSR_S intervals (Table 4). Class A indicates the lowest estimated vulnerability, which gradually increases up to class D, which identifies the most critical structures.

4.3. Combined rating for prioritisation

The proposed approach for combined assessment requires that each bridge is sorted and classified according to both its level of decay, according to the Total Sufficiency Rating for deterioration (TSR_D), and its seismic vulnerability (TSR_S), as well as the related classes.

Deterioration and seismic classes express a different level of urgency for interventions, as stated in the fundamental principles of the Italian regulations [72,73]. Specifically, in case of dangerous lack of safety towards static actions (i.e., dead and live loads), countermeasures shall be immediately taken. On the contrary, should an existing structure not be verified towards an aleatory action (e.g., earthquakes), the Italian Department of Civil Protection clarified that seismic retrofit must be planned, but the execution cannot be considered immediately mandatory to preserve the structure's operativity [74]. In addition, it is stated that maintenance should be prioritised [74].

Acknowledging this principle, in the proposed procedure, the worst class (D) related to deterioration effects denotes the need for immediate measures, while class D related to seismic vulnerability leads to intervention planning. A summary of each class meaning, in terms of desirable time for intervention, is provided in Table 5.

According to the background document of the Seismic classification of buildings in force in Italy [75], the value of probability of

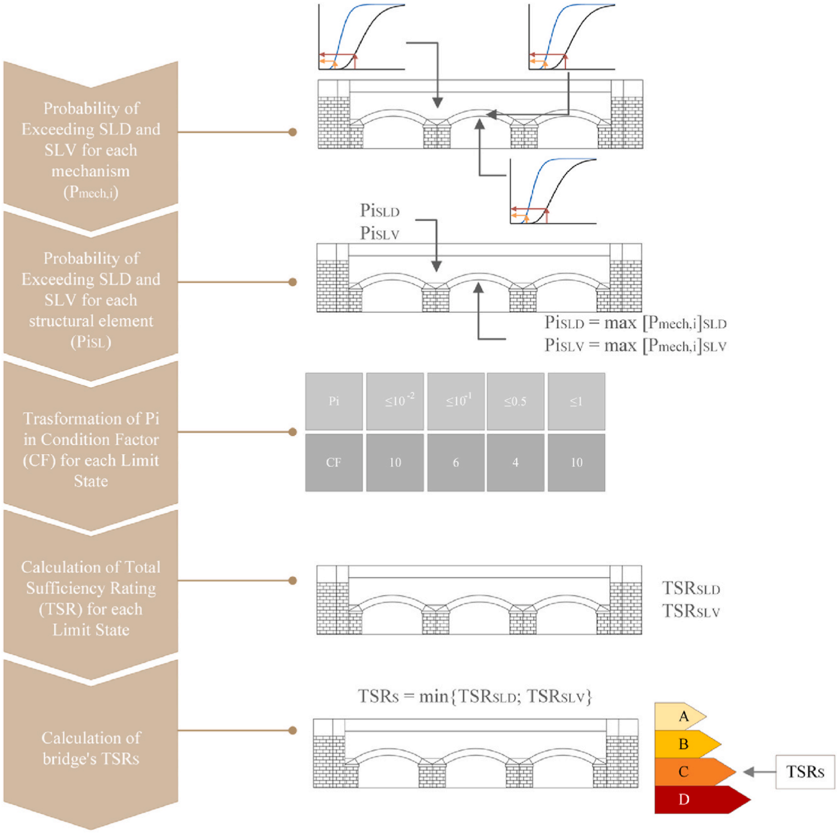


Fig. 18. Flowchart of the seismic assessment phase.

Table 3
Values of the Condition Factor (CF) and related probability ranges.

Exceedance Probability	Condition Factor
$0 < P \leq 10^{-2}$	10
$10^{-2} < P \leq 10^{-1}$	6
$10^{-1} < P \leq 0.5$	4
$0.5 < P \leq 1$	1

Table 4
Seismic classes based on minimum resulting TSR_S.

	Seismic classes	TSR_S
Priority ↓	A_S	76-100
	B_S	51-75
	C_S	26-50
	D_S	1-25

exceeding LSLS for a new structure can be assumed equal to 10^{-2}. Thus, structures in the best class (A_S) present a probability of exceeding comparable to new structures, and therefore "No need for planning" refers to the fact that no intervention should be needed during their service life. On the other hand, structures in the worst class (D_S) have a probability of exceeding comparable to that of the case identified by the Italian Department of Civil Protection [74], for which the time of intervention is set up to 2 years. Intervention times for intermediate classes (B_S and C_S) could be specified by stakeholders, also based on their capacity in allocating funds for mitigation.

Table 5
Level of decay/seismic vulnerability and desirable time for intervention for each defined class.

Classes	Level of deterioration/seismic vulnerability	Desirable time for intervention – static safety	Desirable time for seismic retrofit intervention
A	Slight	Long-term intervention	No need for planning
B	Moderate	Mid-term intervention	Long-term planning
C	Severe	Short-term intervention	Mid-term planning
D	Very severe	Urgent intervention	Short-term planning

Deterioration state and reduced load-bearing capacity can strongly influence not only the bridge safety, as recent events have demonstrated ([76], referring to Italy), but also the seismic response of the structure [57,77,78].

Therefore, the proposed combined classification was defined as illustrated in Table 6, where a greater weight was assigned to deterioration.

Within the same combined class, values of *TSR* (for deterioration and seismic) may be used to sort bridges, thus allowing the most critical structures to be identified and prioritised, which represent a major advantage of the proposed procedure.

With this aim, the quantitative nature of TSR_D and TSR_S can be exploited to obtain a combined scoring of bridges within the same combined class, through multi-criteria decision-making (MCDM) approaches. These approaches were used by researchers to evaluate optimal intervention alternatives, for seismic retrofit [79–81], energy efficiency [82], and even multiple target performances [83]. These methods have also proved useful in calibrating seismic assessment and prioritisation procedures for building stocks [84,85]. The method of Weighted Aggregated Sum Product Assessment (WASPAS) [8] was adopted in this paper. The WASPAS method is the aggregation of two simple and well-known MCDM approaches, i.e., the Weight Sum Method (WSM) and the Weighted Product Method (WPM). The relative ranking of the ith bridge according to WSM ($Q_i^{(1)}$) and WPM ($Q_i^{(2)}$) is computed as illustrated in equation (4).

Both TSR_D and TSR_S are normalised to 100 (i.e., the ideal rating), and w_D and w_S represent the weights of deterioration and seismic criteria, respectively, such that the sum of weights is unity. The combined WASPAS ranking is then obtained by introducing a coefficient (λ) of aggregation (Eq. (5))

$$Q_i^{(1)} = \left(\frac{TSR_D}{100} \bullet w_D\right) + \left(\frac{TSR_S}{100} \bullet w_S\right) \quad ; \quad Q_i^{(2)} = \left(\frac{TSR_D}{100}\right)^{w_D} \bullet \left(\frac{TSR_S}{100}\right)^{w_S} \tag{4}$$

$$Q_i = \lambda \bullet Q_i^{(1)} + (1-\lambda) \bullet Q_i^{(2)} \tag{5}$$

While preserving a simple and understandable formulation, the WASPAS approach showed an increased accuracy compared to WSM and WPM [8,9]. A practical advantage is that the relative importance of the deterioration and seismic evaluations (w_D and w_S), as well as the aggregation coefficient (λ), can be assumed in agreement with owners and stakeholders, considering the seismicity and environmental conditions of the region.

5. Application of the ranking procedure to Padova bridge inventory

5.1. Stock taxonomy and examples of application

The above-mentioned combined procedure was applied to the bridge inventory managed by the municipality of Padova. The present section provides the distribution of both deterioration and seismic classes. The application to a whole bridge inventory allowed the identification of macro-classes of bridges which are most susceptible to decay and/or seismic vulnerability. In addition, some general considerations were drawn about possible repair and retrofit interventions.

The analysis of the stock taxonomy providing the distribution of bridge sub-classes is reported in Fig. 19.

Table 6
Combination matrix of deterioration and seismic classifications.

Seismic \ *Deterioration*	A_D	B_D	C_D	D_D
A_S	A	B	C	D
B_S	A	B	C	D
C_S	B	B	C	D
D_S	C	C	D	D

R.c. and precast r. c. girder bridges represent the most common observed sub-classes; however, the portion of other subclasses is not negligible.

Fig. 20 shows two application examples of the multi-risk procedure, for a severely degraded masonry and r. c. structure. The types of degradation phenomena that affected these bridges are typical of the relevant macro-classes.

The masonry case study is a single-span arch bridge located in the historical centre. Due to the action of vegetation extending roots into the masonry joints, the bridge suffered significant damage to spandrel walls and voussoirs. At the intrados of the barrel vault, displacement or loss of some bricks was observed. Overall, the evaluated deterioration level resulted in a D_D-classification. The vulnerability of the spandrel walls at the DLS determined the C_S seismic classification. The combined evaluation resulted in class D.

The r. c. case study is a multi-span bridge, part of the city beltway. This implies a high penalty factor, due to the importance of the bridge within the network. The bridge exhibited widespread concrete spalling and reinforcement corrosion, particularly severe for the piers, and moderate for deck elements (at the intrados) and abutments. Poor waterproofing aggravated the deterioration phenomena. The low TSR_D obtained led to deterioration class D_D, highlighting the urgency of maintenance. The seismic classification (B_S) was governed by the LSLS, specifically by the shear failure of the squat abutments, while slender multi-frame piers, more susceptible to flexural mechanisms, provided lower failure probabilities.

The combined evaluation resulted in class D for both bridges, suggesting the urgency of intervention for these case studies. Eventually, based on this assessment, the city government proceeded to demolish and rebuild the r. c. structure, and to deeply intervene on the masonry arch bridge, with the addition of a new bearing structure and the restoration of the entire masonry portion, thus restoring the road section of both bridges to a safe condition. This also demonstrates the importance and practical impact of this study.

5.2. Ranking of the bridge stock by deterioration

Focusing on the evaluation of deterioration, the most efficient classes (A_D and B_D) were more frequently obtained, followed by class C_D and lastly class D_D that, thanks to the overall ordinary maintenance program carried out by the municipality over the years, was the least frequent (Fig. 21). This decreasing distribution was found for both the whole stock and for the subset of bridges outside the historical centre. Within the HC, where older bridges are found, a peak of C_D-classified structures was observed. Nevertheless, these global results suggested that an urban bridge stock comprised of heterogeneous structures, in terms of both age and materials, despite an ordinary maintenance program, may include a significant number of structures, almost 10% in this case, which need urgent interventions.

Fig. 22 presents the distribution of obtained deterioration classes based on typological parameters. Structures with very heavy degradation effects were mainly found in the subset of roadway bridges, especially within the historical centre. Focusing on age, a portion of bridges built before 1980 showed a significant level of degradation and were thereby classified D_D, while none of the bridges built in the last 40 years presented serious decay conditions. Although there are documented examples in the literature of rapidly evolving decay effects in recent bridges, e.g., orthotropic deck bridges [86], outcomes obtained from the current application corroborate the influence of age on structural degradation. It is also significant that a peak of bridges classified in the worst class (D_D) is comprised in the period between 1940 and 1980, where new construction materials and typologies arose. The most interesting aspect is that this construction period showed a higher portion of very deteriorated structures than the preceding period (before 1940).

Deterioration appeared to be affected by deck materials. Masonry bridges were mainly subjected to moderate/severe level of degradation, rather than very heavy, despite the advanced age of these structures. Both concrete and steel structures were more frequently heavily degraded than masonry structures. Precast r. c. structures showed lower level of degradation. However, these evaluations were based on rapid visual inspections, without carrying out any tests. Deterioration on prestressed bridges might affect pretension cables, with no visually evident effects. Thus, for this macro-class of structures, deeper evaluations are recommended [10].

The amount of strongly degraded structures by crossed obstacle showed a worst condition for bridges passing over roads, railways, while surprisingly the presence of water and wet environment did not appear to affect the level of deterioration more significantly than other environmental factors. However, this result is likely to be related with construction materials. Indeed, bridges passing rivers and canals are mainly ancient structures (as presented in section 3), most of which are masonry arch bridges, less subjected to very severe

Material	*Static scheme*	*Sub-class*	*Nr. of bridges*
DM	Arch	Single span (SS)	25
		Multi span (MS)	14
DC/DPC	Arch	Tied-arch – SS	2
		Deck-arch – SS	7
	Girder	SS	39
		MS	34
DS/DCS	Reticular	SS	2
	Arch	Tied-arch – SS	2
		Deck-arch – SS	1
	Girder	SS	4
		MS	13
	Pedestrian	-	17

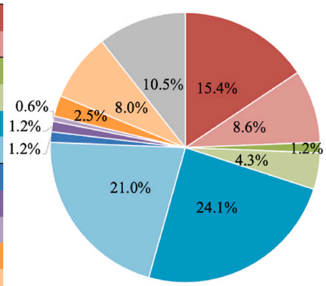


Fig. 19. Identification of sub-classes of bridges of the Padova inventory.

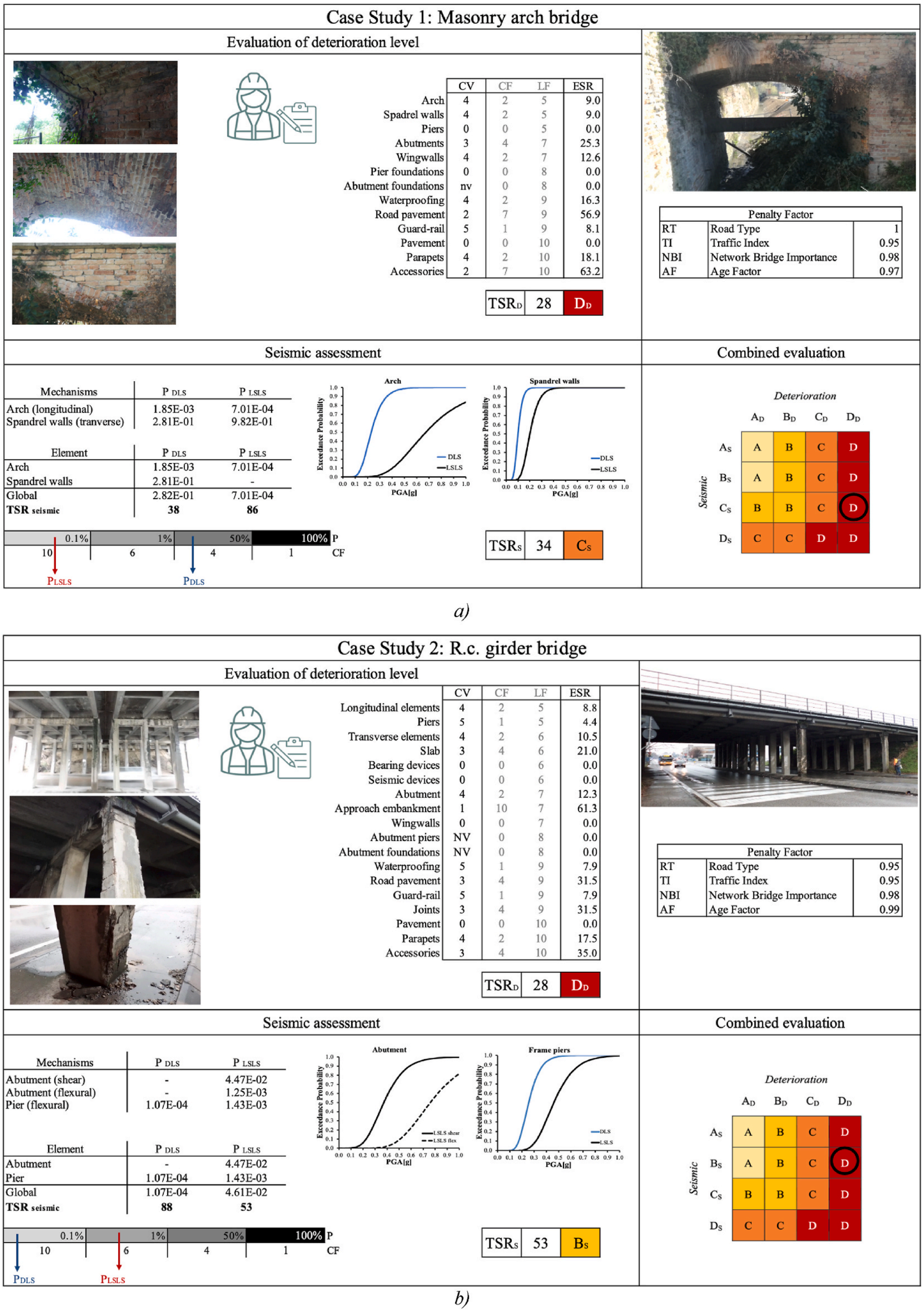


Fig. 20. Application examples of the combined procedure: a) masonry arch bridge; b) r. c. girder bridge.

deterioration than other materials.

The most frequently observed deterioration types by construction materials are showed in Fig. 23. Masonry bridges were mainly subjected to mechanic action of vegetation, longitudinal cracking in the vault and material loss at the intrados. R. c. structures (both ordinary and prestressed) were mainly affected by deterioration of material due to insufficient rainwater drainage, concrete spalling

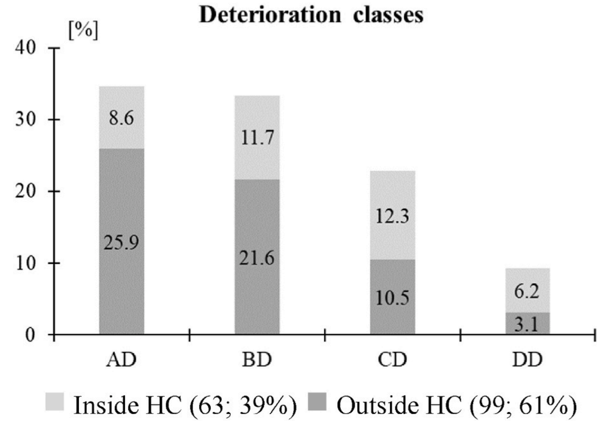


Fig. 21. Distribution of deterioration classes obtained for Padova bridge inventory.

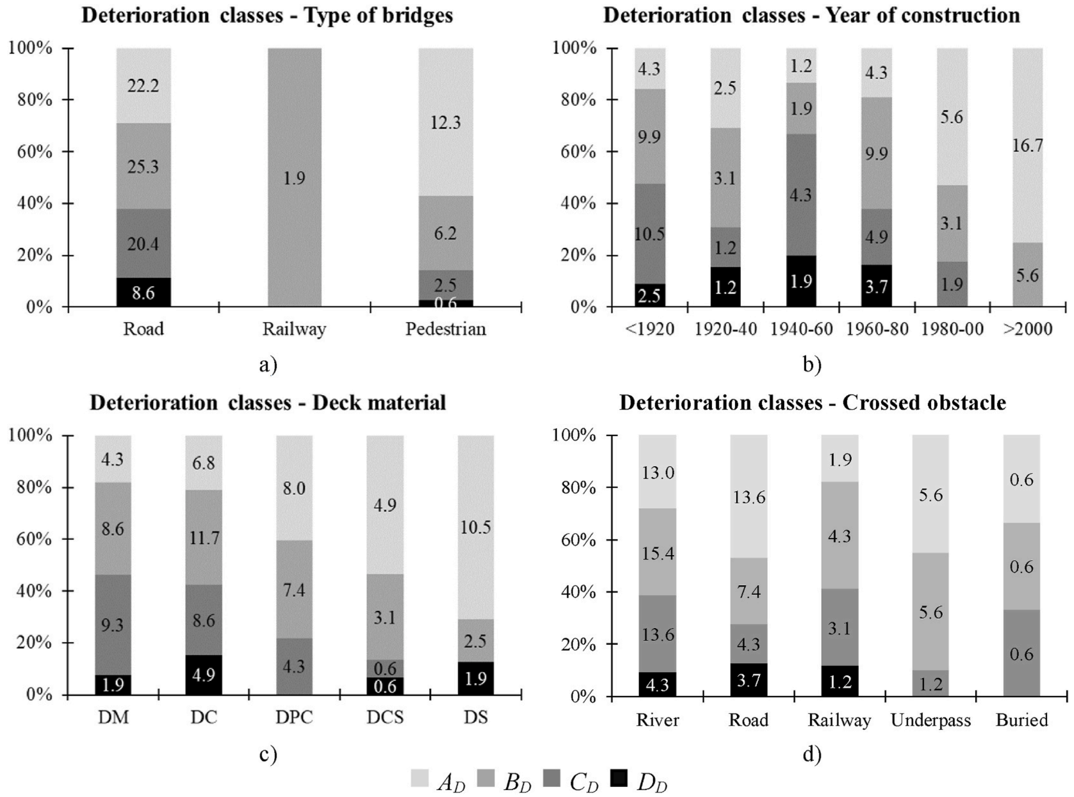


Fig. 22. Distributions of deterioration classes for typological parameters.

and rebar corrosion, and deterioration of supports/bearing devices.

Steel bridges mostly suffered for insufficient rainwater drainage, corrosion of members and joints, while in cable stayed and suspended bridges relaxation and decay of cables was locally observed.

The observed damage shows that not only maintenance and restoration interventions, but also preventive measures, such as improving drainage systems and limiting vegetation growth, can be of paramount importance for reducing the deterioration effects.

5.3. Ranking of the bridge stock by seismic vulnerability

The proposed procedure for seismic rating was applied to a subset of 145 bridges, considered susceptible to seismic damage. A limited number of structures (17) were identified as less prone to seismic damage, due to their lightness and flexibility (e.g., stay-cable and suspended pedestrian bridges), and were thus excluded from this evaluation, also on the basis of the low seismicity of the site.

The proposed procedure considers the effect of seismic hazard in the prioritisation, as the probability of exceeding each limit state

Fig. 23. Deterioration types commonly observed in bridges of Padova inventory.

depends on the locally expected PGA. In this case, the municipality of Padova is characterised by a low base seismicity, with a not negligible amplification related to the soil type. However, since the procedure was applied to an urban stock of quite homogeneous seismic hazard and soil type, results were not influenced by local hazard, and they can be considered related to typological and structural features of the analysed inventory. In fact, given the expeditious nature of the procedure, no experimental tests on soils were carried out; thereby, local amplification effects were not considered.

Globally, most bridges of the Padova inventory were classified C_S, with an even more pronounced peak for the subset within the historical centre, which showed 57% of C_S-classified bridges. Outside the HC, most bridges (64%) resulted in the less vulnerable classes (A_S and B_S) (Fig. 24). A generalised greater vulnerability was thereby observed for the network within the historical centre. This result, as well as the prevalence of C_S-classified ancient bridges (Fig. 25), was explained by seismic classification associated to construction materials, as almost all masonry bridges were classified C_S. Indeed, although masonry arch bridges are quite robust structures, they are

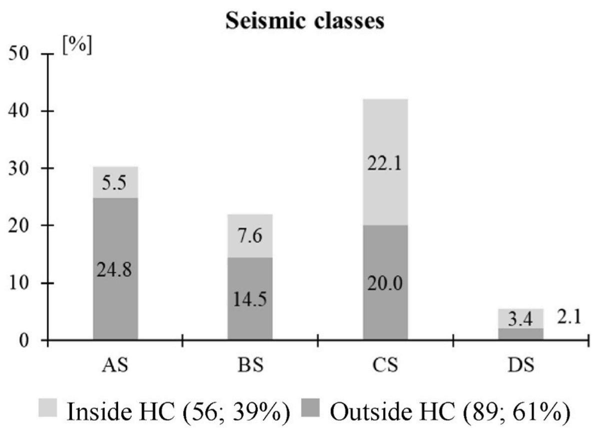


Fig. 24. Distribution of seismic classes obtained for Padova bridge inventory.

very susceptible to seismic damage, specifically due to overturning of spandrel walls [28]. This is a rather easily reparable damage; however, it may compromise the serviceability of structures during emergency phases. Thus, the impact of this type of damage shall be evaluated also weighting the importance of masonry arch bridges within the network.

The distribution of seismic classes during construction period showed a clear trend of increasing of A_S bridges by decreasing ages. The subset of structures dated back to the period 1940–1960 showed the highest relative portion of bridges with high seismic vulnerability (D_S).

The frequency distribution of seismic classes for deck materials showed, as mentioned, that almost all masonry bridges were classified C_S, while for the r. c. subset (considering both ordinary and precast) the greatest relative portion, although still small, of D_S structures was observed. Only 22 steel bridges were included in the seismic assessment, because of the above-mentioned exclusion of pedestrian bridges from the evaluations. None of the analysed steel bridges was classified D_S; however, with a small sample size, caution must be applied, as findings might be hardly generalisable to other stocks of bridges.

Fig. 26 illustrates interesting results in terms of frequency of seismic classes for girder bridges (with both r. c. and steel decks). They showed a lower seismic vulnerability for structures with small width. Such a trend was not so clear in the case of span length; however, also in this case smaller structures appeared in general less seismically vulnerable. The subset of multi-span girder bridges (Fig. 27), with r. c. or steel deck, demonstrated the influence of the pier type in their seismic vulnerability, in agreement with [7,87]. Over half of girder-deck bridges with pier walls were classified as D_S, as they have squat piers with elevated probability of exceeding shear damage LS.

These findings suggested prevailing mechanisms and critical issue for each sub-classes of bridges included within the Padova inventory, keeping in mind that the severity level of results is related to the seismicity of the site.

Masonry arch bridges (both single- and multi-span) showed higher probability to exceed DLS than LSLS: seismic classification of these macro-class was mainly driven by exceedance of DLS for overturning of spandrels (class C_S). One single case was found of semi-circular arch with low ratio of arch thickness to span length (s/L). This case showed a very low TSR_S (corresponding to class D_S) given by DLS of global longitudinal mechanism involving arch and abutments, while this critical mechanism showed a probability of exceeding LSLS comparable to DLS for spandrel walls (class C_S).

The seismic classification of multi-span girder bridges (with both r. c. and steel decks) was controlled by the following mechanisms. Multi-span bridges with squat pier walls appeared subjected to shear failure of these elements, with a higher probability of exceeding DLS (class D_S) than LSLS (class C_S). Multi-span bridges with slender and lightly reinforced single piers are expected to suffer of flexural pier failure with a more probable exceedance of DLS (class C_S) compared to LSLS (class B_S). A quite common critical mechanisms, observed on both single- and multi-span bridges was related to bearing devices; in particular steel support devices appeared to control both DLS and LSLS in several bridges, with similar probability of exceeding both limit states (class C_S). When the previous critical mechanisms could be excluded, abutment failure was the expected mechanism for steel and r. c. bridges. However, this mechanism had lower probability of exceedance leading to seismic classification from C_S to A_S for slender abutments, and from B_S to A_S for squat elements, depending on the reinforcement ratio.

The application of the seismic-based ranking procedure and classification suggested which retrofit interventions are needed, according to structural types, to reduce seismic vulnerability. Masonry arched bridges requires application of tie-rods to prevent the overturning of spandrels. This would be a fast and low-impact intervention, which would efficiency improve the reliability towards seismic events of the urban stock. Indeed, with this light intervention and a limited effort, most of the masonry bridges would be A_S-classified. Multi-span r. c. and steel bridges may need to strengthen piers, primarily focusing on shear capacity of squat wall piers. In addition, girder bridges may require replacing aged and inadequate support devices with novel isolation systems, thus also reducing actions on substructures.

5.4. Overall deterioration and seismic ranking of the bridge stock

Relative frequencies of degradation and seismic classes are displayed in Fig. 28, for the dataset of 145 bridges of the inventory

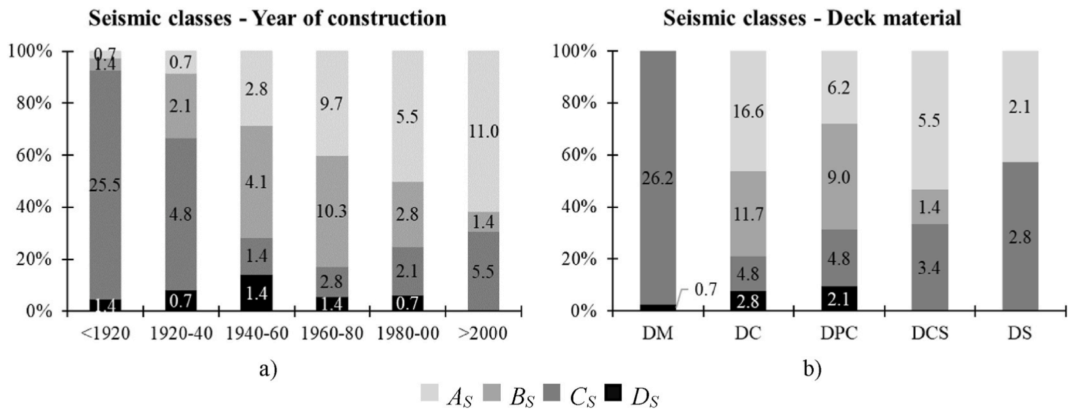


Fig. 25. Distributions of seismic classes per typological parameters.

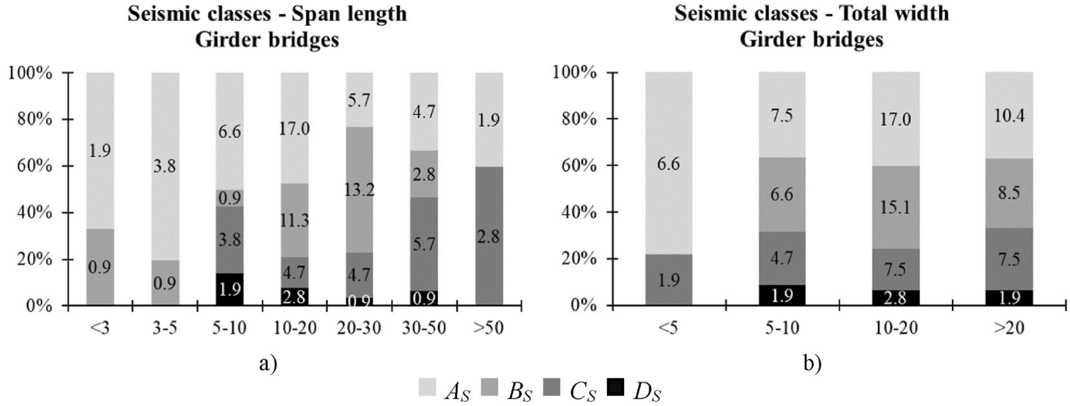


Fig. 26. Distributions of seismic classes for girder bridges according to span length and total width.

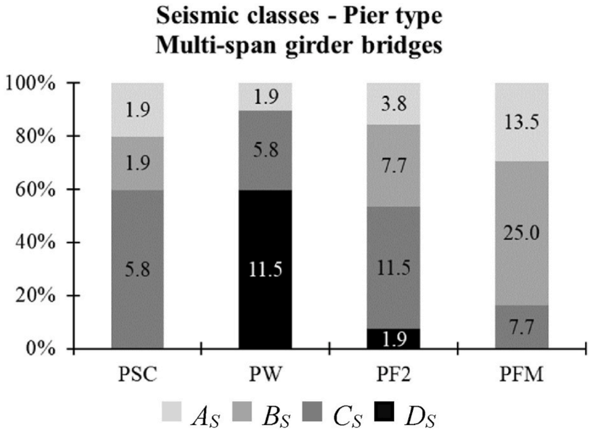


Fig. 27. Distributions of seismic classes for multi-span girder bridges according to pier type.

included in the application of the seismic-based ranking procedure, and for its subsets based on deck materials.

Overall, the Padova bridge inventory showed a prevalence of structures within seismic classes either A_S or C_S, with a deterioration level from slight to severe. Most of masonry bridges, as already mentioned, were classified as C_S, and presents a moderate/severe level of deterioration. R. c. bridges in the analysed inventory showed a prevalence of seismic classification B_S and A_S, whereas distribution of deterioration classes was more heterogeneous. However, this macro-class also included cases of very-severe observed deterioration, as well as very vulnerable structures which seismic deficiencies were related to key elements, such as piers or supports. Lastly, steel bridges showed a prevalence of slightly degraded structures, with an either slight or severe seismic vulnerability; no steel structure was D_S-classified.

All types		Deterioration classes			
145	[%]	A_D	B_D	C_D	D_D
Seismic classes	A_S	13.1	12.4	4.1	0.7
	B_S	5.5	6.2	6.2	4.1
	C_S	11.0	15.2	12.4	3.4
	D_S	0.7	1.4	2.8	0.7

a)

DM		Deterioration classes			
39	[%]	A_D	B_D	C_D	D_D
Seismic classes	A_S	0	0	0	0
	B_S	0	0	0	0
	C_S	17.9	33.3	38.5	7.7
	D_S	0	2.6	0	0

b)

DC/DPC		Deterioration classes			
84	[%]	A_D	B_D	C_D	D_D
Seismic classes	A_S	13.1	19.0	6.0	1.2
	B_S	9.5	9.5	10.7	6.0
	C_S	4.8	7.1	3.6	1.2
	D_S	1.2	1.2	4.8	1.2

c)

DS/DCS		Deterioration classes			
22	[%]	A_D	B_D	C_D	D_D
Seismic classes	A_S	36.4	9.1	4.5	0
	B_S	0	4.5	0	4.5
	C_S	22.7	13.6	0	4.5
	D_S	0	0	0	0

d)

Fig. 28. Distributions of deterioration and seismic classes in Padova bridge inventory.

The combined class was then assigned, according to Table 6, to the dataset of 145 analysed bridges. Fig. 29 shows, through a Sankey diagram, the portion of bridges for each coupled classification (seismic and deterioration), and how they resulted in final combined classes. In general, also for the adopted combination rule, deterioration classes prevailed on the combined classification. Nonetheless, a significant decrease of class A was observed, compared to classes A_D and A_S.

Fig. 30 shows the frequency distributions of combined classes disaggregated according to typological parameters, to identify bridge sub-types commonly requiring urgent retrofit and restoration interventions. According to the year of construction, most ancient bridges, which were mainly masonry arch bridges, commonly belonged to classes B or C; the largest portion of D-classified structures was observed for the periods from 1920 to 1980. The two decades from 1940 to 1960 also presented the highest portion of C-classified structures, resulting to be a critical period. Very recent structures (from 2000) belonged to less vulnerable classes, as may be expected. Distribution of combined classes for deck materials confirmed ordinary r. c. and steel bridges as critical, mainly due to deterioration classes. However, through the combined evaluation, a portion of precast r. c. structures were included in class D, scheduled for urgent interventions. Focusing on the static scheme, bridges with Gerber saddlers resulted the most critical according to distribution of obtained classes. Lastly, multi-span bridges showed a larger portion of class D, apart from bridges with more than ten spans, which appeared less critical. However, caution must be applied due to small size of the sub-sample (3 multi-span bridges with more than ten spans), furthermore comprised of quite recent structures. Generally, it is plausible that multi-span bridges were more vulnerable to seismic events and degradation phenomena, due to the presence of critical elements such as piers.

Combination of deterioration and seismic evaluations led to an increase in the number of bridges within class D, which should be taken into consideration by the administration in charge for urgent interventions. In practice, the number of interventions which can be planned in a very short-term is constrained by the amount of funds that can be allocated and managed and by the human effort employed. In this application the final percentage of D-classified structures resulted just over 10% of the analysed inventory, leading to a manageable outcome.

An interclass prioritisation for D-classified structures is then proposed, as an example of WASPAS multi-criteria decision-making approach. Considering the low seismicity of the area, and the above-mentioned code approach in the evaluation of safety towards static and seismic actions (Section 4.3 [74]), a weight of 90% is assigned to the deterioration level (thus 10% to seismic vulnerability). The aggregation coefficient is set equal to 0.5.

Results of interclass prioritisation are summarised in Table 7. The priority list appears to be governed by the deterioration level; however, bridges with a serious seismic deficiency (TSR_S<10) are moderately moved backward in the ranking, increasing their priority for retrofit and maintenance interventions. Of course, in different environmental and seismicity conditions, the weights and the coefficient to be applied may vary, according to expert judgement and in agreement with the administration.

6. Conclusions

In this work, a prioritisation approach for bridge stocks based on seismic vulnerability and overall bridge deterioration state has been proposed. The method allows assigning seismic and deterioration classes to the bridges, and an overall class used for the final prioritisation. In addition, the method provides quantitative indices for each bridge of the stock and thus allows defining a detailed priority list, sorting bridges within the same class, giving a consistent support to decision making of an administration in charge of bridge management.

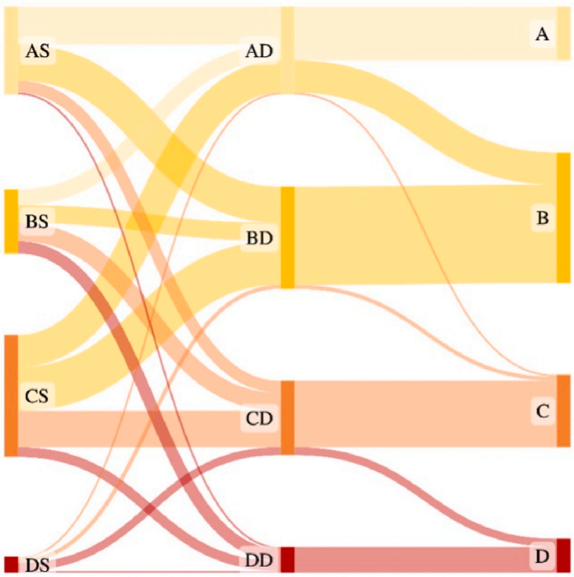


Fig. 29. Sankey diagram of combined classification based on deterioration and seismic classes.

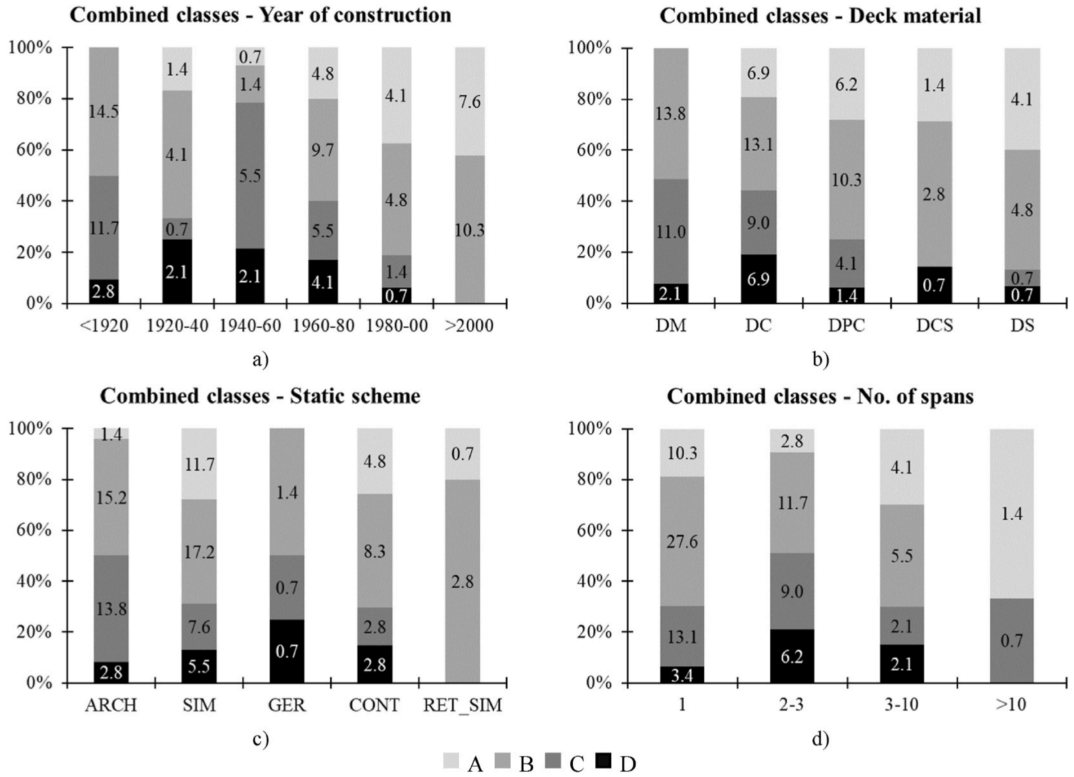


Fig. 30. Distributions of combined classes according to typological characteristics.

Table 7
Priority list of bridges within combined class D.

Position	TSR_D	TSR_S	Qi - WASPAS
1	12	40	14.17
2	25	38	26.18
3	29	9	26.40
4	28	34	28.57
5	28	36	28.76
6	27	58	29.62
7	28	53	30.17
8	29	47	30.62
9	35	9	31.48
10	36	8	32.09
11	30	54	32.11
12	29	68	32.24
13	28	86	32.56
14	37	8	32.92
15	30	69	33.25
16	30	70	33.33
17	40	9	35.68

This combined method was applied to an urban bridge stock, managed by the municipality of Padova, in North-East Italy. The inventory, which included 162 bridges of various types, has been extensively presented in this contribution, to provide a complete and exhausting characterisation of a bridge asset. Indeed, these data may be useful to calibrate datasets with poor information; furthermore, inventory of bridges are required to increase the national database of public infrastructures (AINOP) [12], as well as other digitalised platforms [11].

Results of application of the combined priority lists have been discussed. According to priority list based on deterioration, almost

10% of the stock needed urgent restoration interventions, percentage which was only slightly increased by the combined prioritisations, including the evaluation of seismic vulnerability. These percentages should be considered typical of the specific stock, characterized by being located in an area with a relatively low seismic hazard, and managed by an administration that has always carried out ordinary maintenance over the years. However, the information drawn about the type of deterioration effects and the most evident seismic vulnerabilities should be regarded as typical of the analysed structural sub-classes in general.

Moreover, the analysis of the typical defects and seismic vulnerabilities of these bridges, led to some considerations on the suitable retrofit and strengthening interventions according to the structural types. According to the combined evaluation, the period 1940–1960 resulted rather critical, with a great portion of bridges (almost 80%) classified C or D, while r. c. and steel were observed as most vulnerable materials. Regarding the static scheme, girder bridges with Gerber saddlers showed the worst distribution of combined classes.

Lastly, the proposed procedure exploits multi-criteria decision-making (MCDM) approaches to define interclasses priority lists, bridging the gap between the procedure defined by the Italian Guidelines for existing bridges [10], which relies on a non-quantitative classification approach, and the needs of the administrations to prioritise interventions, at least in the most urgent or populated risk classes.

This study did not include the evaluation of hydraulic and hydrogeologic risks in the prioritisation, which should be object of future developments. The proposed procedure and its application contribute to the recent growing interest and debates concerning management, maintenance, and monitoring of bridge assets, which was rekindled by recent tragic collapses. Practical implications have been observed and further are expected from the application of this procedures to bridge stocks, which effectively support decision-making process of administrations and stakeholders.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data may be provided by authors, upon reasonable request, only in aggregate form.

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