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TOWARDS A TAXONOMY FOR PORTUGUESE RC BRIDGES

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Abstract. *This study focuses on the detailed characterization of a significant share of the Portuguese roadway bridge stock to be used for macro-area seismic loss assessment purposes. The majority of the RC bridges and viaducts in Portugal have indeed never witnessed a major earthquake event hence their behaviour under such circumstances is rather unknown. As a result, a comprehensive understanding of the vulnerability of such structures is of utmost value. Starting from information on over 5'000 existing bridges, drawn from a representative database, the geometrical properties of the RC portion are statistically analysed with the aim of establishing a set of bridge classes. Subsequently, variability and uncertainty are modelled through a complete statistical characterization of the collected information. Moreover, a refinement of existing taxonomy schemes for bridges is herein proposed. The outcome of the present study can be used for the assessment of such a large bridge stock, being adopted, for instance, as input to generate automatized calculation environments to develop fragility models for each bridge class and subsequent loss estimation exercises.*

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1 INTRODUCTION

The present work aims at processing statistical information on the Portuguese bridge stock and more detailed summary statistics on reinforced concrete (RC) ones to be used for macro-scale level bridge seismic loss assessment. Furthermore, the possible refinement of exiting bridge taxonomies is investigated. This endeavour is framed by the fact that the largest majority of the bridges and viaducts in Portugal have never experienced seismic extreme event actions therefore their seismic response is rather unknown.

Considering the historical seismicity of the Portuguese territory, Portugal has been struck by a very destructive seismic event in the past, the well-known 1755 Lisbon earthquake, during which about 10% of fatalities occurred and about 85% of the building stock has been destroyed [1], leading to the complete redesign of the city. After the 1755 Lisbon earthquake, several studies focused on that extreme event and comprehensive studies about the building response to earthquakes have been carried out. The collection of damage information from surveys in the different areas of the city led to building provisions that were used to reconstruct it. It was only with the 1909 Benavente earthquake that seismic specifications for buildings to withstand earthquakes were prepared, after which the 1955 Symposium on Seismic Actions (Ordem dos Engenheiros) highlighted the need of urgent seismic design provisions, marking the beginning of novel seismic studies for Portugal. It was therefore in 1958 that the Regulamento de Seguranca das Construções contra os Sismos was published to define the seismic hazard levels of several Portuguese regions and the principle of structural design to withstand seismic actions. In 1961, the focus was no longer on buildings only. In fact, at that time, the Regulamento de Solicitações e Edifícios e Pontes (Code for actions on building and bridges) followed, including earthquake-resisting buildings' and bridges' design specifications. In 1983, the Regulamento de Seguarnça e Acções para Estruturas de Edifícios e Pontes (Regulation for Safety and Actions for buildings and bridges) was published, along with codes for reinforced and prestressed concrete structures (1983) and steel structures (1986) [2].

This historical overview highlights that the structural damage information we can infer from the available literature about the Portuguese historical earthquakes is related to buildings. Moreover, the illustrated Portuguese seismic code evolution reflects the lack of seismic design regulations in bridges before 1961. Therefore, a Portuguese bridge stock systematic characterization and knowledge about its seismic performance are rather needed, other than helpful to make proper post-disaster management plans [3, 4].

Bearing such needs in mind, this work provides a first step towards a systematic and detailed characterization of the Portuguese national bridge by means of a taxonomy proposal. This work will contribute to the expedite vulnerability assessment of the roadway network [5], as well as to the improvement of the emergency phase management in the immediate aftermath of an earthquake. It will also help to identify e.g. structures that have to be retrofitted or to conduct the prioritization schemes in terms of use of available resources. Application wise, the proposed taxonomy will find room in webGIS software platforms for the real time seismic risk assessment of infrastructure networks [6, 7], to be used by different stakeholders, such as decision makers, practitioners, insurance and reinsurance companies, amongst others.

2 BRIDGE TAXONOMY

The design differences among different bridges strongly affect the seismic response of each individual structure. To measure such differences, it is first necessary to define bridge properties with sufficient detail so that the expected response under a certain earthquake excitation is accurately defined, yet the computational effort to obtain it is minimized [8]. The taxonomy is an ensemble of strings, numbers or symbols, which all together constitute a code that can be assigned to each structure. Each element of such a code represents specific structural properties, which can be associated with structural type, geometric or material characteristics [9]. A good taxonomy must be capable of representing the similarities of an individual bridge or bridge classes.

A bridge taxonomy can be particularly useful for:

- the rapid individual structure assessment;
- a better organization of national infrastructure inventory databases;
- the organization of retrofitting strategies and bridge maintenance operations;
- the study of health monitoring sensors' allocation.

In seismic prone areas, the bridge taxonomy can be thought to expedite the physical damage estimation, as well as the loss assessment in terms of repair costs, casualties, or recovery process duration. It facilitates the identification of bridge classes, within which the seismic response is similar, so that earthquake engineering investigations at macro-scale level can be better accomplished. From a considerable amount of data, the taxonomy allows to guarantee a systematic ordered simplification of the infrastructure population's structural characteristics, yet to reflect their relationships. Therefore, a specific code, which is meaningful from the structural stand point, can be assigned to each individual structure, and can be easily integrated in computer code applications. Starting from a bridge population one can consider the series of these representative codes and conduct seismic assessment analyses. Nevertheless, in order to guarantee the correct flow of information from the input (the bridge population) to the output (damage estimate, loss assessment results, etc.), the taxonomy should have a clear, detailed, collapsible, and expandable definition [10]. Some bridge taxonomies can be found in literature, such as the comprehensive work carried out within the SYNER-G project [9]. The present work leverages on the SYNER-G outcomes, proposing an improved taxonomy definition to the Portuguese context.

3 CASE-STUDY BRIDGE STOCK

In this section, the main geometrical and material properties of nearly 5000 bridges located throughout the Portuguese territory are scrutinized. The construction typology is also crucial to define the response of the bridge therefore this information is added to the discussion within Section 4, which addresses the definition of the bridge taxonomy.

Firstly, the year of construction is analyzed, as it represents a good indicator of the design code used at the time of design/construction of a specific structure. Afterwards, general statistics on the frequency of the use of different materials are prepared. Then, bridge length and horizontal regularity classes have been defined, taking into account how the bridge response is greatly affected by such variables. Finally, a statistical distribution has been assigned to each geometrical variable.

3.1 Year of construction

The year of construction can be an initial good indicator of the seismic performance if coupled with the information about the design codes in force at the same period. From 1983 onwards, Portugal has adopted a seismic code with provisions to design bridges. Looking at the overall dataset, the construction year between 1900 and 2017 has been grouped in decade ranges. As Figure 1 shows, the vast majority of the bridges for which the year of construction is known (3992 bridges) has been built after 1980. One could therefore expect that most of the bridges has been designed to withstand seismic actions. Further investigation of the seismic code evolution and effective employment could provide a deeper understating of the overall expected seismic performance, especially when overlapped with the seismic hazard defined in the code and the additional information about the design principles forced by the code, such as the capacity design.

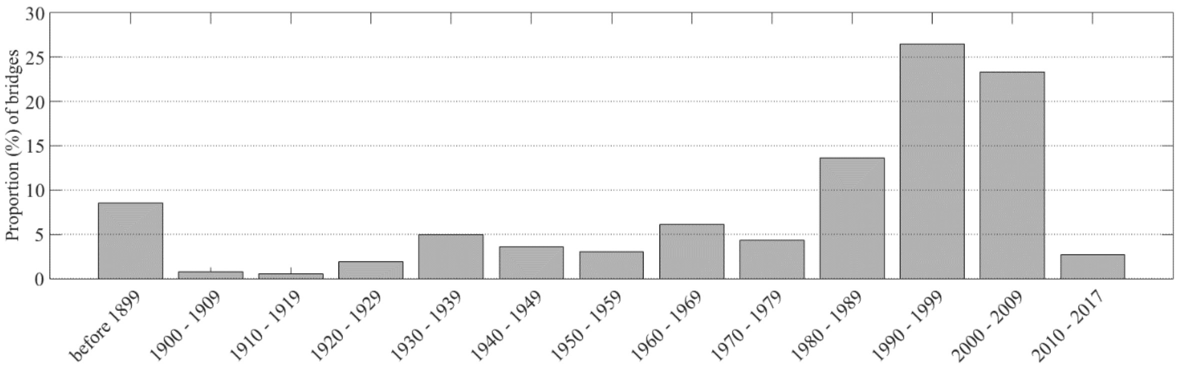

Figure 1: Percentage of RC bridges in terms of construction year.

3.2 Construction material

Once the year of construction is known, another fundamental variable that strongly affects the structural behavior is the material used. As far as the construction material is concerned, nine main cases have been considered. The considered materials are: unreinforced concrete (C), reinforced concrete (RC), steel (ST), masonry (MS), unreinforced concrete and other materials (C-O), reinforced concrete and other materials (RC-O), masonry and other materials (MS-O), steel and other materials (ST-O), and at least three different materials without prevalence of any of the aforementioned ones (Mixed). Figure 2 represents the pie charts associated with the corresponding percentage of each material in each Portuguese district and the corresponding values. In the same figure, all the georeferenced bridges are represented by the small dots.

In this initial stage, for simplicity purposes, the pre-stressed concrete bridges have been considered as part of the reinforced concrete bridge class. On the other hand, the Masonry bridge class includes brick masonry, stone masonry and grouted brick masonry. The steel bridge class includes several types of bridge components assembly techniques, along with specific types of steel used. In fact, for instance, riveted, welded, bolted, and ARMCO steel belong to the same class. What has been named as “other materials” includes wood, FRP external reinforcement, natural stone and reinforced earth.

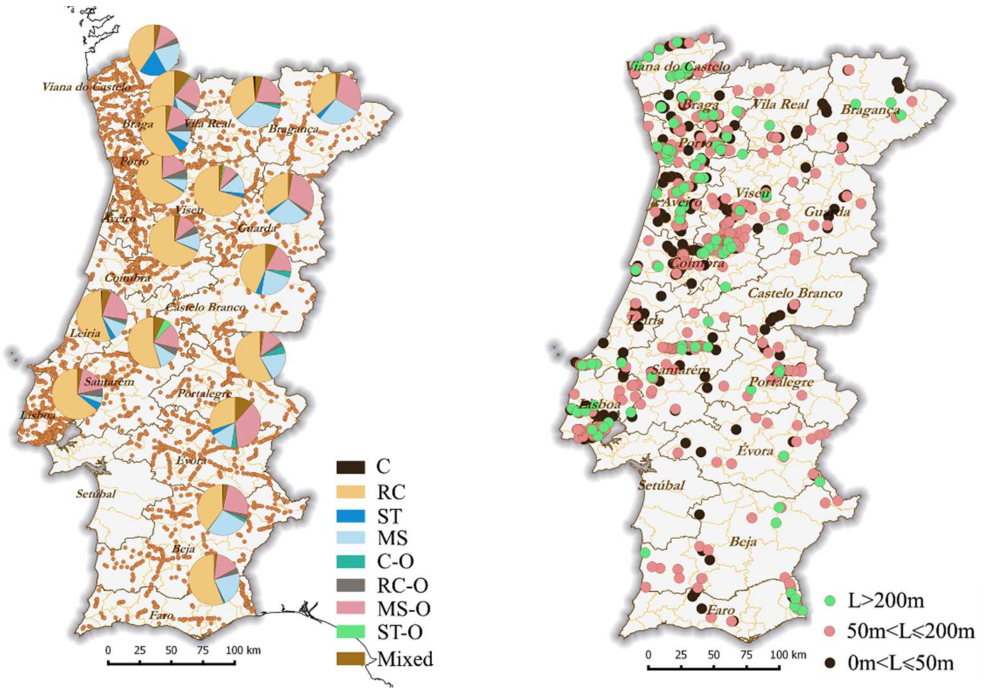

Figure 2: Portuguese bridges (brown dots) and bridge material pie charts for each Portuguese district (*left*), and Portuguese RC bridges grouped according to bridge length classes (*right*).

The pie charts in Figure 2 show that the prevalent material throughout the database is reinforced concrete, followed by masonry. For this reason, this preliminary approach towards a taxonomy proposal is focused on the RC bridges sub-stock. For this main category, sub-classes in terms of bridge length and regularity in plan are shown in the following sections.

3.3 Length, regularity in plan and year of construction of RC bridges

Based on the overall distribution of the observed bridge lengths, the RC bridge sub-population was subdivided in the three length classes:

i. $0m < L \leq 50m$;
ii. $50m < L \leq 200m$;
iii. $L > 200m$.

For each bridge class, further subdivision has been made in terms of construction year before and after 1980, as represented in Figure 3.

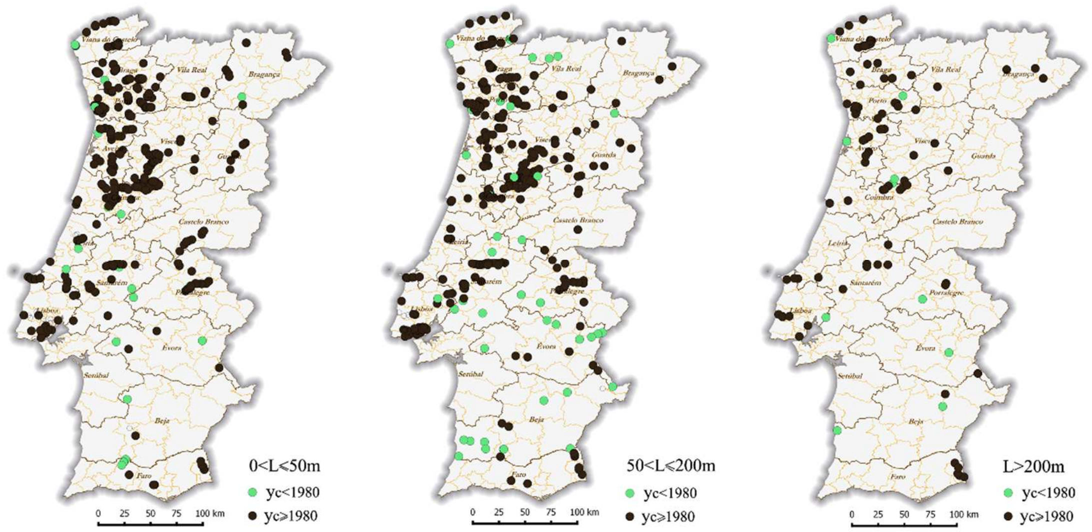

Figure 3: RC bridges build before (green) and after 1980 (black) per length class.

Subsequently, three regularity bridge classes have been defined. The bridge span configuration was not known, but only the number of spans and their length. Therefore, a simplified horizontal regularity index has been defined according to Equation 1 and Equation 2. For each bridge, Equation 1 evaluates Δ_{Lspan_i}, the difference between each span length, $Lspan_i$, and the corresponding average value, $Lspan_{ave}$, normalized to $Lspan_{ave}$. The regularity index, RI, of Equation 2 takes the mean absolute value of the Δ_{Lspan_i}.

$$\Delta_{Lspan_i} = \frac{Lspan_i - Lspan_{ave}}{Lspan_{ave}} \quad (1)$$

$$RI = mean(abs(\Delta_{Lspan_i})) \quad (2)$$

As such, an RI value that is close to zero characterizes a regular bridge whilst as the value become larger the bridge assumes increasing irregularity. Three regularity classes have been tentatively defined according to the following threshold values:

- Regular bridge (R): RI < 0.1
- Semi-regular bridge (SR): 0.1 ≤ RI < 0.4
- Irregular bridge (IR): RI ≥ 0.4

The division of the bridges for what concerns the in-plan regularity, according to the length classes, is illustrated in Figure 4.

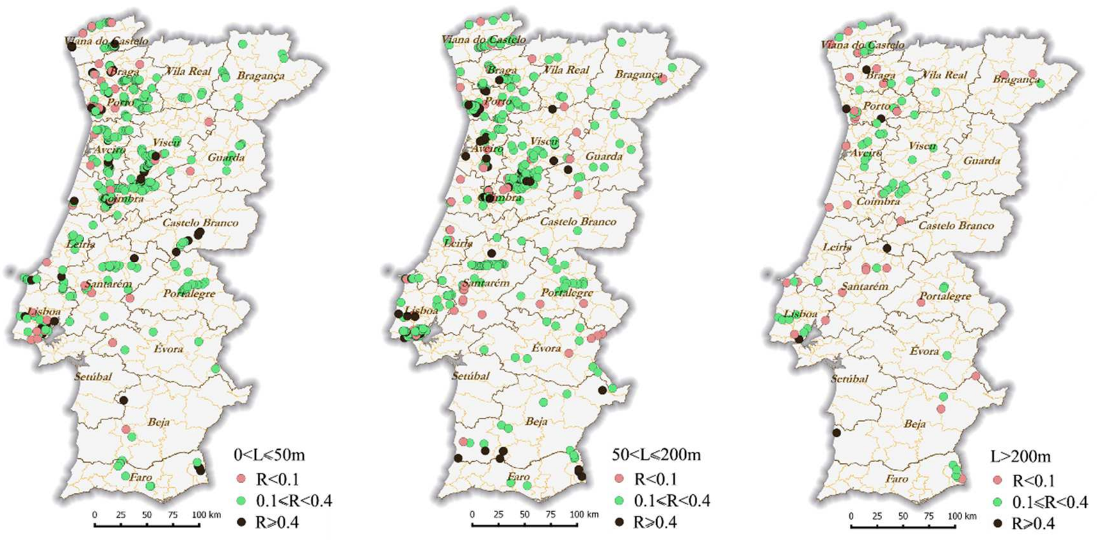

Figure 4: RC bridge in-plan regularity classes per length class.

The bridge classes represented in Figures 2 to 4 are summarized in the chart of Figure 5, in which the percentage of each bridge class with respect to the overall case study is indicated.

3.4 Summary statistics

Within the structural seismic assessment framework at macro-scale level, the definition of the structural fragility curves plays a crucial role [11]. In fact, they are typically assigned to each individual structure to estimate the potential damage level, given a certain intensity measure level. These curves can be derived by selecting an analytical approach among the other methods (empirical and expert-based). Although this method is considered the most accurate, it requires a significant computational effort. In fact, typically, nonlinear time history analyses of individual structures have to be carried out at several intensity measure levels to characterize the structural performance. In turn, the output of these analyses will be probabilistically post processed so that the fragility curves will be defined as lognormal cumulative distributions, characterized by mean and standard deviation inferred from the data.

As highlighted in previous studies [8, 12], when dealing with populations of structures, the aforementioned procedure is time and computationally consuming hence some simplifications become particularly advantageous. In particular, the large amount of details that one can obtain from a national inventory should be condensed in reduced information for practical use. One typical example is the simplification in structural classes of the structural portfolio, which can significantly speed up the computational onus. The aforementioned studies characterized the parameters that mainly affect the seismic bridge response through a statistical distribution and the same approach is adopted herein.

The skewness of the data and the higher frequencies for the lower intermediate values of each parameter affect the results of the commonly used goodness-of-fit tests. In fact, the Chi-Square has been selected to test if the data follows a given distribution. However, the p-values obtained suggest that the hypothesis according which the data follows a certain distribution should be rejected, which not necessarily means that the data does not follow that distribution. As such, at this first stage of the study, the distributions have been assigned to each parameter looking at the comparison between the probability density function obtained with the fitted distribution and the histograms associated with each variable.

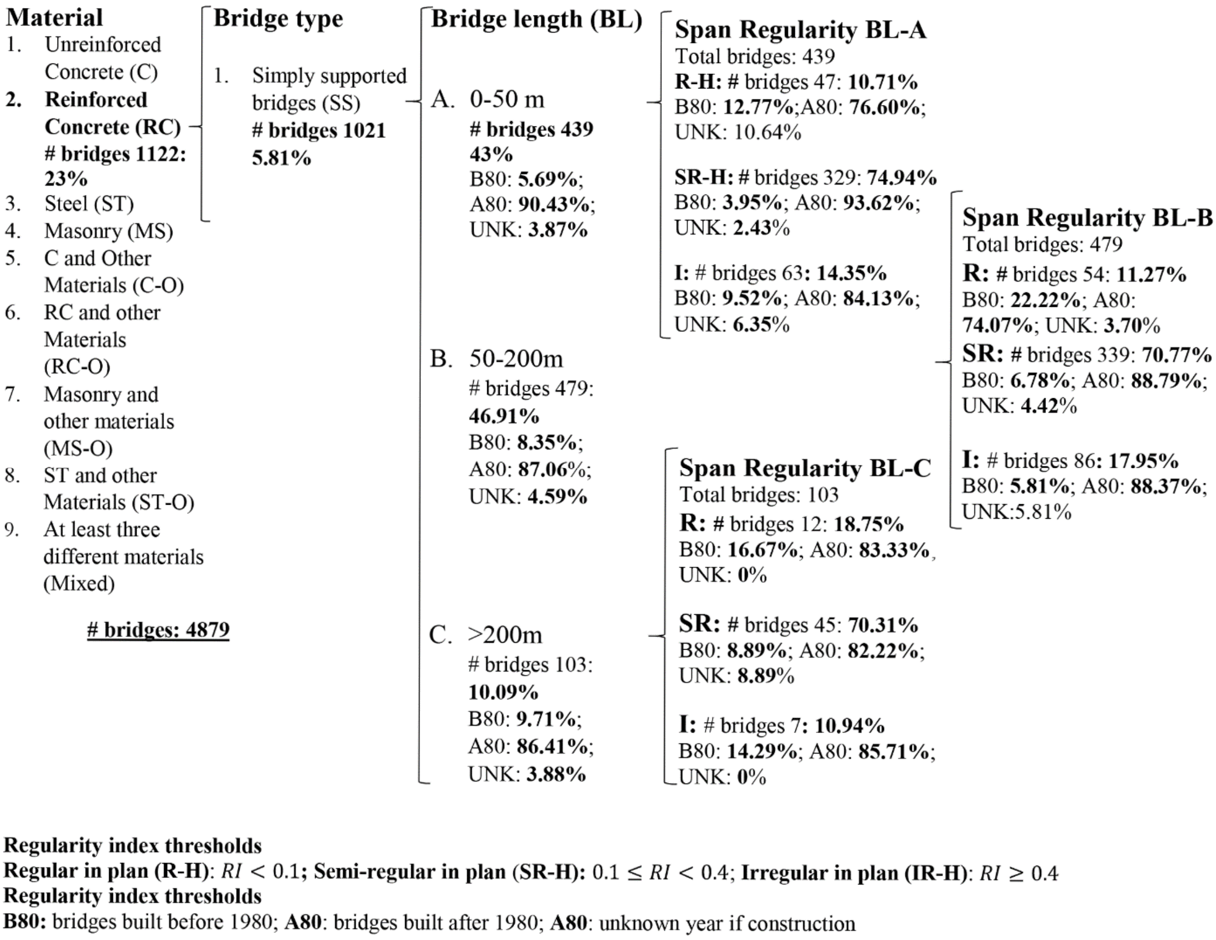

Figure 5: Bridge classes represented in Figures 2 to 4.

3.5 Geometrical layout properties – distribution fitting

The main geometrical properties of the bridges contained in the case-study database are related to spans, piers and superstructure. The main parameters of the statistical distributions associated with each variable are indicated in Table 1. Specifically, Burr and Lognormal distributions have been assigned. The number of spans and the number of columns per pier have been considered as relevant parameters to characterize each bridge however, as discrete variables, only frequency values have been collected and no distribution has been assigned.

Variable	Lower bound	Upper bound	Distribution
Theoretical span length [m]	2	119.40	Burr
Clear span length [m]	1.75	114.90	Burr
Total length [m]	2.5	878.08	Burr
Theoretical pier height [m]	2.74	54.50	Burr
Clear pier height [m]	0.30	59.00	Burr
Superstructure area [m^2]	36.00	24322.82	Lognormal
Superstructure width [m]	1.80	273.00	Burr

Table 1: Statistical distributions for geometrical layout properties.

4 EXTENDED BRIDGE TAXONOMY

The vast majority of the work in terms of taxonomy definition for earthquake engineering purposes has been conducted for buildings. Available bridge taxonomies are few and they omit a certain number of important bridge characteristics, which the present work aims to include towards the definition of a more comprehensive scheme. The detailed analysis of about 5000 Portuguese bridges allowed thus the updating of the bridge taxonomy proposed within the SYNER-G project. The updated taxonomy is presented in Table 2, where the parts added by the present work are highlighted in bold.

Infrastructure type (TY)		
• **Bridge (Br)** • **Underpass (Under)** • **Agricultural passes (Agr)**	• **Viaduct (Vd)** • **Pedestrian bridge (PBR)**	• **Overpass (Over)** • **Tunnel (Tun)**
Material (MM1)	Material (MM2)	
• Concrete (C) • **Concrete and others (C-O)** • Masonry (M) • **Masonry and others (M-O)** • Steel (S) • **Steel and others (ST-O)** • Iron (I) • Wood (W) • Steel (S) • Wood (W) • **Steel and concrete (S-C)** • Mixed (MX)	• **Unreinforced concrete (UC)** • Reinforced concrete (RC) • **Reinf. conc. and other (RC-O)** • Post-tensioned or Pre-stressed (PC) • High strength concrete (HSC) • Average strength concrete (ASC) • Low strength concrete (LSC) • Unreinforced masonry (RM) • Reinforced masonry (RM) • **ARMCO steel type (ARMCO)** • **Riveted steel (RivS)** • **Welded steel (WS)**	• **Reinforced adobe (RA)** • Fired brick (FB) • Hollow clay tile (HC) • Stone (S) • Lime mortar (LM) • Cement mortar (CM) • Mud mortar (MM) • Concrete masonry unit (CMU) • Autoclaved aerated conc. (AAC) • High % of voids (H%) • Low % of voids (L%) • Regular cut (Rc)
	Material (MM3)	
	• **External reinforcement (ExtR)**	• **FRP external reinforcement**
Type of Superstructure (TD1)	Type of Deck (TD2)	Deck characteristics (DC)
• Girder bridge (Gb) • Arch bridge (Ab) • Suspension bridge (Spb) • Slab bridge (Sb) • **Tubular (Tub)** • **Tubular (ARMCO)** • **Mixed (Mx)** • **Other (Oth)**	• Solid slab (Ss) • Slab with voids (Sv) • Box girder (B) • Modern arch bridge (MA) • Ancient arch bridge (AA) • **Pre-cast arch (PreA)** • **Single arch bridge (SigleA)** • **Multiple arch bridge (MultiA)**	• Deck width is explicitly given when known • **Length class (0-50; 500-200; 200-inf)**
Deck Structural System (DSS)		
• Simply supported (SSu) • Continuous (through bearings) (Is) • **Gerber beam (Ger)**		
In-plan Regularity (RegH)		
• **Regular (R)**	• **Semi-regular (SR)**	• **Irregular (IR)**
Pier-deck connection (PDC)		
• Not Isolated (monolithic) (NIs) • Isolated (through bearings) (Is)		
Type of pier-deck connections (TC1)	Number of piers for column (NP)	
• Single-column pier (ScP) • Multi-column piers (McP)	• The number of piers for column is explicitly given if known	
Type of section of the pier (TS1)	Type of section of the pier (TS2)	Height of the pier (HP)
• Cylindrical (Cy) • Rectangular (R) • Oblong (Ob) • Wall-type (W)	• Solid (So) • Hollow (Ho)	• The height of piers is explicitly given if known
Vertical regularity (RegV)		
• **Symmetric (Sym)** • **Asymmetric (Asym)**		

Table 2: Extended taxonomy (based on SYNER-G proposed taxonomy for road and railway bridges).

5 CONCLUSIONS

The study presented in this paper sought to fill existing gaps in the characterization of RC bridge populations through taxonomy schemes. Specifically, a database of nearly 5000 bridges located throughout the Portuguese territory was used as case-study. A thorough analysis of this dataset in terms of used construction material was carried out. The subsequent preselection to identify the RC concrete bridges led to a subgroup of 1122 bridges, whose scrutiny in terms of bridge lengths and in-plan regularities led, in turn, to further smaller subgroups that are expected to share similar seismic response. Statistical distributions to be used in seismic analysis applications were then defined for the following variables: theoretical span length, clear span length, total length, theoretical pier height, clear pier heights, superstructure area and superstructure width.

Finally, as main outcome, the collection and the analysis of the case-study was used to define a more comprehensive bridge taxonomy that will be helpful in the expedite bridge vulnerability assessment of a large number of structures, as well as for improvement of existing seismic risk assessment platforms developed for the Portuguese territory. The main novelty of the proposed taxonomy is the introduction of the infrastructure type category, which provides to the stakeholder an idea about the use of the infrastructure itself. Moreover, the main additional improvements to the previously proposed taxonomy schemes were in terms of construction material, type of structure and configuration properties by including either the in-plan or the vertical regularities.

Future development of the present work will focus, at first, on the identification of possible outliers in the data. The vertical irregularity will also be further analyzed to reflect the bridge pier configurations, which significantly affect the seismic response of the structure. Then, specific case studies will be selected according to the newly defined bridge taxonomy and vulnerability assessment will be systematically performed.

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REFERENCES

[1] P. Clarke, C. Parrak, Portugal – 1755 – Earthquake, Natural disaster, Shelter Projects 2013-2014, 2013.

[2] M. Paz, *International Handbook of Earthquake Engineering – Codes, Programs, and Examples*. Springer, 1994.

[3] R. Monteiro, R. Delgado, R., Pinho, Probabilistic Seismic Assessment of RC Bridges: Part I - Uncertainty Models, *Structures*, **5**, 258-273, 2016.

[4] R. Monteiro, R., Delgado, R., Pinho, Probabilistic Seismic Assessment of RC Bridges: Part II - Nonlinear Demand Prediction, *Structures*, 5, pp. 274-283, 2016.

[5] R. Monteiro, Sampling based numerical seismic assessment of continuous span RC bridges, *Engineering Structures*, **118**, 407-420.

[6] V. Silva, M. Marques, J. M. Castro, H. Varum, Development and application of a real-time loss estimation framework for Portugal. *Bulletin of Earthquake Engineering*, **13**, 2493-2516, 2015.

[7] C. Zelaschi, G. De Angelis, F. Giardi, D. Forcellini, R. Monteiro, Performance based earthquake engineering approach applied to bridges in a road network. V. Plevris eds. *5th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering (COMPDYN 2015)*, Crete Island, Greece, May 25-27, 2015.

[8] C. Zelaschi, R. Monteiro, R. Pinho, Parametric characterization of RC bridges for seismic assessment purposes, *Structures*, **7**, 14-24, 2016.

[9] K. Pitilakis, H. Crowley, A.M. Kaynia, *SYNER.G Typology Definition and Fragility Functions for Physical Elements at Seismic Risk. Buildings, Lifelines, Transportation Networks and Critical Facilities*. Springer, 2014.

[10] K.A. Porter, *A Taxonomy of Building Components for Performance-Based Earthquake Engineering*. PEER Report 2005/03, Pacific Earthquake Engineering Research Center, College of Engineering, University of California, Berkeley, 2005.

[11] C. Zelaschi, R. Monteiro, R. Pinho, Improved fragility functions for RC bridge populations. V. Plevris eds. *5th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering (COMPDYN 2015)*, Crete Island, Greece, May 25-27, 2015.

[12] C. Zelaschi, R. Monteiro, R. Pinho, Simplified period estimation of Italian RC bridges for large-scale seismic assessment. *7th European Congress on Computational Methods in Applied Sciences and Engineering (ECCOMAS)*, Crete Island, Greece, June 5-10, 2016.