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A MECHANICAL APPROACH FOR ESTIMATING REGIONAL FRAGILITY CURVES OF EXISTING RC BUILDINGS STOCK IN PUGLIA

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Abstract

The study of the seismic vulnerability of Reinforced Concrete (RC) buildings is a topic of large interest for the scientific community and public institutions, who have the task of providing mitigation strategies for the seismic risk for a wide and inhomogeneous portfolio of buildings with very limited economic resources.

With this regard, within the research project ReLUIS 2014-2018, typological and structural information about recurrent classes of RC buildings was collected in some municipalities of Puglia, Italy. Based on these data, it has been possible to identify some representative "Index" buildings, characterized by common morphological, mechanical and geometrical features and identified by a set of relevant characteristic parameters having a defined variation within a plausible range.

In this paper, based on the available dataset of building information in some municipalities and on the results of seismic vulnerability analyses about residential RC building typologies, the fragility of representative Index buildings has been investigated. In particular, by using the data collected from a previous large-scale investigation performed in the Municipality of Bovino, preliminary regional fragility curves have been derived for of the index buildings previously defined. The significant mechanical parameters have been varied within pre-defined ranges; for each obtained "sample" simulated design has been made deriving the computational model; at last, the assessment has been performed through the development of a pushover-based procedure. The variation of the parameters and their combination have been carried out in order to appraise their influence in the regional seismic fragility.

Keywords: Existing RC buildings, regional scale, fragility curves, mechanical vulnerability approach, typological data.

1 INTRODUCTION

The vulnerability assessment of existing buildings at the regional scale is a topic of main interest for the scientific community, especially considering the high fragility of the existing building stock, which often is not able to cope with the hazardous actions provided by earthquake events. To this aim, the mitigation of seismic risk and the definition of prioritization scales for optimizing the destination of funds is a major priority of administrations and public authorities. Considering the significant amount of time and economic effort necessary for performing detailed investigations and analyses on individual buildings, the first option is represented by fast approaches. These are typically based on the compilation of survey forms containing few observational parameters, which are combined for providing a synthetic indirect seismic vulnerability index [1-6].

Such an approach, however, can be also useful to identify, in a municipality, the recurring structural typologies and accordingly derive vulnerability functions representative of the local building stock. With regard to the choice of modelling and analysis, two main approaches are proposed in the scientific literature:

1. Definition of an "Index" or "Archetype" Multi Degree of Freedom (MDoF) - Building;
2. Definition of an "Equivalent" Single Degree of Freedom (SDoF) or other simplified models.

The first approach is aimed at performing detailed numerical modelling and analyses of a single building, which is assumed to represent a certain typology [7]. The use of simplified models, like SDoF [8], provides instead several, basic models whose capacity is directly defined through analytical and mechanical approaches, such as the pushover-based ones. In both approaches, the results in terms of fragility and vulnerability can be conditioned by several factors. In the first, the result is strongly influenced by the features selected for the Index building, with a dominance of intra-building variability. In the second approach, the vulnerability is the result of the analyses on a lot of simplified models and the danger can be instead represented by the residual inter-building features.

The proposal of this work is to combine the abovementioned methodologies and study the analytical fragility (and thereafter the vulnerability) at a large scale by analysing a sample of Index buildings. These ones have been automatically generated, accounting for the variation of all the possible geometrical and mechanical parameters for which there is an uncompleted knowledge in the structural typology investigated and that have a significant influence on the reliability of structural response under seismic actions [9-10].

2 BRIEF STATE OF THE ART ABOUT REGIONAL SCALE VULNERABILITY ANALYSES

When speaking of structural safety of existing buildings, the main task of governments is to mitigate risk and estimate repair costs, and to this aim, they need models able to account for the specific features of the local building stock and predict damages and losses caused by hazardous events [11]. It is evident that a smart and efficient policy for the analysis of very large buildings' portfolios at the regional scale should be based on fast methods [12].

To this scope, the Italian Civil Protection Department (DPC), within the ReLUIS project, has developed the "CARTIS" form [13], which allows to define some urban sectors, characterized by homogenous typologies of RC and masonry buildings. From the data collected, it is possible to define the more vulnerable structural typologies, by the computation of a simplified vulnerability index. The subsequent step is the mechanical analysis of the structural typologies that, as defined in the previous section, can be investigated in two different ways. In this phase, especially for the simplified models, the scientific literature provides several analytical methodologies able to estimate the structural capacity of the building investigated, by relating the seismic intensity with the damage states/losses.

One of the most important analytical approach is represented by HAZUS methodology [14], in which the aim was to estimate the losses suffered by buildings and civil infrastructures due to seismic events. The methodology consisted in the classification of buildings within 36 predefined structural typologies and, subsequently, the computation of the fragility and losses, through the evaluation of parameters based on the yielding and ultimate capacity. In [15], a procedure for evaluating the structural capacity of some building classes was proposed, in which each building was produced by performing a simulated design according to the construction year and number of storeys. By varying the geometrical and mechanical parameters, the procedure accounted for some pre-defined collapse mechanisms, expressed in terms of base-shear coefficient versus global drift. The failure mechanism was the lowest value obtained. Similarly, in [16], a mechanical pushover-based approach called Simplified Pushover-Based Earthquake Loss Assessment (SP-BELA) was developed. By using this procedure, the authors estimated the collapse mechanisms through the evaluation of the base shear capacity, obtained by a pushover with an inverse triangular load profile. In recent works [17-18], the authors developed a procedure called simple lateral mechanism analysis (SLaMA), which consisted in the estimation of the probable global capacity through a pushover analysis carried out “by hand”. The main novelty, comparing to previous works, consists in the consideration of additional failure mechanisms such as the local capacity of each structural element and the behaviour of beam-column joints. It is worth mentioning that in the abovementioned proposals, the computational effort increases when one considers the variation of mechanical and geometrical parameters. However, the procedures are applicable to one or more numerical models, representative of a single or of a building class, by using simplified and 2D models, in order to subsequently define their fragility and vulnerability.

The aim of this work is to provide a pushover-based tool able to investigate the seismic behaviour of buildings belonging to a structural typology, by varying mechanical and geometrical parameters, through an effective simulated design. In particular, it is accounted for the variation of the mechanical strength of concrete in situ [19-21]. The novelty of the tool is the capacity of accounting for detailed Finite Element (FE) structural models, according to the idea of the Index building. In addition, the tool produces pushover curves of all the models generated, which can be used for producing pushover-based fragility curves, for the limit states desired, by using the software SPO2FRAG [22-23].

3 PROPOSAL OF A MECHANICAL APPROACH FOR ESTIMATING REGIONAL FRAGILITY

Thanks to a specific toolkit implemented in VBasic, the proposed procedure allows to perform the fragility analysis of building typologies selected on the base of the preliminary knowledge of the building stock, as shown in the flow chart of figure 1.

Firstly, based on observational data obtained from websites, cartographies and GIS tools, it is possible to define the homogeneous urban sectors in the municipality investigated, recognizing the recurring building typologies. Subsequently, for each typology, input data are defined according to the parameters provided by the “CARTIS form”, such as the construction year, the constructive typology, the minimum and maximum total height, the minimum and maximum dimension in-plan and so on. This operation allows to associate an “Index Building”, defined in terms of geometrical and mechanical parameters, to each typology. In particular, each index building is characterized by parameters such as the height of the storeys, the length of the bays in both main directions, the percentage of openings in masonry panels, the dimension of the visible structural elements and so on. The complete definition of the index building is finally provided through additional deterministic parameters evaluated after a simulated design according to the technical code of the construction year. It is worth mentioning that situations without a physical meaning (e.g. structure unstable under gravity loads; element sections that not respect minimum area requirements, …) are dismissed from the set. After these operations, a FE model representative of the structural typology is constructed by varying the deterministic parameters within the pre-defined ranges. Henceforth, for a same Index building, the toolkit generates all the possible numerical combinations by manipulating the parameters of the FE model. The tool has been designed with a VBasic language, because it can be directly linked with the input files of the FE software adopted, here, SAP2000.

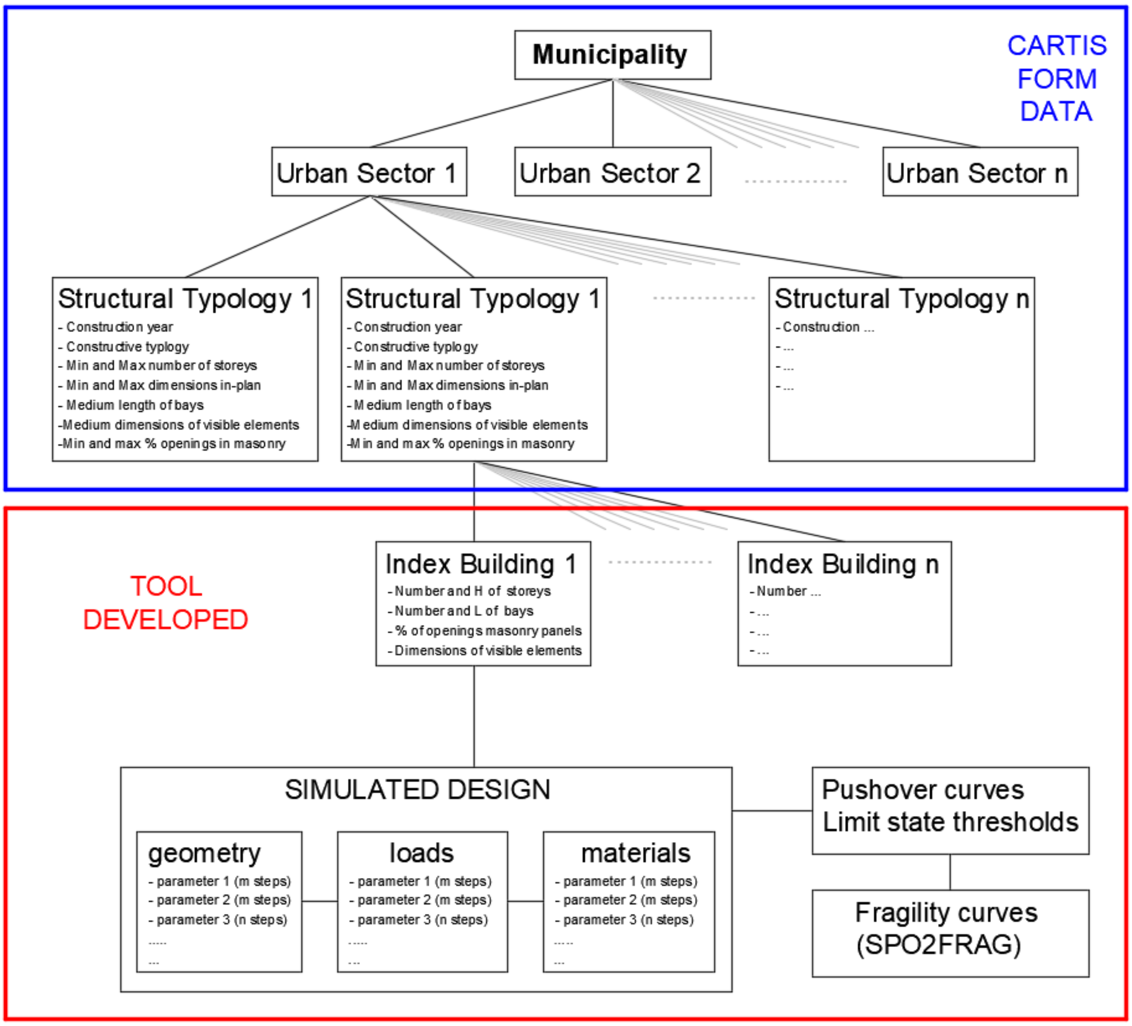

Figure 1: flow chart of the procedure developed

For quantifying the number of numerical models that the tool developed is able to generate and to investigate, one has to consider that for a building, by varying n parameters (n_{par}) in a range subdivided into m steps (m_{steps}), the total number of models (N_{models}) produced are computable as follow:

$$N_{models} = \prod_{i=1}^{n_{par}} m_{steps,i} \tag{1}$$

Hence, by performing nonlinear FE models (details will be provided in the next section), pushover analysis is performed for each building. In particular, the pushing direction is chosen based on the weak direction, deducible from the first period (T_1) of the structure and the load pattern adopted is proportional to the first modal shape.

The output of the procedure is represented by the pushover curves of all the models and the information about the achievement of the limit states to be checked. In fact, in order to define the fragility curves of the sample produced, it is necessary to define (at least) the threshold related to one serviceability and one ultimate limit state.

In this case, the tool has been set up for providing the displacements (δ_{roof}) of the roof at Immediate Occupancy (IO) and Life Safety (LS) limit state. In particular, the criterion adopted for the threshold's definition is a local one, in which the limit state is achieved when the first structural element reaches its limit state capacity.

The abovementioned pushover curves are used as the input for SPO2FRAG software [22-23]. This latter is a user-friendly tool, able to provide fragility curves for the limit states investigated, after the definition of the limit state thresholds, which represent the Engineering Demand Parameter (EDP). The fragility curves in output are characterized by an Intensity Measure (IM) assumed as the Spectral Acceleration at the first period ($S_a(T_1)$) of the equivalent SDoF of the system investigated.

Based on the parameters varied and on the number of models developed, the fragility curves obtained from the Index building show a range of variability that can be more or less large. Supposedly, for the sample represented by the index building, the median curve represents the regional fragility curve. It is also worth mentioning that the result is valid for the same IM selected.

4 SIMPLE APPLICATION OF THE METHODOLOGY: THE CASE OF MUNICIPALIY OF BOVINO

The case study presented regards the municipality of Bovino, in the Province of Foggia, Italy, for which the compilation of the "CARTIS form" has allowed to define the urban sectors and collect data about the building typologies, and additional studies and detailed investigations have been made [24].

The urban sector selected (blue area in figure 2) is the one where the prevalent structural typology is composed by RC frame buildings with an elongated rectangular shapes in-plan (here, the other structural typologies have been not considered). Within the structural typology selected, considering the ranges of the parameters selected in the preliminary survey, a couple of index buildings has been defined, indicated by the red dots in figure 2.

The first building (B1) was built in the 60' and it is a residential building. Concerning to the geometrical features, it is constituted by 6 storeys and pitched roof, for a total height of 22.5 m and dimension in-plan of about 20 m x 15 m. Some of the structural elements have been surveyed, with dimension of some columns about 30 cm x 60 cm and some deep beams about 40 cm x 50 cm. The second building (B2) was built in 70' and it is a residential building. This kind of building is characterized by 3 storeys and pitched roof, for a total height of 12 m and dimension in-plan of about 13 m x 26 m. Even in this case, some dimension of the visible structural elements are available, such as columns of 40 cm x 50 cm and deep beams of 40 cm x 60 cm.

Figure 2: Urban sectors in Bovino municipality and localization of Index buildings B1 - B2

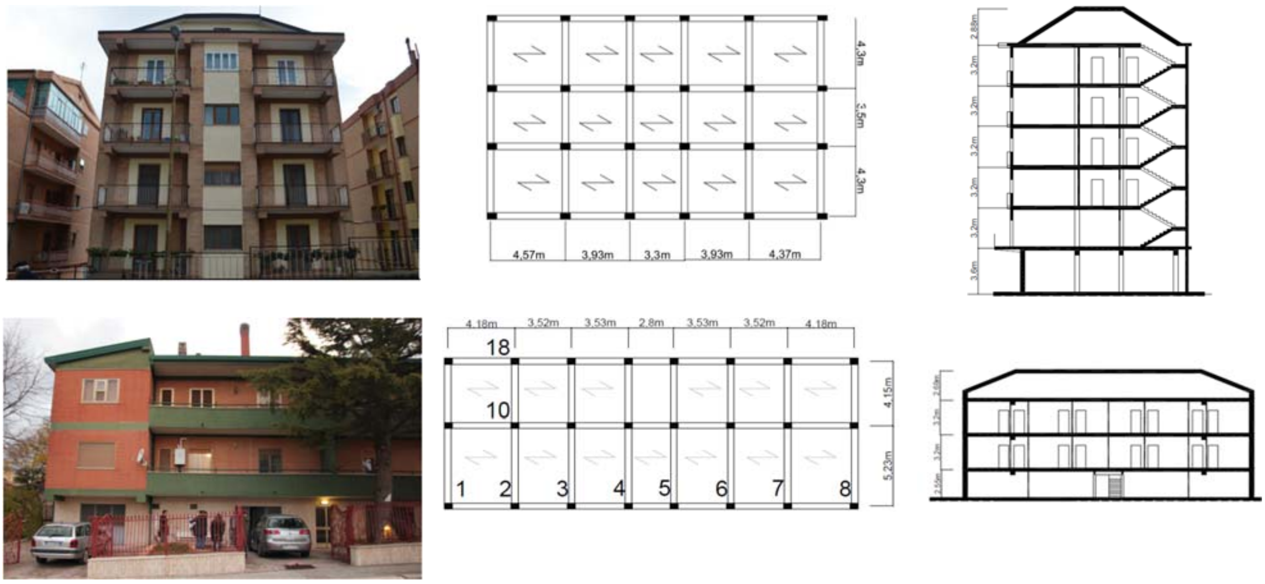

Figure 3: Picture and supposed geometrical features of Index buildings B1- B2

The pictures and the geometrical data about the index buildings selected are shown in figure 3. It is worth mentioning that the data of the buildings are not complete and sufficient for an effective numerical model. Hence, some dimensions have been fixed as the medium value obtained from the CARTIS form and loads have been supposed according to the using destination of the buildings.

In a view of the vulnerability analysis at the regional scale and considering the potentiality of our tool, these assumptions do not represent a limit or a mistake, because it is possible to account for the variation of all loads, geometrical and mechanical parameters.

4.1 Numerical models and variation of mechanical parameters

In order to perform the approach developed, B1 and B2 has been simulated through the FE software SAP2000. In particular, beams and columns have been modelled as frame elements, with fixed restraints at the base of the columns. The horizontal slabs have been simulated as rigid, by using internal constraints. Staircases have been considered in the numerical models in terms of mass. The pitched roofs have been modelled according to geometry surveyed and neglecting the nonlinear behaviour of this part.

The loads applied on the numerical models have been defined as permanent loads (G_1 and G_2) and live loads (Q). The weight of the masonry panels has been considered.

Concerning to the modelling in nonlinear field, each frame element has been modelled by assuming a lumped plasticity approach and introducing plastic hinges at the end sections of structural elements, with the remaining part of elements elastic. The plastic hinges have been automatically defined, according to constitutive law proposed by FEMA-356 [25]. The inelastic mechanisms of plastic hinges have been assumed ductile, by excluding the shear and brittle mechanisms in this phase. Differently from the beams modelling, the plastic hinges in the columns have been considered by combining the axial and bending stresses, where the axial loads are computed from the seismic combination of vertical loads. In addition, the columns' hinges take into account the bidirectional behaviour of the sections.

Considering the construction year of the B1 and B2 and the technical law of that time [26], the mechanical parameters considered for the variation are the concrete class, the steel rebar class and the percentage of steel reinforcement in the columns (% A_s). In particular, each class of concrete and reinforcement steel can be associated, respectively, to a cubic concrete strength (R'_{ck}) and to a yielding steel strength (f_{yk}). According to the [26], from the R'_{ck} and f_{yk} values, it is possible to compute the values of admissible tensions (respectively $\sigma_{c,adm}$ and $\sigma_{s,adm}$), useful for performing the simulated design. In table 1 are shown all parameters considered and them values.

Concrete class		Steel Reinforcement class			Reinforcement in the columns
R'_{ck} (MPa)	$\sigma_{c,adm}$ (MPa)	Tag class	f_{yk} (MPa)	$\sigma_{s,adm}$ (MPa)	% As
20	7,25	FeB22k	220	120	1
25	8,50	FeB32k	320	160	2
30	9,75	FeB38k	380	220	3
35	11,00	FeB44k	440	260	

Table 1: Mechanical parameters varied

According to the eq. 1, 48 FE models have been developed for each Index building. By using the tool developed, the simulated design has been performed, in order to define the unknown elements useful for the modelling but considering some boundary conditions for avoiding not practical situations. In particular, the columns have been designed accounting for the only axial stress, while the beams have been designed by considering the only bending moment and a double reinforcement. Some dimensions have been preliminarily fixed, by considering the construction criteria of the building time. In particular, the base of deep beams has been setted according to the thickness of masonry panels and the height of flat beams has been setted according to the height of the slab.

Once that all parameters have been defined by simulated design, the numerical models have been made, such as shown in figure 4. All models have some difference, which will highlighted in the pushover results shown in the next section.

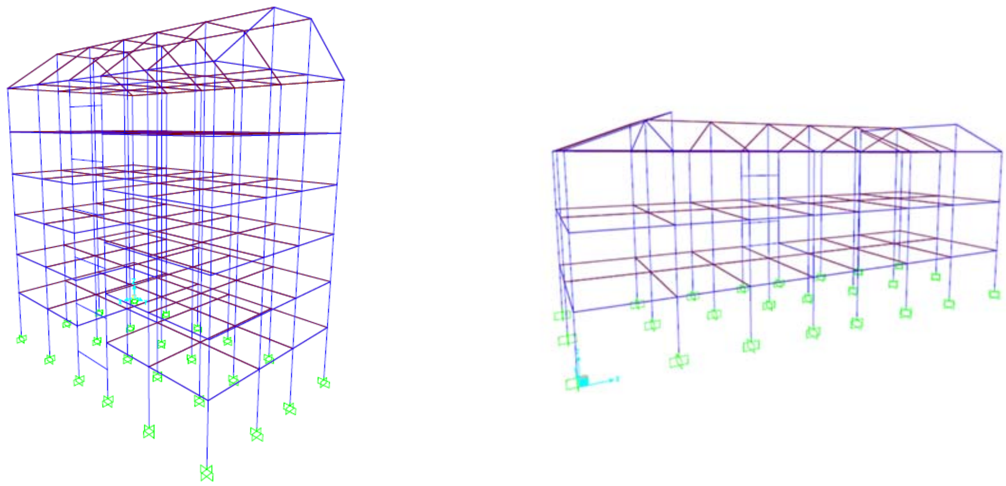

Figure 4: Numerical models of B1 and B2, made in SAP2000

4.2 Seismic fragility through pushover-based approach

As first evaluation, the results of eigenvalue analysis have been restored, in order to define the T_1 range of the Index buildings, where T_1 is the period in the weak direction (it is also the pushing direction). In particular, for B1, the range of T_1 is about 0.83s – 0.95s, while for B2, the range of T_2 is about 0.31s – 0.36s.

Subsequently, for each numerical model, a pushover analysis has been carried out and the results are displayed in figure 5, in two base shear (V_b) - δ_{roof} graphs. In each graph, the values of the parameters for the external curves (red and blue curves), in terms of V_b, have been reported. It is worth nothing that, the procedure developed makes sense considering that the higher curve (blue curve) is not the one with greater values of the mechanical parameters (green curve). This is mainly due to the simulated design routine, which provides approximations about the dimensions of structural elements and the related alterations of the structural behaviour, within the analysis.

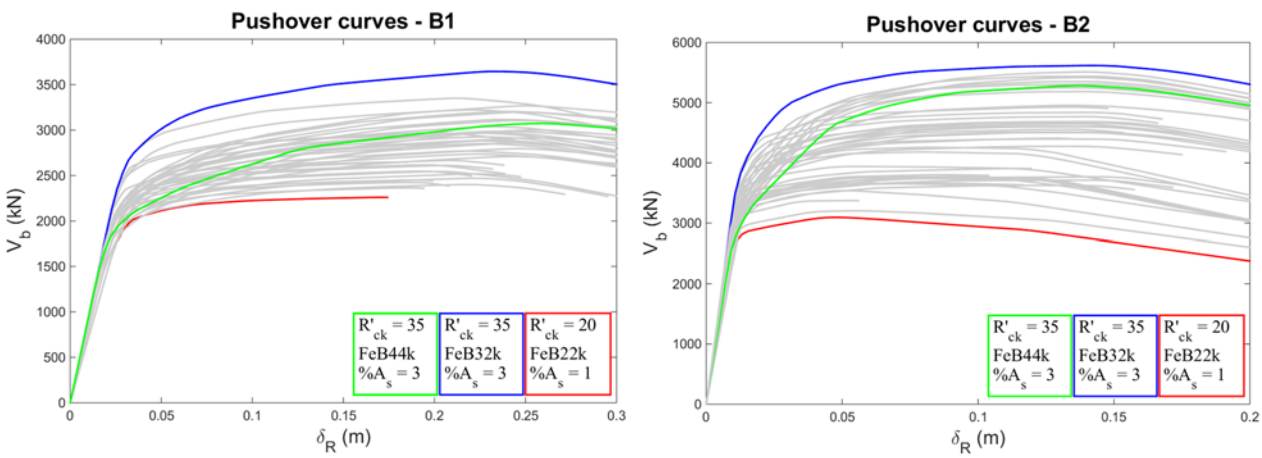

Figure 5: Pushover curves of B1 and B2

From each analysis, the achievement of the limit states investigated (IO and LS) has been defined, in terms of δ_{roof}. At element level, the IO is achieved when the rotation of the end section is equal to the yielding one (θ_y), while the LS is achieved when the rotation of the end section is equal to the ¾ of the ultimate one (¾ θ_u). Operationally, when the first structural element achieves the rotation correspondent to the ones abovementioned, the limit state is achieved. The criterion followed, which is a local one, allow of defining the limit state by identifying the step of analysis in which the wanted condition occurs. This latter procedure is the easier one from the computational efforts point of view, despite we are going to perform assessment, which have not to be conservative.

The pushover curves and the limit state thresholds, obtained from the tool application, are the input of SPO2FRAG. From each pushover curve, by assuming the same masses and the same heights of storeys, it is possible to find the pushover-based fragility curves for IO and LS limit states, using as EDP the Roof Drift Ratio (θ_{roof}) and as IM the $S_a(T_1)$ of the equivalent SDoF structure. Although the masses change of low quantities due to the simulated design that provides different dimensions of structural elements, these variations can be reasonably neglected. In addition, considering that the T_1 value of each structures is different, in order to plot all fragility curves in a singler graph, it is necessary to scale all the curves at a unique value of IM. To this scope, once that the fragility curves have been computed by using SPO2FRAG software with the period of the equivalent SDoF, the abscissa of each graph has been scaled through a simplified approach [27]. This latter provides of scaling each fragility curves by using a scale factor computed as the ratio between the medium value of the $S_a(T_1)$, for the T_1 of the numerical model and the medium value of the $S_a(T_{1,med})$, for the medium first period ($T_{1,med}$) established for the sample of buildings. Each evaluation of $S_a(T)$ have been made by assuming as input the accelerograms at the base of SPO2IDA tool [28], as well as for SPO2FRAG.

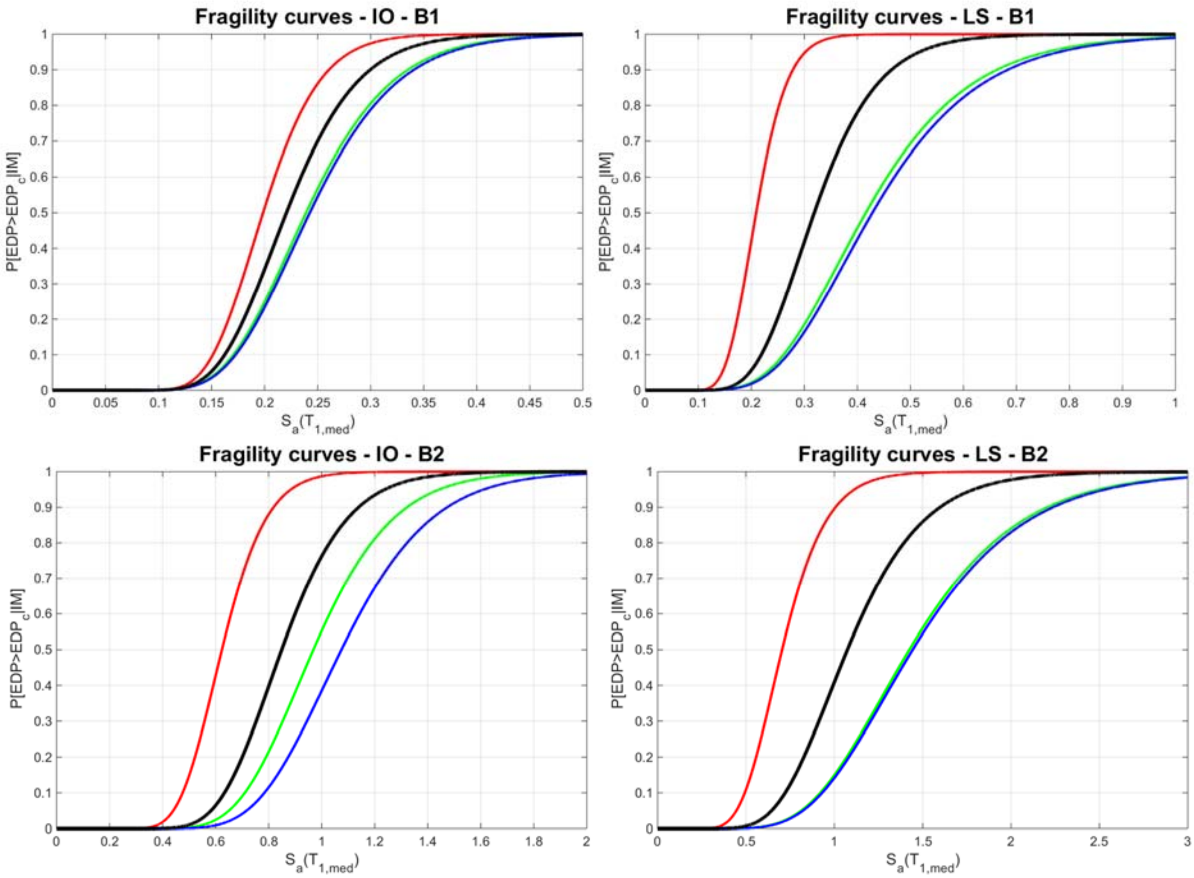

Figure 6: Fragility curves of B1 and B2, for IO and LS limit states

The results provided by the software is displayed in figure 6. In particular, it shown the range of fragility curves, for each limit state and for a value of $S_a(T_{1,med})$ evaluated with a $T_{1,med}$ equal to 0.90s for B1 and a $T_{1,med}$ equal to 0.33s for B2. The colour of the curves is the one of the pushover curves shown in figure 5. From the ranges obtained, the regional fragility curves of the samples investigated have been characterized by the mean of the median (μ_{reg}) and dispersion (β_{reg}) of all curves. The regional fragility curves have been depicted in black in figure 6 and the values of μ_{reg} and β_{reg} are reported in table 2.

Index building	IO limit state		LS limit state	
	μ_{reg}	β_{reg}	μ_{reg}	β_{reg}
B1	0.2206	0.2389	0.3187	0.2937
B2	0.8492	0.2291	1.0740	0.3101

Table 2: Median and dispersion of regional fragility curves of B1 and B2

5 CONCLUSIONS AND FUTURE DEVELOPMENTS

In this work, a new procedure for the study of the fragility of the existing building stock at regional scale has been presented.

After the surveys on the territory to investigate, some observational data have been collected by using the CARTIS form. From this latter, it is possible to identify firstly urban sectors, after structural typologies and finally index buildings, useful for the study of the vulnerability of recurrent typologies of buildings.

Each Index building has been characterized by some inferable geometrical and mechanical parameters, which are the base of the procedure. The tool developed is able of varying these parameters through a simulated design procedure, developed based on the technical laws of the construction years of the buildings investigated.

In the case shown, after the presentation of the surveys carried out in the municipality of Bovino, Province of Foggia, Southern Italy, two Index buildings have been characterized. The tool developed has been used for varying only three mechanical parameters, which are the concrete class, the steel reinforcement class and percentage of reinforcement in the concrete columns. From the combination of the possible values of these parameters and the simulated design, for each Index buildings, 48 numerical models have been generated.

Each building has been investigated through a pushover-based approach and the results have been the input of SPO2FRAG software, which is able to provide fragility curves of the numerical models, for each limit state to investigate, by using simplified procedures.

The results have allowed of defining the regional fragility curves for those Index buildings, which cannot be a complete information, because only few parameters have been changed.

The future developments of this work are oriented on the development of a Matlab tool, able to write and to analyse FE models in open source codes. This upgrade can make improvements, from the time and computational efforts point of view, besides to ease the increase of the parameters to vary. Moreover, by following the procedures developed in previous research works for taking into accounts the effect of infill panels in the seismic response of RC frame buildings [29-31] and considering the regional variation of masonry infill parameters [32-33], the tool will be extended for incorporating the variation of the fragility due to the infill presence.

It is worth noting the potentiality of the tool presented for manifold reasons. Firstly, the tool can be used for analysing the fragility and vulnerability of structural typologies diffused on more large geographic areas, by considering the variation of the geometrical and mechanical parameters in larger ranges. Furthermore, the tool can be adapted, in order to model also other kinds of structural typologies, such as masonry buildings. Finally, the tool can be improved for taking into account more details in the numerical model behaviour, such as the influence of non-structural elements and the brittle mechanisms (shear and beam-column joints).

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