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ASSESSMENT OF RETROFITTING TECHNIQUES FOR SEISMICALLY-VULNERABLE RC BUILDINGS IN PORTUGAL

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Abstract

Approximately half of the building stock in Portugal is built in reinforced concrete and nearly 60% was designed before 1983, when the first modern seismic code was implemented in the country. Recent studies indicate that a large portion of the population is exposed to a high level of seismic risk. As such, the need for upgrading the building stock through the implementation of adequate retrofitting solutions is a topic of relevance in terms of preventing the consequences of a future seismic event. This paper presents a comprehensive review on various seismic retrofitting techniques and reports a numerical study which aims at evaluating their relative efficiency when applied to various RC building classes representative of the Portuguese building stock. The final goal of the research is the proposal of guidelines for the selection of retrofitting techniques based on cost-benefit analysis.

Keywords: Seismic retrofit, RC buildings, FRP, Steel bracing

1. Introduction

A large number of existing reinforced concrete (RC) buildings in European areas susceptible to be affected by moderate to high intensity seismic events. These buildings were designed and constructed without any special consideration of horizontal actions, as the codes at the time did not account for these type of loads. Thus, these structures lack adequate lateral load-carrying capacity, have limited ductility and are expected to sustain severe damage or even collapse under the action of a seismic event. Therefore, it is essential to evaluate the seismic performance of existing buildings and implement dependable and efficient seismic upgrading techniques when necessary.

The purpose of the present study was to assess, through numerical analyses, a RC frame designed mainly for gravity loads and representative of the construction procedures typical of structures built in Mediterranean countries, like Portugal, Italy or Greece, in the late 1970's. For this, the provisions of EC8-3[1] were used to evaluate the demand-to-capacity ratios of the vertical elements of the structure. Another objective was to identify a possible retrofitting option and evaluate the seismic behavior of the RC frame with the upgrade solution.

In the present paper, a summary of the literature review on the retrofitting techniques considered in this work is provided, followed by a description of the case study building and its assessment in terms of shear and chord rotations capacities of members. Afterwards, the seismic retrofitting options are presented and a new evaluation is performed. Finally, the obtained results are discussed and conclusions are drawn.

2. Review of seismic retrofitting techniques

The goal of seismic retrofitting is to provide buildings with increased strength and ductility to satisfy the required seismic capacity[2]. As such, the retrofitting strategy involves repairing deficient regions, improving the stiffness, strength and ductility of the elements and providing additional load carrying systems [3]. Many techniques and design strategies have been subject of investigation and adopted in the past to upgrade existing buildings, such as confinement of elements using concrete, steel or fiber polymers, adding steel elements, modifying the structural system with the addition of shear walls or applying base isolation systems, among others.

The retrofit with fiber reinforced polymers (FRPs) is being widely used in recent years, due to its numerous benefits, such as the enhancement of the compressive strength and ultimate compressive strain of elements, its easy and fast installation, the high strength to weight ratio and resistance to corrosion [4]. In addition to the mentioned characteristics, this intervention technique offers some advantages over concrete jacketing, for instance, the smaller final columns cross-section, allowing for optimization of floor area, less disruption of occupancy when installing and slight pollution with dust, debris and noise. Several studies have been conducted regarding the effectiveness of using this technique to strengthen and repair existing RC structural members. The application of this technique to RC members such as beams [5],[6],[7],[8] columns[5],[9],[10],[11], and joints [12],[13],[14],[15] showed the efficiency of FRP's for seismic retrofit, generally improving the strength and deformation capacity. Fig. 1 shows a schematic representation of an application of FRP to a beam-column joint.

Taking into consideration the multitude of retrofitting options, the introduction of steel elements might be a reasonable alternative to other techniques, owed to their ease of design and detailing, and a cleaner and less intrusive implementation, offering a wide range of applications [16]. One of the interventions using steel elements is the employment of steel braces. Typically, this technique is adopted to increase lateral stiffness and strength, either of a specific story or of the overall structure. Several authors [17], [18], [19] have established the benefits of steel bracing, stating the efficiency in improving the performance of RC frames. Compared with other techniques, such as the use of RC shear walls, steel bracing has a reduced weight and impact on the foundations.

Steel bracing systems usually consist of concentric X-diagonal, V or inverted-V braces, and fall into two main groups: external braces and internal braces[20]. In the former, steel elements are attached to the exterior of the building. Architectural concerns and difficulties at the connection of the steel bracing to the RC frames are some of the drawbacks of this method. As for the internal braces, the buildings are retrofitted by positioning a bracing system inside the individual bays of the RC frames. Whilst this method does not interfere with the exterior architectural design, it can cause some disruption on the inside.

This technique is generally regarded as an effective way to improve the seismic performance of existing RC buildings. Reported research have emphasized the benefits of implementing steel bracing, for instance, increase of shear capacity, reduced displacements and decreased drifts[21]. Fig. 2 illustrates how the steel bracing intervention can be materialized in the case of direct internal braces.

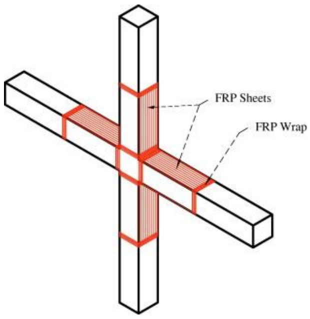

Fig. 1 – Schematic illustration of FRP retrofit configuration in an interior joint [22]

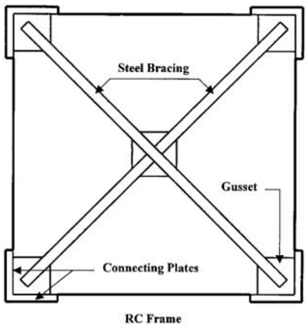

Fig. 2 – Direct internal bracing of RC frames [20]

3. Case study frame

3.1 Description

As a case study for the retrofitting techniques mentioned above, a RC structure considered to be typical of the building practices in countries such as Portugal in the late 1970's was chosen. As per the applicable regulations at the time, it was designed to withstand vertical loads only. Two full-scale models of this structure were tested at the JRC ELSA laboratory at Ispra, Italy within the framework of the ICONS research program. The frame was subjected to pseudo-dynamic (PsD) tests to assess the earthquake performance.

As shown in Fig. 3, the structure under study consists of a RC four-story frame with three bays, two of 5 m span and one of 2.5 m span. The inter-story height is 2.7 m and equal beams in terms of geometry and reinforcement were considered on all floors, with a slab of 0.15 m x 2.0 m on each side. All beams in the direction of loading are (width) 250 mm x (height) 500 mm, while transverse beams are (width) 200 mm x (height) 500 mm. Regarding the vertical elements, all but Column 2 (the wider interior one) have the same geometric characteristics along the height. The column cross-sections are presented in Fig. 4.

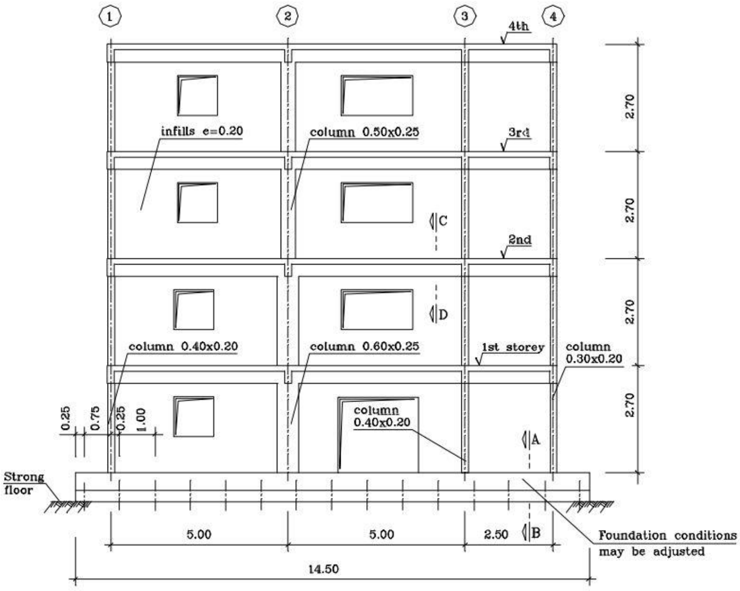

Fig. 3 – Elevation view of the RC frame [23]

As it was common practice several years ago, smooth steel bars were considered for the longitudinal reinforcement. Also, the reinforcement splicing, joints and stirrups detailing should be paid special attention, due to the fact that these are representative of the lack of confinement that is usual in non-ductile RC buildings of the late 1970’s. All columns show a longitudinal reinforcement lap-splice of 70 cm at the base of the first and third stories, creating a duplication of the nominal reinforcement at these locations. Other deficiencies can be identified in terms of current seismic design requirements, such as inadequate transversal reinforcement, maximum distance between longitudinal bars, absence of transversal reinforcement at the joints, inadequate bends of the stirrups, among others.

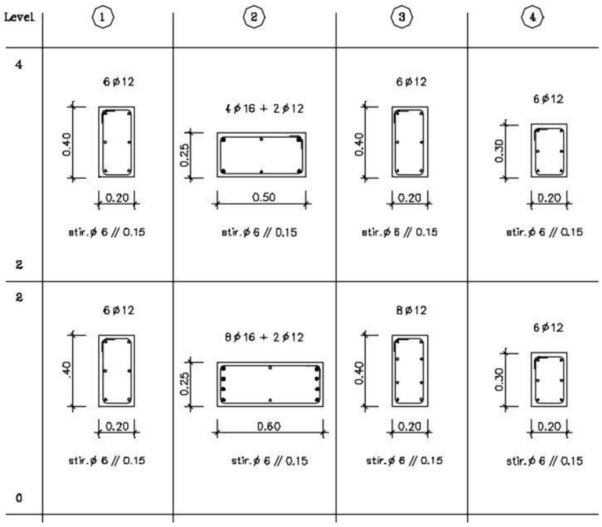

Fig. 4 – Column cross-sections [23]

During the design phase the considered materials were normal weight low strength concrete, class C16/20[24] and round smooth reinforcing steel, class Fe B22k (Italian standards). These materials were chosen to better simulate the properties of materials used in construction until the late 1970’s in southern European countries.

As stated earlier, the frame was subject to experimental PsD tests. However, for this work, the same frame was numerically evaluated and the results obtained, as well as the numerical modelling options are presented in the next subsection.

3.2 Seismic assessment

The numerical model of the frame was developed using software package SeismoStruct[25]. A distributed plasticity model was considered for column and beam elements and the behaviour of their cross-sections was represented by fibre discretization (200 fibres/section). Following the recommendations of Calabrese et al. [26], a force-based FE formulation was applied to implement the distributed plasticity frame elements and five integration sections per element were considered. Fig. 5 illustrates the numbering of the frame's members in the numerical model.

Regarding the constitutive laws defining the behaviour of the concrete and steel materials, the respective models were chosen based on the results of the experimental tests. Thus, the Mander et al.[27] model was employed for the concrete. Due to significant differences of strength found between each casting phase, different values of compressive and tensile strength were adopted for the columns in the first two floors and the remaining columns. This was not the case for the beams, therefore the mechanical properties were considered the same for all beams. For the steel, the Menegotto and Pinto[28] model was adopted, combined with the isotropic hardening rules suggested by Filippou et al[29].

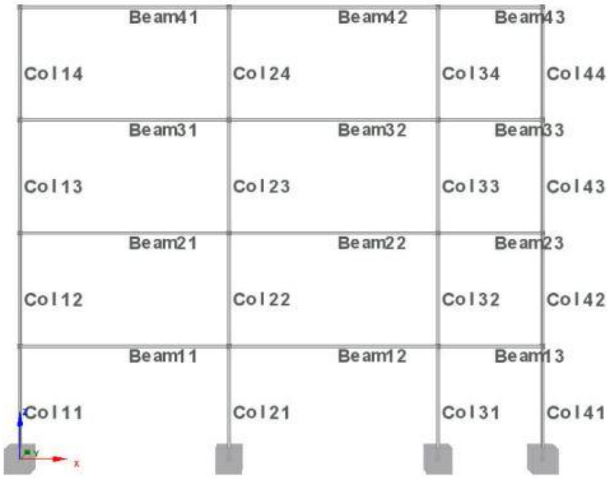

Fig. 5 – Structural member numbering in the numerical model

The seismic assessment of the frame was performed according to the provisions of EC8-3[1]. For the assessment, member chord rotations are determined for ductile elements, whilst shear force is used for evaluation of brittle elements. Members capacities are defined according to the expressions proposed in EC8-3[1], taking into account that for buildings belonging to the Importance Class II, which is the case of the frame in study, only the LS of Significant Damage (SD) needs to be verified. The assessment procedure is carried out through nonlinear dynamic analyses. The base seismic demand was set for Zone 1.3 of the Portuguese territory, on Type A ground. According to the Portuguese NA of the EC8-3[1], different return periods must be considered depending on the LS to be verified, and, consequently, the seismic action was multiplied by the coefficient defined for the LS of SD.

As stated, ductile capacities are defined according to the admissible SD member chord rotation. For this, the expressions proposed in EC8-3[1] were employed, with some approximations introduced to simplify the computation process. For the brittle elements, the shear capacities values were obtained through the expressions of EC8-3[1] and compared with the ones determined regarding the provisions of EC2-1-1[24], and the minimum of these values was considered. In a similar manner to ductile members, approximations were implemented to reduce the dependence on demand parameters.

The results of the assessment of the frame are expressed in terms of demand-to-capacity (D/C) ratios, for each control section, where a value below or equal to 1.0 is representative of a safe situation. It should be noted that the results provided herein refer to the vertical elements only, as these are often the critical members to assess the safety of a structure. The results are illustrated in Fig. 6 and Fig. 7, where the former shows the D/C ratios in terms of shear force and the latter displays the D/C ratios for the chord rotations.

In terms of the outcome of the seismic assessment, the D/C ratios for chord rotation are all below the threshold of 1.0, which indicates that, regarding deformations, the columns are deemed safe. However, the shear capacities of the control sections of Column 2 in the first three stories were exceeded, thus a local retrofitting intervention with FRP will be implemented in the sections that were deemed unsafe. As such, the next subsection will deal with the retrofitting intervention and the assessment of the retrofitted RC frame.

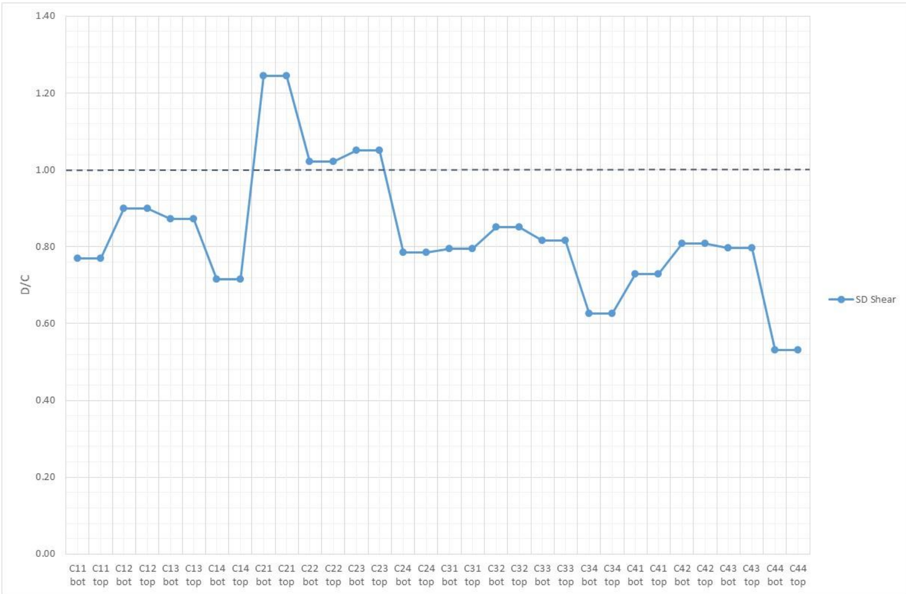

Fig. 6 – D/C ratios: results of shear force on columns for the SD limit state

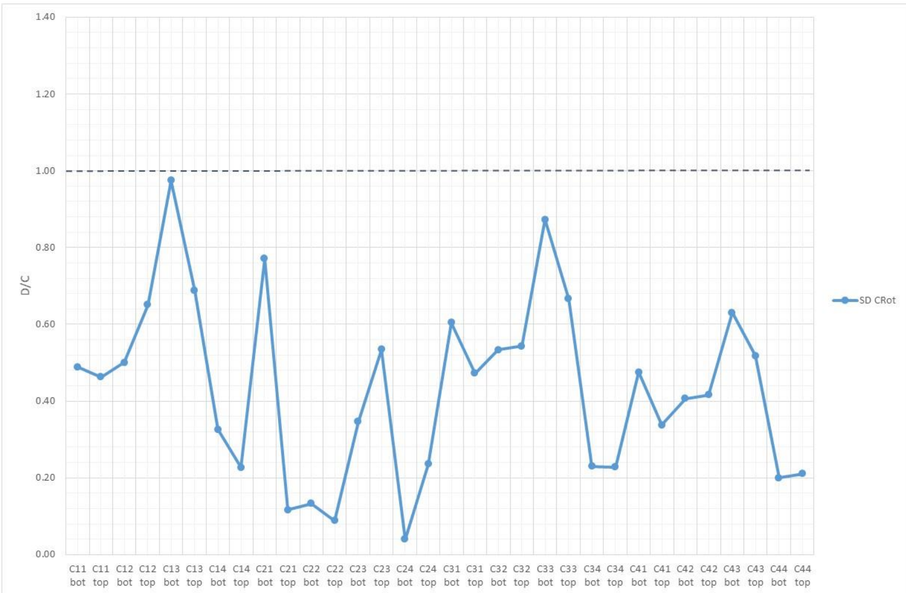

Fig. 7 – D/C ratios: results of chord rotations on columns for the SD limit state

4. Design and assessment of the retrofitted structure

Following the seismic assessment results of the previous section, it was decided to apply a retrofitting technique to the elements that were deemed unsafe, in order to make them compliant with the performance requirements of EC8-3[1]. Due to the several benefits described previously, a solution with FRP was applied to Column 2 in every story. The design values of the material used are presented in Table 1. The solution was then implemented in the SeismoStruct model.

Table 1 – Characteristics of the FRP material used in the retrofit intervention

Nominal Thickness (mm)	Tensile Strength (MPa)	Tensile Modulus (GPa)	Tensile Elongation (%)
1.0	541	27.4	1.82

Following the assessment procedure, nonlinear dynamic analyses were performed to evaluate whether this solution solved the shear problem identified in the assessment of the bare frame. The results obtained are expressed in terms of demand-to-capacity ratios, similarly to the results of the bare frame. Fig. 8 shows the D/C ratios obtained for the shear capacities of the columns of the retrofitted frame. These results validate the intervention, as no D/C ratio is above unity.

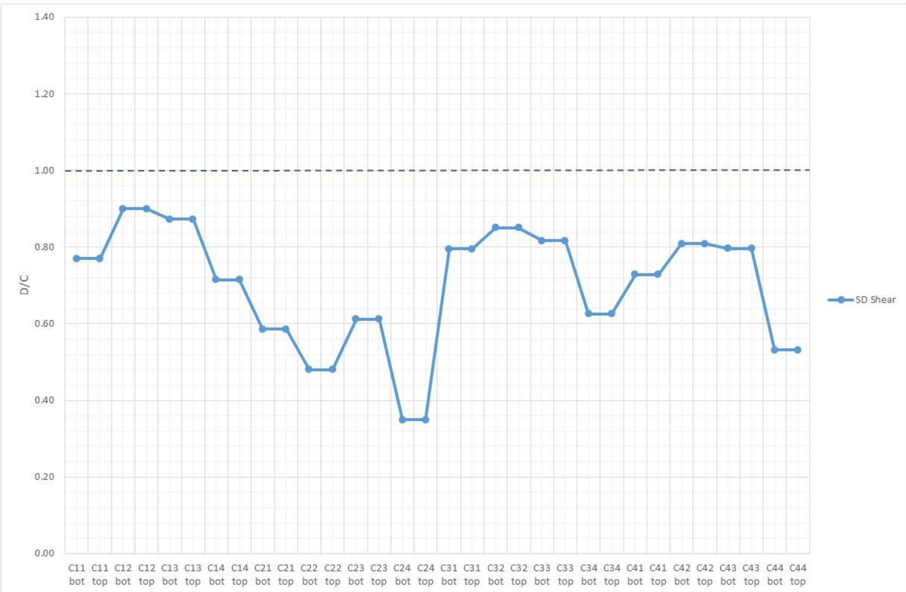

Fig. 8 – D/C ratios: results of shear force on columns with FRP for the SD limit state

Although this is sufficient to determine that the retrofitting action solves the issues presented, as the EC8-3[1] requirements were satisfied, one is led to wonder what would succeed if an event with a higher return period was to occur. This led to the assessment of the structure retrofitted with FRP under a seismic action equivalent to that of the LS of Near Collapse (NC). Thus, new numerical analyzes were performed. The D/C ratios for shear force and for chord rotations are shown in Fig. 9 and Fig. 10, respectively. Whilst the results for shear force show only slightly higher values compared to the LS of SD, the chord rotations capacities were clearly exceeded in several control sections. In fact, the value of the chord rotation at the bottom section of the Column 3 on the third story exceeds more than twice the value of the rotation capacity of that member. All the columns of the third story have D/C ratios above 1.0, and the top section of Column

1 on the second story and the bottom section of Columns 2 and 3 on the first story are also deemed unsafe. It is worth noting, however, that the D/C ratios on some of the remaining control sections are quite high, and, as such, the frame is considered unsafe for the LS of NC, according to the provisions of EC8-3[1].

Observing the results attained, it could be stated that, contrary to the previous assessment, the exceedance of the chord rotation capacities is a global problem, instead of a localized one, thus, a global intervention should be adopted.

Fig. 9 – D/C ratios: results of shear force on columns with FRP for the NC limit state

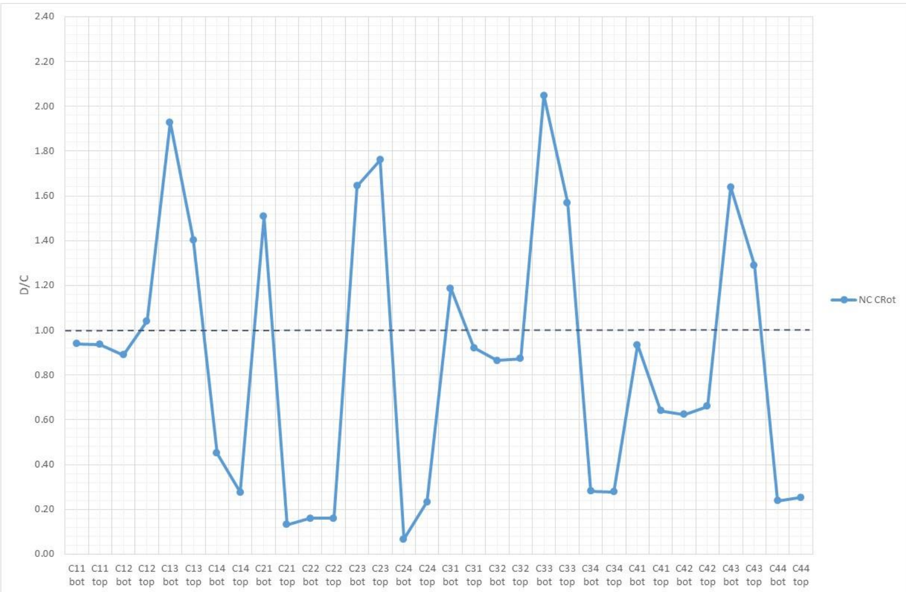

Fig. 10 – D/C ratios: results of chord rotations on columns with FRP for the NC limit state

A global strengthening intervention employing concentric X-diagonal steel braces, in addition to the implementation of the FRP solution, is proposed in order to fulfil the performance requirements of the LS of NC under the corresponding EC8-3[1] seismic action. The design was carried out according to the provisions of EC3-1-1[30] and EC8-1[31], following a displacement-based procedure. The full design process is detailed in Falcão Moreira[32].

Fig. 11 shows the layout of the proposed bracing system. The diagonals consist of circular hollow section (CHSH) steel profiles, directly connected to the beam-column nodes of the intermediate bay of the RC frame. The connection is conceived as capable of transmitting internal forces without developing significant moments. The frame was analyzed under the effect of vertical loads combined with the seismic demand of the LS of NC. The brace cross-section dimensions of the solution adopted can be found in Table 1.

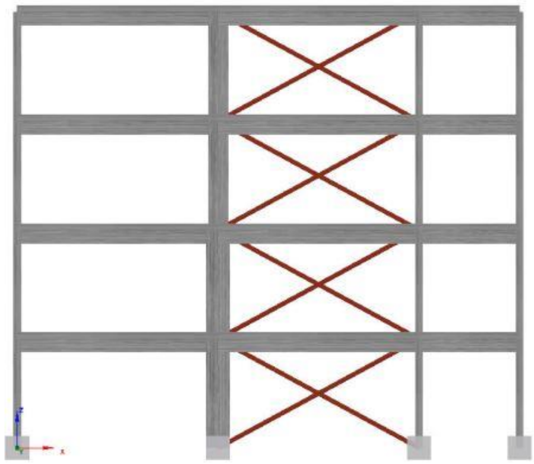

Fig. 11 – Layout of the proposed retrofitting solution

Table 2 – Brace cross-section dimensions

Story	Brace cross-section
4	CHSH 88.9x3.2
3	CHSH 139.7x3.6
2	CHSH 139.7x3.6
1	CHSH 139.7x3.6

As previously referred, nonlinear static analyses were performed and the demand-to-capacity ratios were obtained. Fig. 12 and Fig. 13 show the D/C ratios for the retrofitted solution with steel braces and FRP, the former in terms of shear capacities and the latter for chord rotations capacities. By examining the results obtained, all the D/C ratios are below the threshold of 1.0, both in shear and chord rotation capacities, deeming the retrofitted structure safe under the provisions of EC8-3[1]. It is concluded that, to comply with the requirements of the LS of NC, the intervention solely with FRP is not adequate and a global intervention with steel braces is necessary.

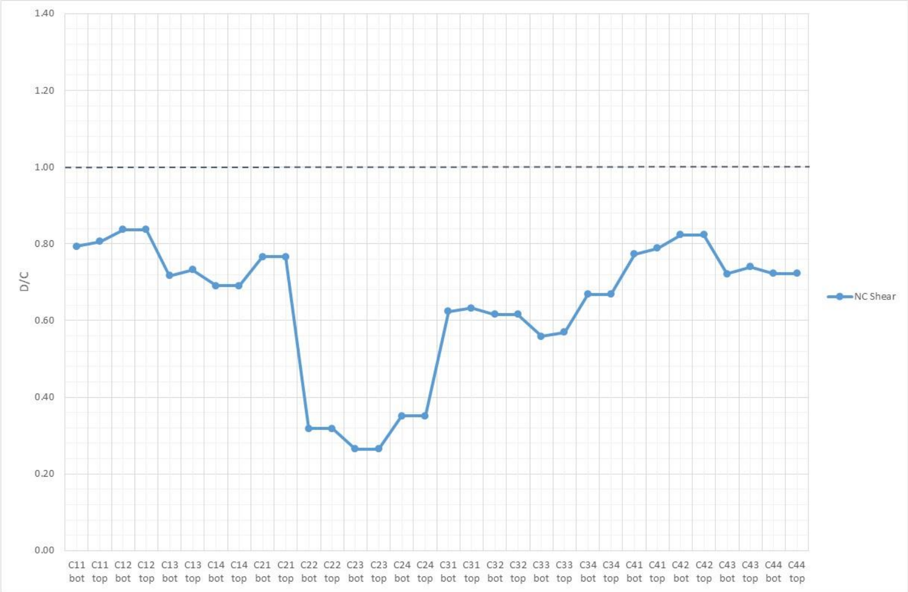

Fig. 12 – D/C ratios: results of shear force on columns with FRP and steel bracing for the NC LS

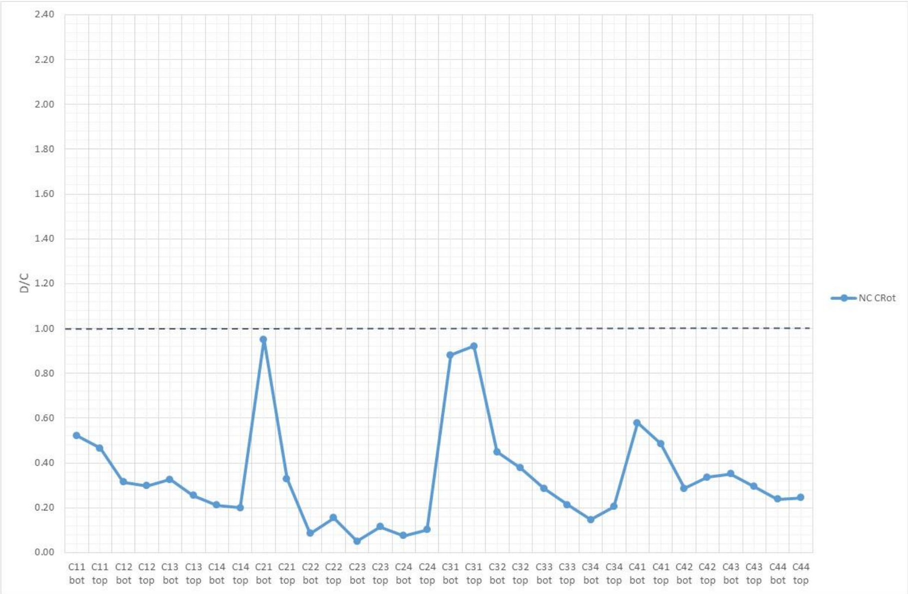

Fig. 13 – D/C ratios: results of chord rotations on columns with FRP and steel bracing for the NC LS

5. Conclusions

This study presented the results of numerical analyses for the assessment and retrofitting of a four-story RC frame designed to withstand mainly vertical loads. An evaluation of the vertical elements of the bare frame was performed, based on the outcomes of the nonlinear dynamic analysis. The frame was deemed unsafe for the limit state of Significant Damage defined in EC8-3 due to some columns exceeding the shear capacity and it was concluded that an intervention was needed.

From among the several existing retrofitting techniques, it was decided to implement a local retrofitting solution applying fiber reinforcement polymers (FRP). A new assessment was performed, and the safety was verified. However, when running the analysis for the limit state of Near Collapse, it was noticed that whist the shear issue was solved, the chord rotation D/C ratios were above 1.0 for several control sections, leading to a global intervention using steel braces. A new assessment of the retrofitted frame with FRP and steel bracing resulted in satisfactory behavior under the seismic action corresponding to Near Collapse.

Thus, it was verified that RC frames with similar characteristics may become compliant with the performance requirements of EC8-3 with a local intervention, and combining this to a global retrofit may offer the structure additional resistance to withstand a seismic event with intensity equivalent to that of the LS of NC.

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7. Copyrights

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