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Optimal ductility enhancement of RC framed buildings considering different non-invasive retrofitting techniques

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ABSTRACT

Existing RC framed buildings lack significant ductility, especially when they have been built with pre-code criteria. Improving their ductile capacity can help to prevent them from the brittle collapse mechanism and to reduce the seismic damage expected. This paper aims to investigate the enhancement of the ductile response behaviour of RC framed buildings considering different non-invasive retrofitting techniques. To do so, a pre-code RC framed school located in the Spanish province of Huelva has been selected as a case study. Five non-invasive retrofitting techniques have been tested: FRP wraps and steel jackets in columns, steel beams and plates under RC beams and single steel braces. They have been selected so that they can be easily implemented in the building. Some of them have been studied in detail in previous works and others have been included for further research in this paper. In order to compare the results obtained, the most typical technique in the seismic retrofitting of RC framed buildings, the addition of X-bracings in bays, has also been tested. Most previous studies on the seismic retrofitting of RC buildings are focused on validating a method based on artificial models. This paper compares the different techniques in terms of the capacity improvement and the damage reduction, performing analyses in detail and adding them in an existing RC building. A sensitivity analysis has been carried out to determine the influence of each technique in the building's ductile capacity considering the finite element method. Nonlinear static analyses have been performed to obtain the capacity, the displacement ductility factor (μ) and the behaviour factor (q) of each model defined. The damage expected has been determined considering the ductile and fragile failure of the elements according to the Eurocode-8 (EC8) requirements. To analyse the suitability and the efficiency of each solution, a benefit/cost ratio has been obtained taking into account the ductility improvement and the damage reduction with regards to the retrofitting costs. The results have shown that the best benefit has been obtained with the addition of steel braces. However, the optimal solutions have been single braces and steel jackets due to their combination between benefit and cost. It has been observed that the solutions that increase the stiffness of the joints have had a higher improvement due to the key role that joints have in the resistant capacity of RC structurers. Also, it has been obtained that the values of the fundamental periods have been reduced, when adding the retrofitting elements and materials, up to 30% owing to the increase of the stiffness of the system. Finally, it must be highlighted that a detailed analysis of the behaviour of the whole building must be conducted in order to avoid additional rotation effects and shear forces that could worsen the building's seismic behaviour.

1. Introduction

Over the last years, there has been a considerable number of earthquakes that have resulted in catastrophic consequences [10]. The behaviour of buildings during an event is one of the most important parameters concerning the destructive potential of an earthquake [31]. Among others, the seismic response of constructions is based on their configuration, their mechanical properties, their ductility, their stiffness and their strength. Seismic design philosophies have been carefully improved in order to control these parameters to design new constructions which can withstand the earthquakes expectedŽižmond and Dolšek [51]. However, buildings built prior to seismic codes are the most

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likely to be damaged by an earthquake [27]. This is due to the fact that they have only been designed considering the gravity loads, omitting the required lateral load resistance.

Schools have been proved to be one of the most vulnerable typologies to earthquakes [22]. Most part of the school buildings were constructed in Spain during the 70 s and 80 s. In the case of the Spanish Huelva province, most of the schools are low-rise reinforced concrete (RC) framed buildings, which were constructed during this period. They share similar constructive and structural characteristics and were designed with typical seismic vulnerabilities: soft-storey mechanisms, wide beams and irregularities in plan and in height. Some seismic regulations were available during that period in Spain. However, they were not very restrictive and were usually omitted by the designers. The first Spanish seismic code which was carefully considered in the design of buildings was the NCSE94 [42] Spanish Ministry of Public Works [Ministerio de Fomento de España] [41]. This was introduced in 1994 so the vast majority of the schools in the area are pre-code buildings. Hence, they present smooth rebar, low-quality structural and constructive materials and insufficient reinforcement rebar, especially in the beam-column joints. Furthermore, the seismic hazard in Huelva is considerable due to the proximity of the Eurasian-African tectonic plates boundary [6]. These aspects account for the need of studying and improving the capacity of these buildings to withstand the earthquakes expected.

Ductility is considered as one of the main parameters that affect the seismic response of buildings. The deformation capacity allows structures to undergo large deformations without a substantial reduction in strength [35]. Hence, improving the ductile capacity of buildings has an impact on the overall seismic response. It helps to prevent the brittle collapse mechanisms and to reduce the expected seismic damage [32]. Moreover, it can reduce the lateral displacement demand, minimising the damage of non-structural elements and partitions. This is of the utmost important for reducing the economic losses. In the case of existing constructions, they have been widely analysed and proved to be of limited ductile capacity [8]. In fact, as buildings built with pre-code criteria do not have a significant ductility they are seismically vulnerableZeris and Repapis [49].

The enhancement of the deformation capacity and the shear strength of structural elements can be achieved by seismically retrofitting the buildings. A literature review on the retrofitting of RC buildings revealed different techniques developed in the last decades and calibrated through experimental and numerical research [7]. Despite its importance in the seismic behaviour of buildings, ductility has not been widely considered in this type of studies [38]. In fact, many of them just tested these techniques to determine the global behaviour improvement of the building. The most typical seismic retrofitting techniques are the addition of steel bracings, shear walls, base isolation or dumping devices [39]. Although these solutions can significantly improve the seismic behaviour of buildings, they generate dust, modify the weight of the structure or affect the architectural configuration of the building (Vielma-Perez et al., 2020). In some cases, it is even not possible to build new foundations, to upgrade existing ones or to place these elements (which usually demand a large space). These factors excessively affect the functionality of the building, reducing their possibilities of implementation. In the case of schools, it is a parameter of utmost importance. Therefore, in order to retrofit these buildings, new realistic and easily implemented solutions must be sought [34].

2. State of the art

A group of schemes that are specifically designed to minimise their impact on the functionality and the configuration of RC buildings are called non-invasive techniques. They are focused on improving the local resistance of the structural members, enhancing the global behaviour of the construction [18]. These interventions must be exhaustively analysed in order to select the most efficient for a specific case [25]. Their influence is generally analysed by means of nonlinear analyses reinforcing the building with the interventions. Moreover, studies on this subject are starting to consider new open-source software, such as the OpenSEEs [33], to carry out the analyses. The goal of this type of studies is to perform exhaustive finite element analyses to determine and ultimately reduce the seismic damage expected. Among these non-invasive techniques, those most implemented are the addition of FRP wraps and steel jackets in columns.

The external jacketing of columns and beam-columns joints with composites of Fiber-Reinforced Polymers (FRPs) has become a well-developed retrofitting technique to improve the ductility of RC buildingsTruong et al. [45]. As stated inVielma-Perez et al. [46], this offers numerous advantages: it is minimally invasive (overcoming the space limitations), it helps to prevent the fragile failure, it is less polluting than other techniques, it improves the strength and confinement of the elements and it does not increase the weight of the structure. The enhancement of the ductile capacity of a building, obtaining the ductility parameters by adding different FRP wraps sizes, was analysed in (Vielma-Perez et al., [46]). However, an artificial building was considered in the analyses and the reinforcement was added in all of the structural members, leading to inefficient results. Some studies have been focused on developing models in OpenSEEs to simulate the addition of FRP. These studies are mainly based on validating the model and consider artificial buildings [25]. InZhou et al. [50], numerical analyses were carried out to study the enhancement of the performance of an RC column retrofitted with FRP. Different methods to calculate the stiffness degradation and the curvature distribution were proposed.

Another type of column jacketing is based on steel, which is known for its ductile capacity. This technique (SJ) can be easily implemented and improves the global structural ductility. Most of the studies added the reinforcement in every RC column as inVillar-Salinas et al. [47]. In this work, only the behaviour factor following the American approach was determined for each model tested. InTrapani et al. [44], an OpenSEEs routine was presented to obtain the optimal position of the steel jacketing of columns. The outcomes were discussed in terms of capacity curves and construction costs. However, they did not consider the seismic damage expected.

Other non-invasive solutions which have not been that widely tested and implemented are the addition of steel beams (SB) and plates (SP) under RC beams. InYen and Chien [48], a plated RC beam subjected to cyclic loads was experimentally tested. Several indexes were determined to further examine the behaviour of the specimens retrofitted. In [29], a model that retrofitted RC beams with bolted side plates was numerically validated. There are some other techniques that add other types of retrofitting material under beams, such as FRP. However, it was found that using FRP composites in order to increase the ductility of building was not that effective [21].

Another solution found to be a promising technique is the addition of single steel braces (VB). In [40], finite element models were experimentally and numerically validated with different types of steel braces. The study revealed that a properly designed system could provide significant improvement in the seismic performance. The results obtained referred to the global behaviour of the building, not focusing on the local performance of the structural members. Specific prototypes that include haunches were experimentally tested in shaking tables in [1]and in [5]. The tests conducted showed that the haunch retrofitting primarily causes an increase in the stiffness and the strength of the structure and, to some extent, in the structural deformability, i.e. producing an enhancement of the ductility. There are other variations of this technique based on adding steel braces near the columns [2]. They are similar to the addition of X-bracings, therefore, they cannot be considered as non-invasive.

Research on the retrofitting of RC buildings is mainly focused on artificial models. This simplification is a disadvantage of the current assessment procedures of real structures. Moreover, for easiness most of the studies did not contemplate the analysis of the building's ductile capacity. Although they considered a finite element software, most of them were based on proposing and validating a model. Hence, they did not prove the efficiency of the techniques in terms of capacity improvement and damage reduction. Moreover, there is a lack of studies on the comparison of the effects of different seismic retrofitting techniques designed for RC constructions. This type of studies is interesting to determine the most optimal solution for specific cases. In fact, the available research on this issue is based on determining the global behaviour enhancement, not focusing on the retrofitting of the local elements.

Therefore, the aim of this paper is to investigate the enhancement of the ductile behaviour of RC framed buildings considering different non-invasive retrofitting techniques. Given the seismic hazard in Huelva, a pre-code RC framed school located in this region has been selected as a case study. Five non-invasive retrofitting techniques have been tested: FRP wraps and steel jackets in columns, steel beams and plates under RC beams and single steel braces. They have been selected so that they are easily implemented in the building. There are numerous retrofitting techniques that can improve the ductility of existing RC buildings. However, only some solutions have been considered owing to their feasibility of application in the case study building, their speed of placement and their small increase in load. Some of them have been studied in detail in previous works and others have been included for further research in this paper. In order to compare the results obtained, the most typical technique in the seismic retrofitting of RC framed buildings, the addition of X-bracings (XB) in bays, has been also tested.

A sensitivity analysis has been carried out to determine the influence of each technique on the building's ductile capacity considering the finite element method. Nonlinear static analyses have been performed to obtain the capacity, the displacement ductility factor (μ) and the behaviour factor (q) of each model defined. The expected damage has been determined considering the ductile and the fragile failure of the elements according to the Eurocode-8 (EC8) requirements. To analyse the suitability and efficiency of each solution, a benefit/cost ratio has been calculated bearing in mind the ductility improvement and the damage reduction with regards to the retrofitting costs.

3. Method

The method proposed in this study is divided into three main parts: the building's configuration, sensitivity analysis and benefit/cost ratio. The procedure followed in this study is shown in (Fig. 1).

3.1. The building's configuration

3.1.1. Data curation

In total, 269 primary school buildings have been identified in Huelva, 82% being RC framed buildings [34]. The case study building selected represents an important portion of the schools buildings' stock in the province of Huelva (Fig. 2). It has been designated as an index-building of a typology, which 75 constructions belong to. The typology represents 34% of the RC schools identified in the province, which share similar structural and constructive characteristics. Data regarding the building have been obtained from on-site visits, expert knowledge and the corresponding code applicable in this period (70–80 s).

The case study is a two-storey RC framed building constructed in the 70 s with typical design details of pre-code RC constructions in Spain. The analysis of the original blueprints has revealed the presence of typical seismic vulnerabilities: smooth rebar, inadequate reinforcement in joints due to insufficient rebar, wide-beams and short columns. In this case, despite the regularity in the building's height, short columns have been identified on the ground floor. In plan, the structural configuration is rectangular and symmetrical. Therefore, torsional effects have not been considered in the analyses. The floor system is composed of 25 cm concrete ribbed slabs supported by wide-beams and columns whose characteristics are listed in Table 1. Since the slabs present a significant stiffness, the effects of the rigid diaphragm have been taken into account. The masses have been applied at the centre of each floor. The columns are all oriented with their strong axis in the X direction. The mass of the structure has been divided into: dead (self-weights, in total 5.5 kN/m^2) and live loads (defined according to Part-1 of Eurocode 8 (EC8-1) (European [24]. Table 2 shows the mass and the height of the existing building.

3.1.2. Numerical modelling

The different prototypes of the building considering the retrofitting techniques have been modelled with the STKO software (ASDEA [9]. The analyses have been carried out with the OpenSEEs software [33]. This is an open-source software based on the finite element modelling approach. The outputs have been handled in Matlab Inc [43].

The nonlinear behaviour of the RC elements has been simulated through a distributed plasticity model. To do so, the RC frames have been modelled with displacement-based fibre elements. The concrete cover has been modelled with the uniaxial Kent-Scott-Park concrete material (Concrete01) [28]. To bear in mind the confined concrete in the core, the strength and strain have been increased according to [30]. The steel fibres have been modelled using the uniaxial Giuffre-Menegotto-Pinto model (Steel02) [26]. Table 3 lists the mechanical properties of the existing building's materials.

The rebar slippage is a phenomenon commonly found in existing RC buildings, which can increase the damage in the structural elements [3]). These effects as well as the presence of the smooth rebar have been taken into account by modifying the steel constitutive law: reducing the elastic modulus and the maximum strength to consider the strain

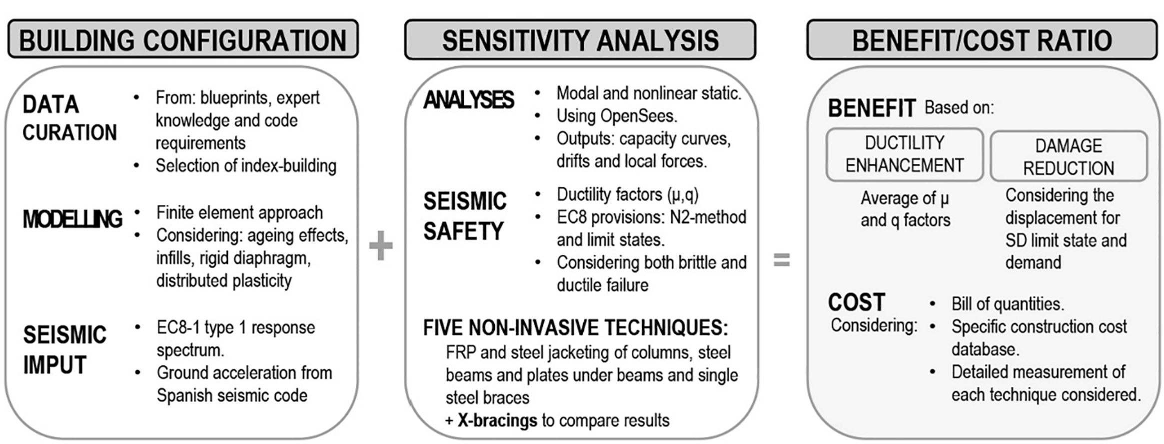

Fig. 1. Flowchart showing the procedure followed in the study.

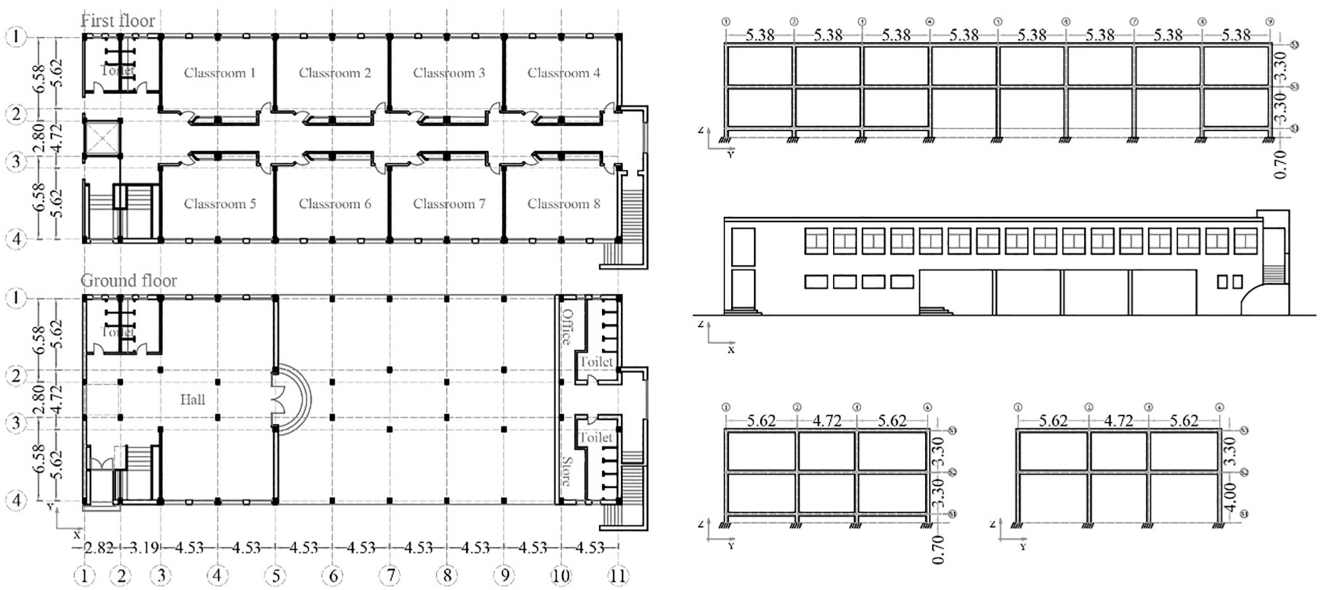

Fig. 2. The school's distribution in plan and elevation. Elaborated by the authors.

Table 1
Geometrical characteristics of the structural elements of the existing building.

Characteristic	Columns	Load beams	Tie beams
Dimensions (cm)	30 × 40	60 × 30	30 × 30
Cross-section (cm^2)	1200	1800	900
Longitudinal rebar (cm^2)	1.572	Top: 0.786 Bottom: 3.495	Top: 0.786 Bottom: 0.786
Transversal rebar (cm^2)	0.196	0.196	0.196
Spacing of stirrups (cm)	15	20	25

Table 2
Total mass and height of the existing building.

	Total mass (ton)	Total height (m)
Initial situation	1058	7.30

Table 3
Mechanical properties of the existing building's materials.

Concrete	f_c (MPa)	ε_c (‰)	ε_{cu} (‰)	E_c (GPa)
Cover	17.5	2	200	30
Steel	f_y (MPa)	f_u (MPa)	ε_{su} (‰)	E_s (GPa)
Smooth rebar	222	36	168	126
Masonry	G_w (GPa)	α	τ_{cr} (MPa)	E_w (GPa)
Infills	1240	0.05	280	4092

f_c -compressive maximum strength; ε_c - strain at maximum strength; ε_{cu} - ultimate strain; E_c - modulus of elasticity for concrete; f_y - yielding strength; f_u - ultimate strength; ε_{su} - ultimate strain; and E_s - modulus of elasticity for steel; G_w - elastic shear modulus; α - post-capping degrading branch coefficient; τ_{cr} - shear cracking stress; E_w - modulus of elasticity of the masonry.

penetration effects, following the approach described in [12]. In order to obtain a realistic performance of the building, the effects of the infills have been simulated following the two diagonal strut approach defined in [19]. A four-branch force–displacement relationship of the diagonal strut from [13]has been assumed. Owing to the building's construction date, the ageing effects have been borne in mind considering two aspects [14]: i) the reduction of the longitudinal and transversal rebar section; and, ii) the degradation of the concrete cover. The simulations have been carried out according to the work developed in [15]. Two types of elements have been defined according to their exposure to the aggressive environment: i) medium and ii) totally exposed. Medium exposed elements are those that can be found within the building's façades. Totally exposed elements are those not covered by masonry walls. Table 4 shows the parameters considered in the simulation according to the exposure type and the approach followed.

3.1.3. Seismic input

The design ground acceleration (a_g) has been determined according to the Spanish updated seismic action values Spanish Ministry of Public Works [Ministerio de Fomento de España] [41]. A PGA value of 0.1 g and the EC8-1 provisions have been considered to define the elastic response spectrum. This action corresponds to a return period (T_R) of 475 years. Since it is a school building, the importance factor (γ_I) is 1.30. The soil is composed of medium–low silt-sand according to a nearby geotechnical study. Therefore, as EC8-1 establishes, a soil type C has been considered.

3.2. Sensitivity analysis

In order to analyse the influence of each retrofitting scheme, a sensitivity analysis has been carried out. The techniques selected have been: FRP wraps and steel jackets in columns, steel beams and plates under RC beams and single steel braces. These are non-invasive techniques since they are specifically added to structural elements, not

Table 4
Ageing effects parameters.

Reduction of rebar	Corrosion level	I_{corr} (μA/cm^2)	D_{loss} (mm/year)	Δ_t (years)	t_0 (years)
Medium exposure	Low	0.5	0.0115	20	30
Totally exposure	Medium	1	0.023	40	10
Reduction of cover	Type of attack	Action			
Medium exposure	Normal	Concrete cover strength has been reduced by half [11]			
Totally exposure	Aggressive	Concrete cover removed			

i_{corr} - mean annual corrosion per unit of anodic area of steel; D_{loss} – rebar diameter loss; Δ_t – period of time that corrosion affects; t_0 - corrosion initiation time.

producing significant changes in the building. Moreover, they are characterised by their speed of placement since they are easy to include. Even, they represent a small load increase since their weight is considerable small in relation to the weight of the structural element and the building. Therefore, they are considered low-impact techniques, not affecting the distribution and functionality of the building. Some of them have already been developed and others are presented in this paper. In order to compare the results obtained, the most typical technique in the seismic retrofitting of RC framed buildings, the addition of X-bracings in bays, has also been tested [36].

Different models have been defined by varying three parameters: i) the amount of reinforcement material; ii) the position of the reinforcement in the structural elements; and iii) the number of structural elements retrofitted. For i), the width, the spacing, the thickness and the size of the reinforcement elements have been varied. For ii), the positions have been defined according to the column's length or the building's directions. In the first case, the reinforcement material has covered: 1/3 of the column length above and below each joint to improve the flexural capacity; 1/3 of the column and beam length; or, the entire length of columns to improve the axial strength. In the second case, the reinforcement material has been added in one or both directions of the building. For iii), different situations have been defined. Prior to the addition of the reinforcement, the weakest or first damaged structural elements have been identified. Once determined, in the first situation, 25% of the first damaged elements have been retrofitted. Then, 50% of these elements have been retrofitted. Finally, all the vertical elements have been retrofitted following the approaches of the rest of the studies. The single steel braces and the X-bracings have been added according to the most efficient positions obtained in [37]. The different configurations to be modelled are shown in Fig. 3, The nomenclature of each model is defined according to the abbreviations in bold.

3.2.1. *Nonlinear static analyses*

Dynamic analyses, such as response history, have been gaining importance in the determination of the seismic retrofitting of buildings [4]. They are mainly focused on considering the parameters variability of the analyses to obtain the behaviour of the buildings. However, it is widely known that they require high computational time. In this study, the capacity of the models has been determined by means of nonlinear static analyses. They have been proved to provide reliable results, requiring much less time of computing. A load-control integrator has been used to apply the gravitational loads. Then, a displacement-control integrator has been considered to scale the forces to reach a displacement, avoiding convergence errors. Only the modal load pattern has been borne in mind in the positive X and Y directions, due to the negligible values obtained for the rest of the patterns.

3.2.2. *Seismic safety*

Once the capacity has been obtained, the displacement ductility factor (μ) and the behaviour factor (q) of each model defined have been determined according to the procedure established in [38]). The seismic safety has been verified using the Capacity Demand Ratio (*CDR*). The damage limit states have been determined according to the procedures established in Part 3 of Eurocode 8 (EC8-3) (European [23], which are: damage limitation (*DL*), significant damage (*SD*) and near-collapse (*NC*). The NC limit is calculated considering two types of failures: a) the fragile (*BF*), which takes into account the shear resistant (V_R; and b) the ductile (*DF*), which considers the ultimate chord rotation (θ_{um}). SD has only been calculated for the ductile failure, considering 75% of the NC. Finally, DL is calculated with the yielding chord rotation (θ_y).

The failure of the structure has been assumed when one of the columns reached the SD state. This limit state has been assumed to be attained when the column's shear (V_{demand}) or chord rotation (θ_{demand}) is equal to or greater than 1 ($V_{demand}/V_R \geq 1$ and $\theta_{demand}/\theta_{um,SD} \geq 1$, respectively). Two additional levels have been calculated to obtain the elements that have almost attained the SD limit state (θ_{demand}/θ_y greater than 0.9 and the elements that have exceeded the θ_y (θ_{demand}/θ_y greater than 1)).

The idealisation of the bilinear curve and the determination of the target displacement have been carried out according to the N2-method as indicated in EC8-1. The N2-method extended version has been considered to account for the effects of the infills following the work developed in [20].

3.2.3. *Retrofitting techniques*

The values of the FRP mechanical properties have been defined according to Zhou et al. [50]. The modulus of elasticity (E_{FRP}) is 231 GPa and the ultimate strain ($\varepsilon_{j,rup}$) is 0.0072 mm. The properties of the structural steel of the jacketing, the braces, the beams and the plates are: yield stress (f_y) 275 MPa, modulus of elasticity (E_s) 210 GPa and weight 76.98 kN/m^3. The simulation of each technique in the software is presented below. The retrofitting techniques considered in this study are shown in Fig. 4.

3.2.3.1. FRP-wrapping of columns. The FRP-wrapping was implemented by using a uniaxial material named "ConfinedConcrete01" [17]. This material bears in mind the degraded linear unloading/reloading stiffness. The model can incorporate a variety of different FRP and steel jacketing configurations, making it more versatile than other existing models in the literature. Such is the case of the other available material in the OpenSEEs library named "FRPConfinedConcrete" presented in [25]. This material was only designed for circular columns and the case study building has rectangular columns. The thickness of the wraps was 1.3 mm. The width and separation of the wraps was varied according to Fig. 3. They were added in every face of the columns and at the base of the beams. In Fig. 5, the stress–strain diagram for the RFP materials considered is shown.

	FRP-wrapping (**FRP**)	Steel jacketing (**SJ**)	Steel beams (**SB**) & plates (**SP**)	Single braces (**VB**)	X-bracings (**XB**)
i) Amount of reinforcement material	- Width: 50 mm - Spacing: 30 mm - Thickness: 1.3 mm	- Width: entire face column - Spacing: none - Thickness: 5 mm	- Width: entire face column - Spacing: none - Plate's thickness: 5 mm - Beam's size: HEB300	- Ø16 mm of diameter	- Ø16 mm of diameter
ii) Position of reinforcement elements	- 1/3 length of columns (**C**) - 1/3 length of columns and beams (**BC**) - Entire length (**EL**)	- 1/3 length of columns (**C**) - 1/3 length of columns and beams (**BC**) - Entire length (**EL**)	- X and Y directions (**XY**)	- X and Y directions (**XY**)	- X direction - Y direction - X and Y directions
iii) Number of retrofitted elements	- 25% of first structural elements damaged (**25**) - 50% of the elements (**50**) - All columns (**AC**)	- 25% of first structural elements damaged (**25**) - 50% of the elements (**50**) - All columns (**AC**)	- 25% of first structural elements damaged (**25**) - 50% of the elements (**50**) - All columns (**AC**)	- 25% of columns in X and Y, both floors (**1**) - 50% of columns in X and Y, both floors (**2**)	- 4 XB in Y-corners, both floors (**1**) - 4 XB in X-middle, both floors (**1**) - 4 XB in Y-corners, 2 in X-middle, both floors (**3**)

Fig. 3. Models analysed in the sensitivity analysis.

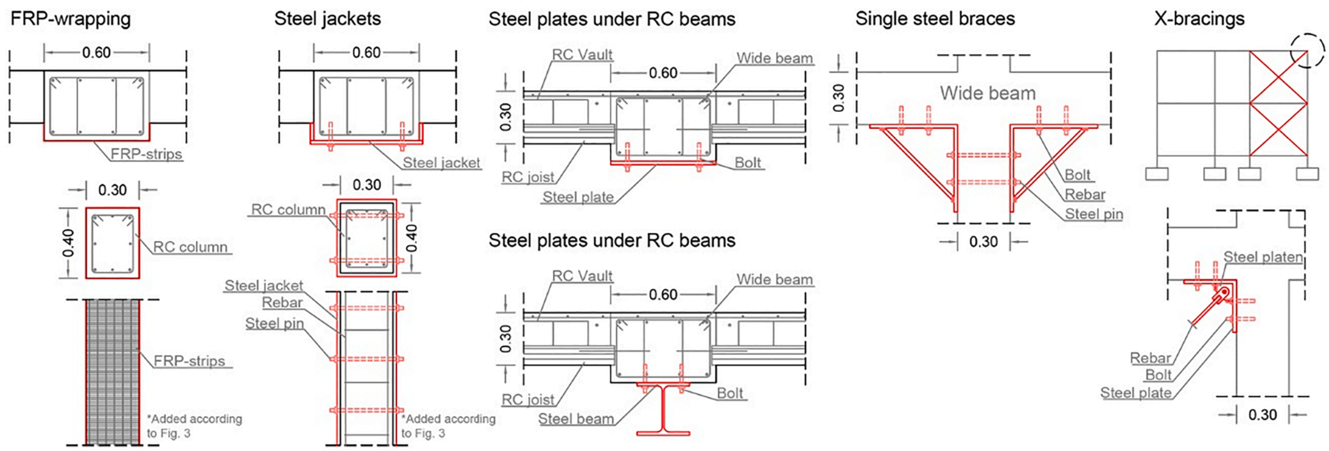

Fig. 4. Constructive details of the retrofitting solutions proposed.

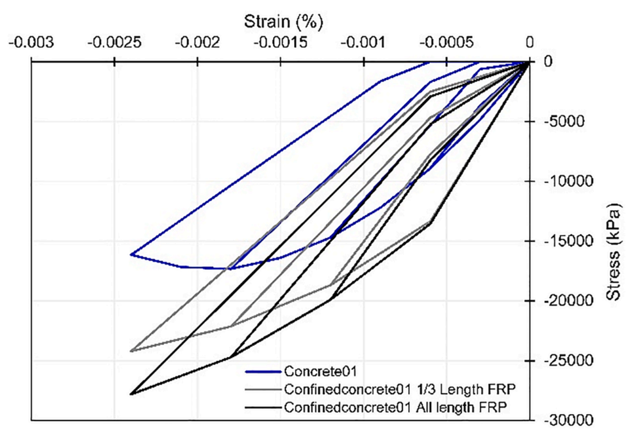

Fig. 5. Stress–strain diagram for the materials considered.

3.2.3.2. Steel jacketing of columns. The addition of steel jackets was performed by using the "ConfinedConcrete01" uniaxial material. The thickness of the jackets was 5 mm. The width was the same as the column's dimension. They were added in every face of the retrofitted column.

3.2.3.3. Steel beams and plates under RC beams. The steel beams and plates were simulated by using the same uniaxial material. The width was the same as the base of the beam. The plates' thickness was 5 mm. The size of the beam was HEB-300. They were added in one or both of the building's directions.

3.2.3.4. Single steel braces. This technique was simulated by adding trusses of Ø16 mm. The trusses form 45° with the beam-column joints and are separated at least 30 cm from the RC elements. The truss considers strain-rate effects and is thus suitable for use as a damping element. They were added in both X and Y directions following the most optimal configurations which resulted in [37].

3.2.3.5. Steel X bracings in bays. The steel braces were added within the bays according to the results obtained in [37]. Truss elements were used to model the Ø16 mm braces.

3.3. Benefit/cost ratio

To analyse the suitability and efficiency of each solution, a benefit/cost ratio (*BCR*) was calculated taking into account the ductility improvement and the damage reduction with regards to the retrofitting costs. The results obtained for the upgraded and the existing building were compared to determine the most optimal configuration similar toTrapani et al. [44]. The BCR was obtained according to Eq. (1).

$$BCR = \frac{B}{C} = \frac{\frac{q_i}{q_{initial}} + \frac{\mu_i}{\mu_{initial}} + \frac{\delta_{demand}}{\delta_i}}{\frac{C_i}{C_{\text{most expensive}}}} \tag{1}$$

The benefit (*B*) of each model retrofitted was assessed by obtaining the enhancement of the ductility and the reduction of the seismic damage. For the first aspect, the ratio between the *q*-factor and μ-factor obtained for the retrofitted (*i*) and existing building (*initial*) was calculated. For the second aspect, the ratio between the displacements (δ) obtained for the failure of the initial ($\delta_{\text{initial-failure}}$) or the retrofitted solution ($\delta_{\text{i-failure}}$) and corresponding to the seismic demand (δ_{demand}) was calculated. The δ_{failure} is the displacement corresponding to the SD limit state. The criteria followed in the determination of the seismic safety is presented in Section 3.2.2.

The cost (*C*) of each solution was determined by a normalised ratio. This was defined as the ratio between the construction costs calculated for each retrofitted model (C_i) and the costs obtained for the most expensive solution ($C_{\text{most expensive}}$). The construction costs were assessed by means of a detailed measurement of a bill of quantities. An updated Spanish construction cost database was used [16]. This database bears in mind the costs of the materials, the labour and indirect costs, the construction duration and the industrial benefit.

4. Results

Prior to the addition of the retrofitting solutions, the weakest or first damaged vertical elements were identified (Fig. 6) according to the seismic safety assessment (Section 3.2.2). This was carried out in order to determine the most suitable position of the retrofitting elements for the FRP, SJ, SB, SP and VB solutions.

Once the retrofitting elements were added, the different models were assessed by means of nonlinear static analyses as mentioned in Section 3. The single-degree-of-freedom (SDOF) capacity curves obtained for each configuration are shown in Fig. 7. They were normalised; i.e., the base shear force (V_b) was divided by the weight (*W*) of the building and the top displacement (*d*) was divided by the total height of the building (H_t).

After assessing each configuration, the benefit was determined in terms of the *q*-factor, the μ-factor and the displacement enhancement. The average X and Y values for each parameter were considered to determine the benefit. Then, the construction costs of each solution were calculated to finally obtain the BCR of each configuration. The results of the analyses are summarised in Table 5. Also, the fundamental periods in the X and the Y directions have been listed. It should be mentioned that

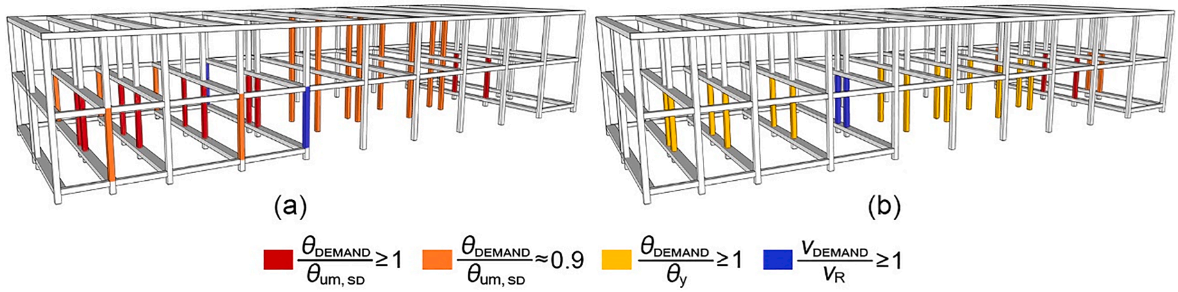

Fig. 6. Damaged vertical elements for the initial configuration in the X (a) and Y (b) directions.

for the initial configuration, the fundamental periods for the SDOF system (T^*) have been 0.23 and 0.20 in the X and Y direction, respectively. For all the models (retrofitted and un-retrofitted), the mode of vibration 1 corresponds to the X-direction and the mode 2 to the Y-direction.

In Fig. 8, the benefit and the cost of each retrofitting configuration shown in Table 5 are plotted.

To obtain a clear picture of the effects of just retrofitting the structural elements in the first and second floors, the deformed shape in the Y direction has been shown in Fig. 9. The initial configuration considering the highest benefit (highest benefit) (29_XB_3) has been selected.

In Fig. 10, the damaged vertical elements for the 29_XB_3 configuration have been shown in order to compare the results.

5. Analysis of the results

According to the damage obtained for the initial configuration (Fig. 6), the columns located in the centre of the frames (10 columns) will collapse due to flexure in the X direction. In the Y direction, they will yield or collapse due to shear. This is mainly due to the soft storey mechanism located in the centre of the building. As seen in Fig. 11, the columns located in the interior part of the building (left part) present more stiffness due to the configuration of the structure. Although their displacement is lower, they are subjected to additional torsional forces due to the "unconfinement" of the soft-storey columns. Therefore, these columns behave worse than the rest, being the first to be retrofitted. The next group of columns to be retrofitted are those located in the soft-storey mechanism.

It should be mentioned that the capacity of the initial configuration was higher in the Y direction of the building. This is due to the greater number of RC frames in this direction. Moreover, the capacity curves show the effects of the infills. In the case of the X direction, the capacity was lower and the infills have not considerably improved it due to the large number of openings in this direction.

In the light of the results, it is evident that, to some extent, the retrofitting solutions assessed can improve the seismic performance of RC buildings. However, this improvement can be more or less significant depending on the position, the amount and the properties of the retrofitting elements. This is also related to the values of the fundamental periods, which have been reduced when adding the retrofitting elements and materials up to 30%.

Concerning the results of the nonlinear and seismic safety analyses, interesting aspects arise when comparing the retrofitted and the non-retrofitted models. FRP–wrapping has been one of the solutions with better benefit ratios, performing better than its most similar solution, i.e., adding steel-jackets. These improvements have been up to 37%, 58% and 46% for the ductility factors and damage reduction, respectively. Despite these high ratios, if considering the costs, this retrofitting solution has resulted the most expensive one. In fact, if more than 50% of the columns are retrofitted (reinforcing a 1/3 or the entire length of the structural elements), the configurations are not optimal. This can be easily observed in Fig. 8; solutions 5, 6, 8 and 9 present the highest cost ratios. It should be mentioned that for three configurations, some columns will collapse in the X direction before the seismic demand requirement. These solutions are those when only 25% of the structural elements have been retrofitted. In the Y direction, the improvement is outstanding, obtaining target displacements near the DL limit state.

Similar results for the capacity curves of the addition of steel-jackets have been obtained but with worse improvement percentages. They have not been higher than 26%, resulting in the worst benefit percentages. Despite the improvement of the initial stiffness compared to the previous solution, this is not enough to obtain higher percentages of improvement. This scheme is cheaper than the FRP-wrapping, leading to higher BCRs when retrofitting more than 50% of the elements. It has been observed that no significant differences can be found when retrofitting just a 1/3 or the entire length of the structural elements. This is due to the fact that the beam-column joints play a key role in the resistant capacity of the RC buildings. This aspect is also observed in the addition of FRP-wrappings.

The addition of steel plates (SP) and beams (SB) under the RC beams has resulted in the lowest reduction of the damage (in some cases just 5%). However, the ductility has been improved considerably. This leads to higher benefit ratios, which are not enough to obtain high BCRs. The unnoticeable reduction of the considerably damage affects the BCR, making these configurations not very optimal. Adding steel beams has been more beneficial but when considering the costs, the addition of steel plates has resulted more optimal since it is cheaper. Similar results have been obtained when adding both retrofitting elements in 25%, 50% and all the RC beams.

Adding single braces (VB) in columns has led to higher percentages of ductility, obtaining higher damage reduction (up to 98%) and benefit improvement (up to 37%) percentages. However, these solutions are expensive since a considerable amount of working hours and material are needed to properly connect the retrofitting element with the RC structure. Moreover, no significant differences have been found when adding the retrofitting elements in both floors. In fact, the results worsen. Nevertheless, the non-invasive technique has obtained the highest benefit improvement.

The addition of X-bracings, as expected, has resulted in the highest benefit improvement. The ductility has been enhanced by up to 53% and the damage reduced by up to 300%. Moreover, this solution has been the cheapest, leading to the highest BCRs. This has been obtained for configuration number 28, which added X-bracings only in the X-direction (worst direction). However, the most beneficial solution has been number 29, which also added X-bracings in the Y direction.

By analysing the deformed shape of the models in detail, it can be observed that the short columns located on the ground floor behave worse if retrofitting elements are added in the floors above. This effect can be seen in Fig. 9. The short columns are subjected to additional rotation effects and shear forces. In fact, the columns located in the middle of the span (not confined) will collapse due to both shear and flexural failure as plotted in Fig. 10. Moreover, the fragile failure occurs in very early steps of the capacity curves. This is related to the failure of these short columns. In some cases, when adding the retrofitting

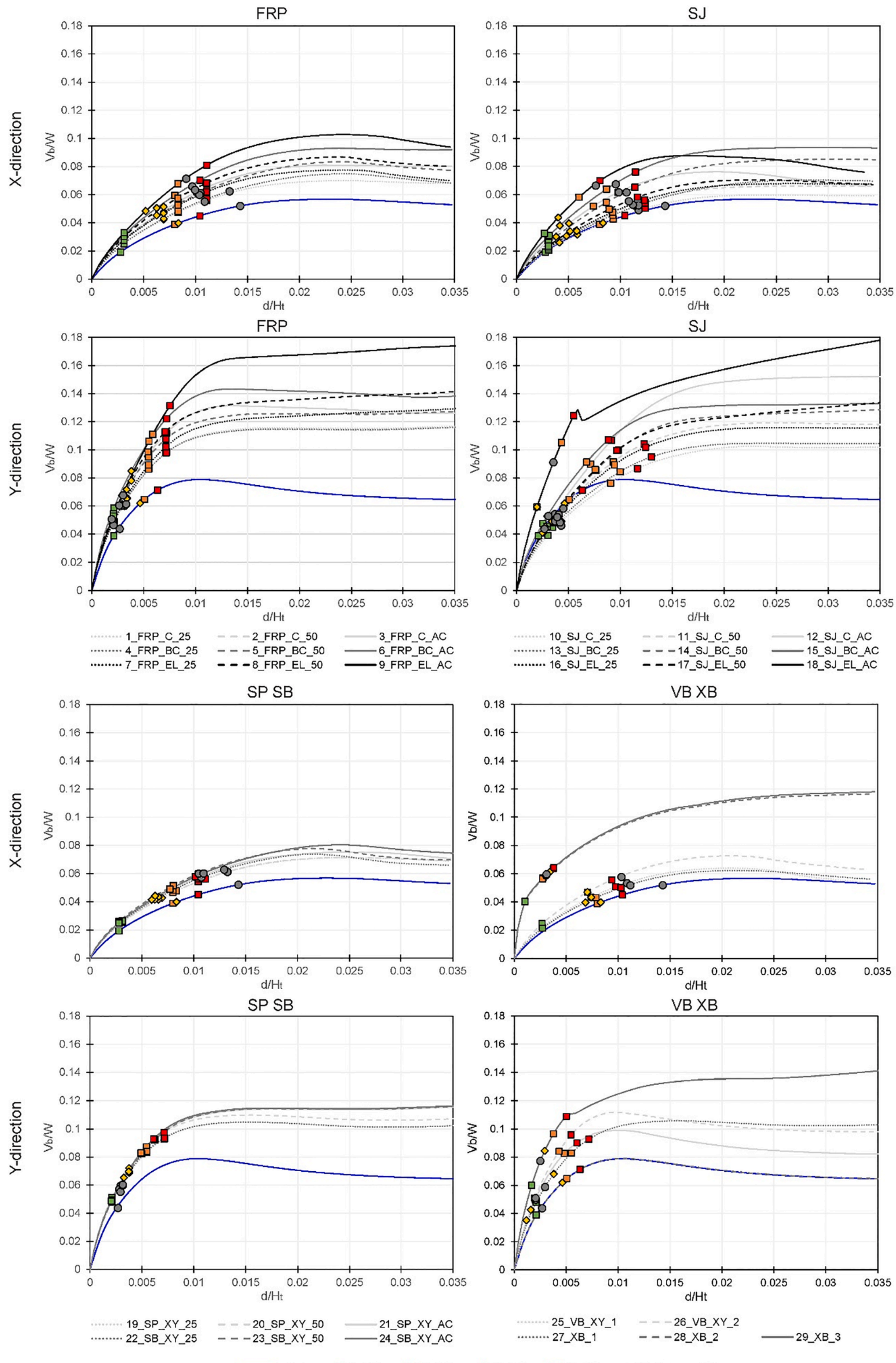

Fig. 7. SDOF capacity curves of each retrofitting configuration, highlighting the existing building capacity and plotting the seismic demand and the failures for each damage limit state.

Table 5
Fundamental periods, q-factor, μ-factor and δ enhancement, construction costs and BCR of each configuration.

N°	Model	T^* (s)		Benefit				Cost		BCR
		X	Y	$q_i/q_{initial}$	$\mu_i/\mu_{initial}$	$\delta_{failure}/\delta_{demand}$	B	€	C	
1	FRP_C_25	0.22	0.20	1.24	1.29	1.21	3.74	5,006	0.02	203.46
2	FRP_C_50	0.20	0.18	1.30	1.37	1.28	3.95	10,012	0.04	107.31
3	FRP_C_AC	0.19	0.18	1.30	1.58	1.39	4.27	20,025	0.07	58.06
4	FRP_BC_25	0.19	0.19	1.24	1.25	1.03	3.52	42,699	0.16	22.46
5	FRP_BC_50	0.19	0.18	1.24	1.25	1.27	3.76	85,399	0.31	11.98
6	FRP_BC_AC	0.19	0.18	1.37	1.56	1.46	4.39	170,798	0.63	6.99
7	FRP_EL_25	0.20	0.18	1.23	1.17	1.24	3.64	68,047	0.25	14.57
8	FRP_EL_50	0.20	0.18	1.22	1.16	1.31	3.70	136,094	0.50	7.40
9	FRP_EL_AC	0.19	0.17	1.25	1.10	1.45	3.80	272,189	1.00	3.80
10	SJ_C_25	0.19	0.18	1.13	1.16	1.06	3.34	4,771	0.02	190.59
11	SJ_C_50	0.18	0.17	1.10	1.14	1.13	3.36	9,350	0.03	97.92
12	SJ_C_AC	0.18	0.16	1.25	1.08	1.26	3.59	14,652	0.05	66.62
13	SJ_BC_25	0.18	0.18	1.08	1.08	1.07	3.22	12,319	0.05	71.13
14	SJ_BC_50	0.18	0.17	1.21	1.05	1.16	3.41	26,376	0.10	35.24
15	SJ_BC_AC	0.16	0.15	1.23	1.21	1.35	3.78	50,810	0.19	20.27
16	SJ_EL_25	0.19	0.17	1.09	1.12	1.12	3.34	19,576	0.07	46.37
17	SJ_EL_50	0.18	0.17	1.14	1.01	1.11	3.26	42,911	0.16	20.69
18	SJ_EL_AC	0.19	0.17	1.29	1.11	1.52	3.91	83,471	0.31	12.76
19	SP_XY_25	0.19	0.18	1.25	1.43	1.05	3.73	18,569	0.07	54.67
20	SP_XY_50	0.18	0.17	1.26	1.43	1.06	3.76	37,138	0.14	27.53
21	SP_XY_AC	0.18	0.16	1.28	1.28	1.22	3.78	74,277	0.27	13.85
22	SB_XY_25	0.18	0.17	1.27	1.45	1.07	3.78	38,872	0.14	26.50
23	SB_XY_50	0.18	0.17	1.29	1.29	1.22	3.80	77,745	0.29	13.30
24	SB_XY_AC	0.16	0.15	1.30	1.25	1.21	3.75	155,490	0.57	6.57
25	VB_XY_1	0.19	0.18	1.41	1.98	1.31	4.70	31,117	0.11	41.07
26	VB_XY_2	0.18	0.17	1.47	1.82	1.37	4.66	62,235	0.23	20.37
27	XB_1	0.18	0.16	1.27	1.48	1.20	3.95	11,201	0.04	95.96
28	XB_2	0.18	0.17	1.38	1.21	2.94	5.53	5,377	0.02	280.07
29	XB_3	0.18	0.17	1.53	1.25	3.01	5.79	16,579	0.06	95.05

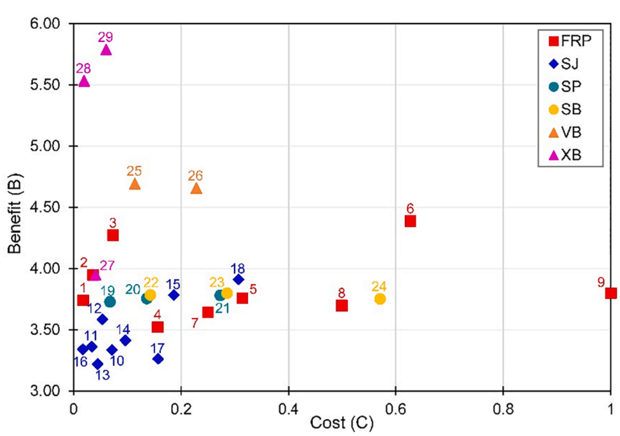

Fig. 8. Benefit and cost of each retrofitting configuration considered.

elements on the second floor, the results have been worse; such is the case of solutions 25 and 26, which added single braces. This effect is generated by the increasing of the stiffness of the rest of the floors but not considering the short-columns' irregularity.

6. Conclusions

In this paper, the enhancement of the ductile response behaviour of RC framed buildings considering different non-invasive retrofitting techniques has been assessed. In order to analyse the suitability and efficiency of each solution, a benefit/cost ratio has been calculated taking into account the ductility improvement and the damage reduction with regards to the retrofitting costs.

The main strengths of this paper are: (i) specific modelling of the retrofitting elements considering the FEM; (ii) the evaluation of the solutions has been calculated by means of a benefit-cost ratio that bears in mind different parameters rather than just only the damage reduction: the displacement ductility and the behaviour factors enhancement; (iii) the seismic safety verification has been carried out according to specific

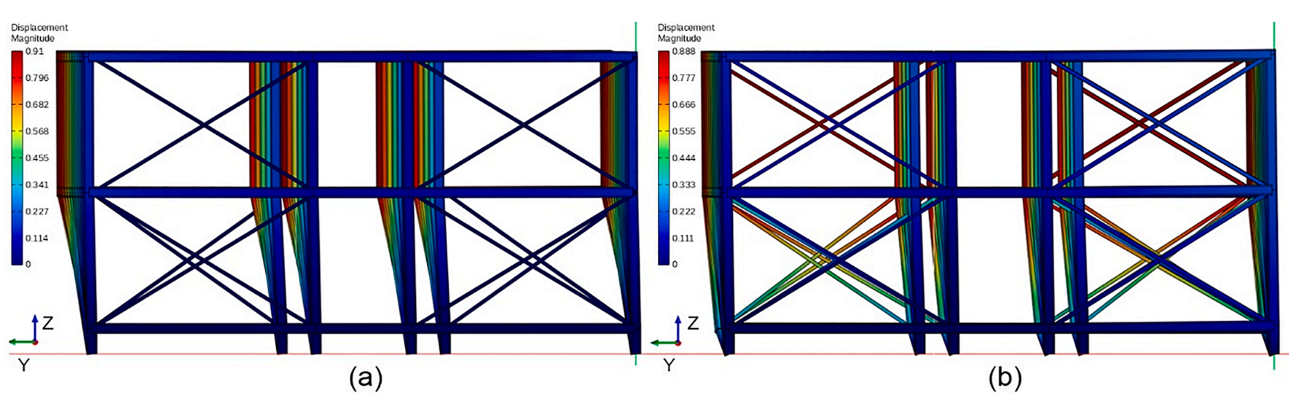

Fig. 9. Displacement in the Y direction for the initial (a) and 29_XB_3 (b) configurations.

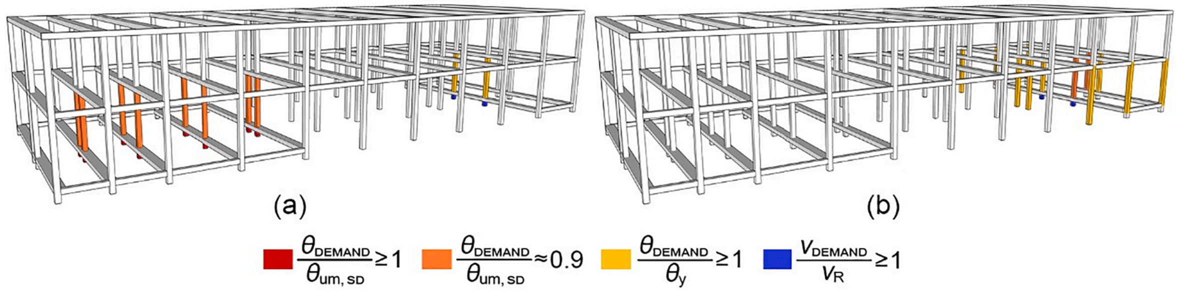

Fig. 10. Damaged vertical elements for the 29_XB_3 configuration in the X (a) and Y (b) directions.

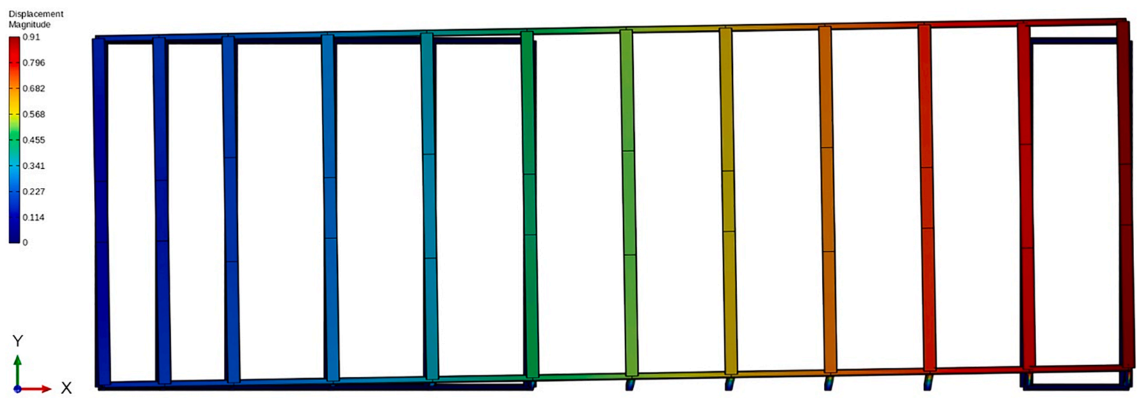

Fig. 11. Deformed in-plan shape of the initial configuration applying load pattern in the Y direction.

requirements established in EC8; (iv) the local damage of the vertical structural elements has been determined; (v) unlike the rest of studies on the seismic retrofitting of RC buildings, the shear failure has been considered and calculated; (vi) a detailed measurement of the construction costs of each configuration has been carried out.

The main contributions of this paper are:

- The results of this study have demonstrated that, to some extent, the retrofitting solutions assessed can improve the ductile response and seismic performance of RC buildings.
- The values of the fundamental periods have not varied considerably. As expected, owing to the increase of the stiffness of the system when adding the retrofitting elements, the fundamental periods have been reduced up to 30%.
- Adding FRP-wrapping in the structural elements has performed well if no more than 50% of them are retrofitted due to its high construction costs.
- The steel-jacketing of RC structural elements has been quite optimal due to its low construction costs. However, regarding the benefit, only a minor improvement has been obtained.
- The steel plates and the beams under the RC beams have produced a negligible reduction of the seismic damage, leading to worse BCRs. No significant differences have been found when adding both retrofitting elements in 25%, 50% and all RC beams.
- Adding single braces in columns has been the non-invasive technique that has obtained the highest benefit improvement, i.e. highest ductility improvement and damage reduction. However, these percentages have been similar when they have been added in just one or in both floors.
- No significant differences have been found when retrofitting just a 1/3 or the entire length of the structural elements. This is due to the fact that the beam-column joints play a key role in the resistant capacity of RC buildings. In fact, solutions that aimed to improve the stiffness of the joints have led to higher improvement percentages.
- Specific analyses should be carried out to determine the worst behaving direction of the building to find out the most optimal retrofitting configuration.
- Some solutions present higher ductility improvement than others. However, it has been proved that enhancing the ductility leads to higher damage reduction, resulting in configurations that are more beneficial.
- Cost-effectively analyses optimise the seismic retrofitting of buildings since they take into account the downtime of costs and control the safety levels.
- Not considering the irregularity of the building and just increasing the stiffness of the rest of the floors has resulted in additional rotation effects and shear forces that affect the short-columns located on the ground floor. Further research and case study testing are surely needed to address, among other aspects, the development of retrofitting techniques and effective design optimisation space restriction techniques that bears in mind the complete behaviour of the building.

CRediT authorship contribution statement

Maria-Victoria Requena-Garcia-Cruz: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Supervision, Validation, Visualization, Writing - original draft, Writing - review & editing. **Antonio Morales-Esteban:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Writing - review & editing. **Percy Durand-Neyra:** Conceptualization, Formal analysis, Methodology, Supervision, Validation, Writing - review & editing.

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.

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