Seismic design of RC frames retrofitted with concentric steel braces

R. Sousa
European Centre for Training and Research in Earthquake Engineering (EUCENTRE), Pavia, Italy

J.M. Castro
Faculty of Engineering, University of Porto, Portugal

ABSTRACT: The implementation in Europe of a new seismic design code (Eurocode 8) will impose strict performance requirements to building structures. This will result in a significant number of existing reinforced concrete structures showing inadequate seismic resistance and hence requiring intervention. One of the available retrofitting techniques consists of inserting steel braces in the original RC structure. In spite of the advantages of using this retrofitting approach, the adoption of this technique is still limited due to the lack of seismic design rules. The interaction between the steel braces and the RC members turns the design in an intricate task. The main goal of the research presented in this paper was to develop a simple yet reliable design procedure that can promote the retrofitting of reinforced concrete frames with steel braces. The proposed method is based on displacements and accounts for the interaction of the steel elements on the deformation capacity of the RC members. To this end, nonlinear static and time-history analysis of reinforced concrete structures strengthened with concentric steel braces have been performed with the objective of deriving a number of key parameters (displacement profiles, yield drifts and target displacements) which are essential for the application of the new design procedure. The paper closes with an application of the proposed method to a RC structure with inadequate seismic resistance. The performance assessment of the retrofitted structure, carried out with nonlinear static analysis, confirms the validity of the design procedure and demonstrates the merits of adopting displacement-based seismic design approaches.

1 INTRODUCTION

Recent seismic events induced severe damage to non-ductile reinforced concrete (RC) buildings proving that many constructions located in seismic zones are unable to withstand moderate to severe earthquakes.

Framed systems are extensively used for building structures in earthquake-prone regions because of their potential for good seismic performance. However, many existing RC structures worldwide were designed for gravity loads only, having therefore inadequate lateral load stiffness and resistance. The assessment and retrofitting of these structures is, thus, urgent.

Global intervention methods may represent a more cost-effective strategy than upgrading of the existing components, especially if the disruption of occupancy and the demolition and replacement of partitions, architectural finishes and other non-structural components are considered (Fardis 1998). This is particularly true for structures where no horizontal load path is available, or in the case of all structural members being extremely flexible. In such cases the methods described above may result in an efficient solution (Pinho 2000).

Traditionally, steel bracing systems have been used to increase the lateral load stiffness/resistance of steel structures. In the past two decades, a number of reports have also indicated the effective use of steel bracing in RC frames (e.g., Youssef et al. 2007, Badoux & Jirsa 1990). Steel bracing of RC buildings started as a retrofitting measure to strengthen earthquake damaged buildings or to increase the load resisting capacity of existing buildings (Maheri et al. 2003).

Increased architectural flexibility, reduced weight of the structure, easy and speed of construction and the ability to choose more ductile systems can be considered as the main advantages of steel bracing in comparison with strengthening based on the inclusion of RC shear walls (Maheri & Ghaffarzadeh 2008).

Despite the several experimental and analytical studies conducted in the last years aiming to understand the behaviour of this type of hybrid structures (Maheri & Sahebi 1997, Badoux & Jirsa 1990), the fact is that only a few have resulted in the proposal of values for the so call behaviour factor to be used in the design process. Moreover, due to the scatter of results, the values obtained in past works do not provide enough confidence to achieve an effective solution.

The aim of the present work is thus to develop a displacement-based design (DBD) procedure for the seismic retrofitting of RC frames with steel braces that overcomes the limitations with traditional force-based design (FBD) procedures. The methodology to be proposed should be simple and easy to apply by the designer, but should produce reliable structural solutions. Moreover, it should take into account the complex interaction between the steel braces and the RC elements.

2 SEISMIC BEHAVIOUR OF HYBRID SYSTEMS

2.1 *Design approaches*

Despite the potential for good seismic behaviour of steel braced RC frames, there is still a lack of design rules for hybrid structures in seismic codes. In order to overcome this situation, several studies (e.g. Maheri & Akbari 2003, Queirós 2009) were conducted with the objective of deriving values of the behaviour factor (q), also known as response modification factor (R), to be adopted in FBD methodologies.

However, due to the changes in the global structural behaviour introduced by the steel braces, the improvement of the seismic behaviour may not be, for certain types of braces, proportional to the increase of lateral strength of the structure.

Moreover, the values of q proposed by different researchers are not entirely consistent due to the relatively complex interaction between the RC members and steel braces. For this reason, it becomes apparent that the seismic design of this type of structures should be carried out focusing on deformation rather on strength control.

Di Sarno & Manfredi (2009) stated that the new bracing system should be designed to absorb and dissipate large amounts of hysteretic energy under earthquake ground motion, at the same time that the original RC system should be capable to withstand the vertical loads and respond elastically under the earthquakes loads. In the present study, however, for economical and structural reasons, it is considered that the original RC system should still be allowed to undergo inelastic deformations.

2.2 *Interaction between the steel braces and the RC frame*

Several studies demonstrated that the lateral stiffness and strength of a hybrid steel braced RC frame results from the contribution of the two lateral resisting systems working independently (Badoux & Jirsa 1990, Di Sarno & Manfredi 2009).

A typical pushover curve of a RC structure retrofitted with concentrically steel slender braces is illustrated in Figure 1 (Queirós 2009). As expected, the onset on nonlinear behaviour of the hybrid structure corresponds to the occurrence of buckling in the first storey brace. However, due to the relatively low contribution of the compressive braces to the lateral resistance, particularly in cases where slender braces are adopted, it is possible to confirm from Figure 1 that the global yield displacement of the structure occurs when the first storey brace yields in tension.

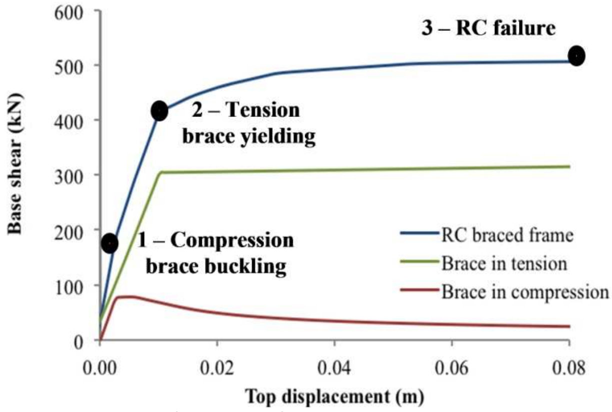

Figure 1. Identification of yield displacement on steel braced RC frames (adapted from Queirós 2009).

Della Corte & Mazzolani (2008) demonstrated that, for cases with stockier braces, the transition from buckling to ultimate state is not as smooth as that illustrated in Figure 1.

With regard to the behaviour of the RC members of the retrofitted structure, Sousa (2010) concluded that the column axial load at the base of the structure can be well estimated by adding the axial load in the original structure with that resulting from the vertical components of the braces assuming that, over the height of the structure, all tensile braces are in the yield state.

Despite the increases of stiffness and strength resulting from the introduction of braces, it is important to note that the increase in brace capacity leads to an increase of the axial forces in the columns. This effect results in a reduction of the column’s deformation capacity and hence, it is possible that a given solution adopted for the braces may lead to premature failure of the RC columns. Thus, since the ultimate displacement of the structure is typically governed by column deformation capacity, it is of critical importance that the design method used in the retrofitting process is able to relate the brace capacity with the deformation capacity of the RC columns.

2.3 *Lateral displacement profiles*

The lateral deformation profile is an important parameter to use in design/assessment procedures relying on equivalent linearization.

Previous analytical studies on hybrid RC-steel structures (e.g., Pincheira & Jirsa 1995) showed that the displacement shapes of this type of structures were relatively uniform and that the storey drifts varied smoothly over the height of the buildings.

Several authors proposed expressions to describe the lateral deformation of building structures (e.g. Priestley et al. 2007). However, most of those expressions have been proposed for RC structures and are generally dependent only on the number of floors.

In a recent numerical study, Sousa (2010) analysed the behaviour of a 1-bay 3-storey RC frame designed for gravity loads according to the current European design provisions for RC structures (CEN 2004). The structure was retrofitted with steel braces with two different values of normalised slenderness ($\bar{\lambda}$ = 2.0 and $\bar{\lambda}$ = 3.0). The retrofitted frames were analysed in the nonlinear finite element software OpenSEES (PEER 2006) under the action of eight earthquake records selected from the PEER NGA database (PEER 2009). For consistency, the ground motions for the analysis had mean period (T_m) values between 0.5 and 0.6s, representative of an intermediate group proposed in the work of Kumar et al. (2010). The deformed shape of the two frames was obtained for two different deformation levels: i) first 'yielding', corresponding to the buckling of the compressive brace located at the first storey, ii) incipient failure of the structure, corresponding to the attainment of the maximum deformation capacity of the most critical RC column in the structural system.

The results obtained were compared with existing expressions for RC structures (Priestley et al. 2007). It was observed that the use of steel braces imposes a higher control of the displacements over the height of the building. Consequently a new expression has been proposed, as follows:

$$\delta_i = \frac{4}{3} \times \left(\frac{H_i}{H_n}\right) \times \left(1 - \frac{H_i}{2.25 \times H_n}\right) \qquad (1)$$

Where δ_i is the lateral displacement of the *i-th* floor, H_i is the height of the floor and H_n it the total height of the structure. It must be emphasized that the expression was validated only with the results obtained for the two frames considered in the study and hence there is a need to conduct additional analysis with different braces (layout and/or strength) and for taller systems.

3 PROPOSAL OF A DESIGN METHOD FOR STEEL BRACED RC FRAMES

3.1 *Basis of the method*

It has been demonstrated that the introduction of steel braces in a RC structure leads to the modification of the behaviour of the original RC system, namely in terms of lateral strength and deformation capacity. Thus, a strategy based on the equivalent linearization approach adopted by the Capacity Spectrum Method (Freeman 1998) appears to be a rational approach for the proposed methodology.

The main idea behind the proposed method is the estimation (without any structural analyses) of the performance of the structure retrofitted with different brace properties or bracing layout.

The main objective of the method is to find the most optimal bracing solution that ensures that the deformation demand imposed on the structure does not lead to failure of the most critical RC element. Focusing on Figure 2 it can be observed that the addition of steel braces, despite modifying the global behaviour of the structure, does not always provide a suitable retrofitting solution. Consequently, in order to define a bracing solution that ensures a given performance level, several brace properties and/or layout need to be evaluated.

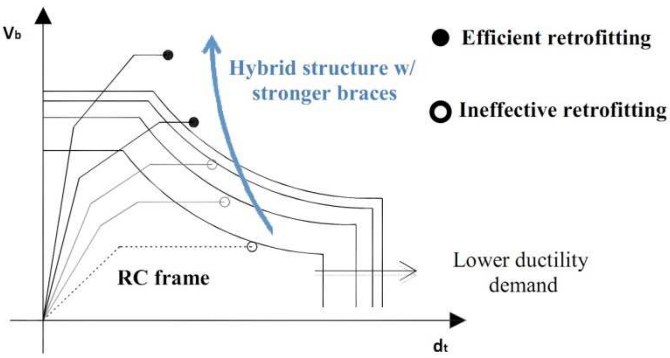

Figure 2. Graphical interpretation of the proposed design methodology based on the Capacity Spectrum Method.

Based on the capacity curve of the original RC structure and on a set of different brace properties and bracing layout, and by employing the proposed methodology, the designer can accurately estimate the performance of the structure (pairs of ultimate displacements-base shear values) without the need to perform several numerical analyses for different bracing configurations.

3.2 *Description of the method*

The proposed method comprised the seven steps described below:

1. Nonlinear static (or pushover) analysis of the RC structure to obtain the capacity curve.
2. Pre-selection of steel brace properties and bracing layout for evaluation of the axial load

installed in the RC columns at the ultimate limit state. The selection is carried out such that the predicted additional axial load together with the static axial load does not lead to premature column failure.

3. Estimation of the yield displacement (Δ_y) using the following expression:

$$\Delta_y = \sqrt{\left(L_i + \frac{N_t \times L_i}{E \times A}\right)^2 - h^2} - b \quad (2)$$

Where L_i is the initial length of the diagonal brace, N_t is the brace tensile capacity, E is the Young modulus, A is the cross-sectional area of the steel brace, h is the storey height and b is the bay length. Further details on the derivation of the above expression can be found in Sousa (2010).

4. Determination of the ultimate displacement (Δ_u) of the structure. This step is performed assuming that the ultimate displacement is governed by the attainment of the maximum deformation capacity of the most critical RC member, typically a base column. For this purpose, an estimate of the additional axial load in the column imposed by the braces (for all combinations of braces and layout) is required. As mentioned before, it is acceptable to assume that at ultimate limit state all the braces reached yield in all the bays over the height of the structure. The ultimate displacement is obtained by calculating the chord rotation capacity of the RC elements based on the calculated values of axial load. With the chord rotation capacity of the critical element, the column drift can be conservatively estimated as being equal to its chord rotation capacity (Mpampatsikos et al. 2008). Note that if shear capacity is limited, additional strengthening, other that steel bracing needs to be considered.
5. Estimation of the lateral strength (V_b) of the hybrid structure as the summation of the base shear of the original RC frame, corresponding to the ultimate displacement calculated in the previous step, with the horizontal component of the tensile capacity of the braces located at the first storey. In this step, the capacity developed by the braces in compression is conservatively neglected.
6. Evaluation of the equivalent viscous damping (EVD) based on the estimated ductility calculated with the yield and ultimate displacements obtained in steps 3 and 4. It must be pointed out that there is not a specific expression available for steel braced RC frames. In this work, and for the sake of simplicity, an expression proposed by Priestley et al. (2007) for RC frames will be adopted:

$$\xi_{eq} = 0.05 + 0.565 \times \left(\frac{\mu - 1}{\mu \times \pi}\right) \quad (3)$$

7. Selection of the most suitable retrofitting solution. This final step requires the conversion of the base shear (V_b), yield and ultimate displacements in parameters of an equivalent SDOF system. This is carried out with the aid of the expression proposed before for the lateral displacement profile. Following that, the damping spectra based on the ductility of each bracing solution consideration is also obtained. All the data is then plotted in the format of an acceleration-displacement response spectrum (ADRS). From this plot, points representing ultimate displacements and corresponding base shears are identified for each retrofitting solution. The acceptability of each bracing solution can be evaluated through comparison of the location of each point in relation to the associated damping spectrum.

4 VALIDATION OF THE PROPOSED METHOD

4.1 *Structure characterization and seismic scenario*

The accuracy of the method will be evaluated through an application to a typical RC building requiring seismic retrofitting. The building considered is a 3-storey, 5-bays RC structure with 4m spacing between frames. The structure represents a building with inadequate seismic resistance in which the elements were only designed for gravity loads according to Eurocode 1 (CEN 2002) and Eurocode 2 (CEN 2004). The dead load considered was 9 kN/m^2 whilst the imposed load was assumed as 5 kN/m^2. The elevation view of one of the RC moment frames is shown in Figure 3. The cross-sections adopted for the beams and columns are illustrated in Figure 4.

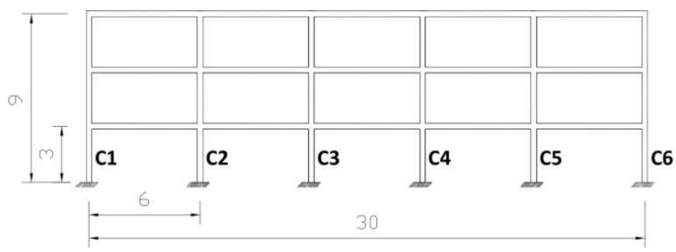

Figure 3. RC frame layout.

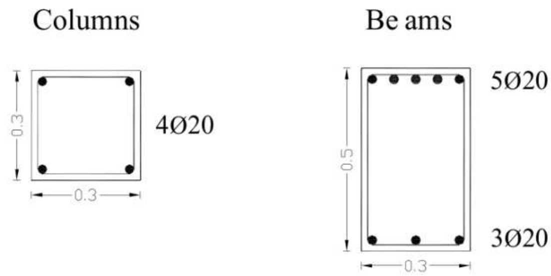

Figure 4. Beam and column cross-sections.

In order to assess the seismic performance of the original RC structure, it is fundamental to define the seismic hazard scenario for the site in which the structure is located. For the purpose of this study the seismic action prescribed in Eurocode 8 (CEN 2004) is considered. The elastic response spectrum adopted is that proposed for seismic action Type 1. Moreover, it is assumed that the structure is founded on a soil of type B according to EC8 and that the reference peak ground acceleration (a_g) is taken as $1.3 m/s^2$.

4.2 *Seismic assessment*

For the sake of simplicity, the assessment of the original RC structure is carried out by applying the Capacity Spectrum Method (CSM). As shown in Figure 5, the bilinear curve does not intersect the response spectrum for the corresponding equivalent viscous damping compatible with the ductility capacity of the structure. This means that a performance point cannot be determined and hence that the structure is not able to resist the design earthquake.

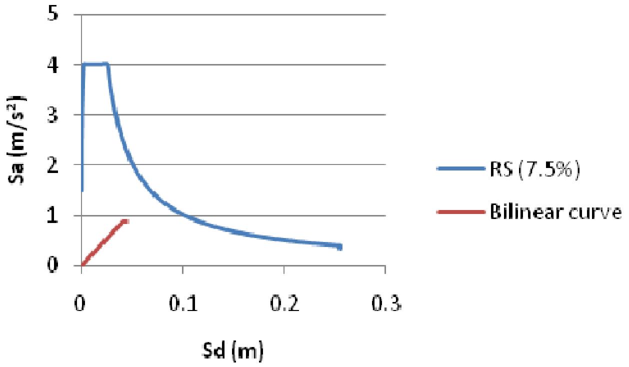

Figure 5. Seismic assessment applying the CSM.

4.3 *Design of the retrofitting solution*

In order to retrofit the structure, three different bracing layouts with constant brace properties over the height of the building are considered (Figure 6).

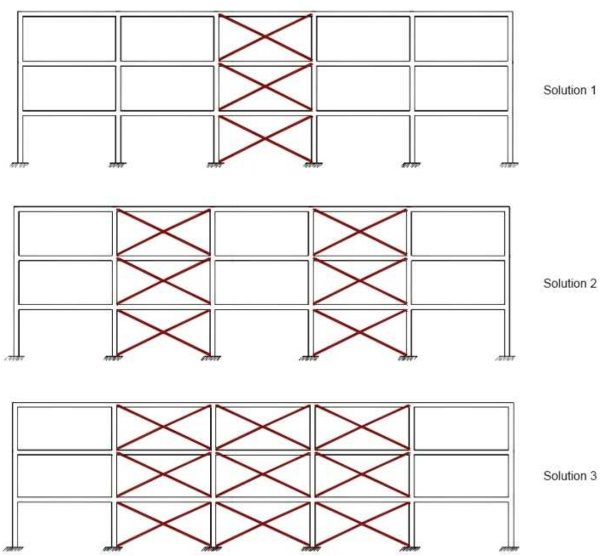

Figure 6. Three bracing configurations (Solutions 1, 2 and 3).

Moreover, five different brace properties were selected and tested for each bracing layout illustrated in the previous figure. The main properties of the steel braces are presented in Table 1.

Table 1 - Properties of the selected steel braces

Brace ID	Outside diameter	Thickness	Sectional area	Slenderness
	D (mm)	t (mm)	A (cm^2)	$\bar{\lambda}$
Brace 1	76.1	3.2	7.3	3.0
Brace 2	88.9	3.6	9.6	2.6
Brace 3	114.3	3.2	11.2	2.0
Brace 4	139.7	3.2	13.7	1.6
Brace 5	139.7	5.0	21.2	1.7

In order to evaluate if any of the solutions satisfies the seismic requirements, the estimated points corresponding to the ultimate limit state of the hybrid structure are superimposed to the corresponding damped response spectra (Figure 7). It should be noted that, for simplicity, and because the damping values for each steel brace are very similar, only the spectrum with the lowest value of damping is plotted. The colours and marks represent the different bracing elements and layout solutions, respectively. Finally, in order to evaluate the differences in structural behaviour of the retrofitted solutions with respect to the original RC frame, a bilinear representation of the capacity curve of the original structure is also represented.

It must be recalled that the solutions representing a good seismic behaviour are the ones in which the points are outside the area of the corresponding damped response spectra. Although the points do not correspond to performance points for the limit state under consideration, their position outside the damped spectrum, ensures the existence of a performance point in an earlier stage.

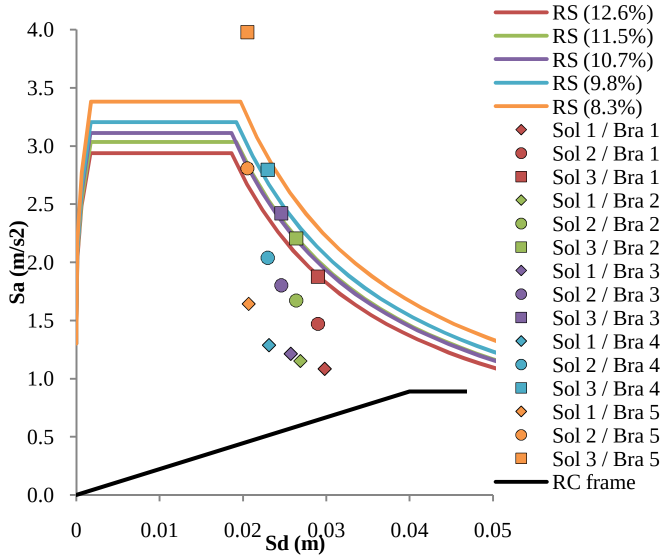

Figure 7. Evaluation of the performance of the different retrofitting solutions.

From Figure 7 it is possible to conclude that only Solution 3 (three braced bays) provides an effective seismic retrofitting for the structure under analysis. From the possible solutions, the use of steel braces other that "Braces 5" is more economical but it is close to the limit of an acceptable seismic performance. On the other hand, if the objective is to develop a solution that mitigates damage, then Solution 3 with "Braces 5" appears to be more advisable.

4.4 *Accuracy of the method*

A pushover analysis of the retrofitted frame (Solution 3 with "Braces 4" and "Braces 5") was performed in order to investigate if the proposed design method produced a reliable structural solution. The results from the pushover analysis along with the representation of the performance point are presented in Figure 8.

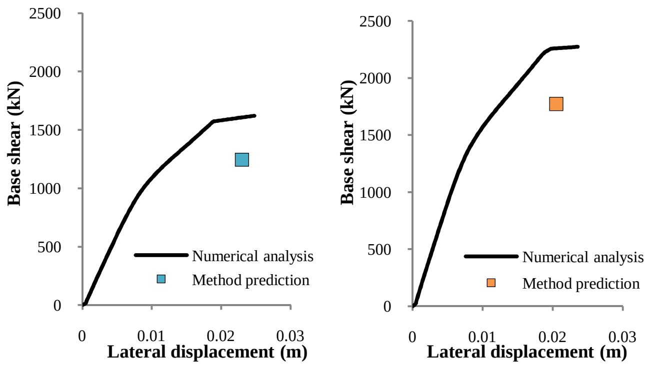

Figure 8. Comparison of the method predictions with a pushover analysis – Solution 3 with "Braces 4" (left) and "Braces 5" (right).

The results confirm that the ultimate points estimated using the proposed method are consistent with the global behaviour of the structure observed in the pushover analysis.

The observed differences are a result of approximations assumed in the design process, namely with respect to the actual load installed in the steel braces. Thus, the lower value of the estimated base shear is a result of neglecting the component of the braces in compression which, in cases of stocky braces, can be relevant. Moreover, the eventual increase in the flexural moment capacity of the RC columns due to the higher level of axial load, with the consequent increase of the base shear, was also neglected. Finally, the lower values obtained for the lateral deformation capacity are the result of assuming that all steel braces, both in compression and tension, were at full capacity in all storeys. This assumption resulted in a conservative (upper) estimate of the axial load installed on the RC columns leading to a reduction in their de-formation capacity.

It should be mentioned that the limitations discussed above could be overcome if the axial loads developed in the braces were evaluated in a more accurate away. For a given ultimate displacement, the lateral frame deformation of the hybrid structure could have been estimated for each storey based on the expression proposed for the lateral displacement profile. With the relative displacement of each storey, the brace axial load could be assessed and hence a more accurate estimate of the axial loads installed in the columns. Nevertheless, the adoption of such an iterative strategy will lead to an additional effort that, based on the accuracy of the results obtained, may not be justifiable.

5 CONCLUSIONS

This paper focused on the seismic retrofitting of RC frames with steel braces. Previous analytical and experimental studies indicated that the application of steel braces in RC frames might significantly improve the performance of RC buildings with inadequate seismic behaviour. In some applications this technique may be more advantageous in comparison with other retrofitting approaches.

One of the main factors that limit the application of this retrofitting technique is the limited design guidance provided by the current seismic codes. In the present work the behaviour of hybrid structures has been analysed in detail. The knowledge acquired, combined with the recent developments in seismic design, namely the Direct Displacement-Based Design method proposed by Priestley et al. (2007), resulted in the proposal of a design approach for the retrofitting of regular RC frames with steel braces. The proposed method is simple, intuitive and easy to use in practical applications. In order to simplify the process, some approximations have been made without jeopardizing the required accuracy inherent to the structural design.

It must be emphasized that despite the proposed method being applicable to any RC moment frame, due to the lack of displacement profiles for taller buildings at this moment its use is recommended only for low-rise structures.

Another issue that can be expected regarding high-rise buildings is related with the predictable development of high levels of axial load in the columns at the lower storeys. To avoid this potential problem, the proposed retrofitting technique can be combined with other types of interventions available for strengthening RC elements (e.g., the use of FRP). On the other hand, since the seismic loads are concentrated at the base of the building and decrease over the height, the retrofitting solution can be optimized by changing the brace strength based on the expected seismic demand.

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