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A Displacement-Based Design Procedure for Seismic Retrofitting of Reinforced Concrete Frames using Braced Ductile Shear Panels

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Abstract

This paper presents some results of numerical investigations carried out on a new dissipative bracing system for seismic retrofitting of reinforced concrete (RC) frames. A displacement-based design procedure was applied with the aim of enhancing the seismic performance of a non-ductile five-storey RC frame using braced ductile shear panels. The procedure was able to satisfactorily achieve the target displacement and was validated using the results of nonlinear dynamic analyses. The effects of the application of the dissipative bracing system on the seismic response of the multi-storey RC frame were assessed. The results of the numerical investigations showed that the proposed bracing system can protect the primary structural elements of the frame preventing them from damage under severe seismic actions. A more uniform distribution of inter-storey drifts was registered for the retrofitted frame compared to the bare counterpart, avoiding the development of a soft-storey mechanism at the second level.

Keywords: dissipative bracing system, reinforced concrete frame, seismic retrofitting, displacement-based design procedure.

1 Introduction

Existing buildings in seismically active regions are prone to severe damage and even collapse during severe earthquakes due to large lateral deformations and low energy dissipation capacity. Passive energy dissipation systems can significantly reduce the ductility demand on structures subjected to earthquakes. They are usually used for enhancing the seismic performance of structures by adding supplemental damping and/or stiffness to the structures, reducing the damage of the primary structural elements. Moreover, new design methodologies that can overcome the deficiencies of the traditional force-based design method are needed. Displacement-based design procedures can represent a sound alternative to the conventional methods. According to these alternative approaches, structures are designed to achieve displacements corresponding to a specified limit state.

This study presents some results of numerical investigations carried out on an innovative dissipative bracing system for seismic protection of frames. The proposed system, named as braced ductile shear panel (BDSP) system, is composed of ductile shear panel and concentric braces. Previous numerical investigations (Valente et al., 2011) show that the BDSP system provides structures with high stiffness and presents excellent energy absorption capacity and stable hysteresis characteristics. It can be used as a primary lateral load resisting system for new or existing steel frames. The present work investigates the likelihood of application of the proposed dissipative bracing system to the case of non-ductile RC frames subjected to seismic excitation. A simplified model of the bracing system was developed for global analyses of multi-storey frames. A displacement-based design procedure for RC frames equipped with BDSP system was presented and applied to a case study frame. The procedure was able to satisfactorily achieve the target displacement and was validated against nonlinear dynamic analyses. The favourable effects of the BDSP system used as retrofit measure on RC frames were assessed.

2 Description of the bracing system

The proposed bracing system is composed of four concentric braces, placed in series with a yielding rectangular ductile shear panel, as shown schematically in Figure 1. The four short I-shaped braces transfer the lateral displacements arising from the lateral load on the frame to the shear panel. The ductile shear panel consists of non-slender in-plane plate elements, stiffened around the perimeter by boundary flanges, and capable of achieving high levels of ductility, when strained inelastically in a shearing mode. The series configuration ensures that the strength of the ductile shear panel defines the limiting seismic strength demand on the bracing system. The length-to-thickness ratio of the shear panel is limited such that a stable hysteretic behaviour can be ensured for a substantial number of load cycles, even at high levels of ductility demand. It is well known from extensive experimental investigations of eccentrically braced frames, particularly those with short length shear links, that cyclic shear yielding can be a stable and dependable mechanism for dissipating seismic energy in a structural system. The proposed system is thought to be used both in new buildings and as a retrofit measure for existing buildings. The device is designed so that it can be considered sacrificial, meaning that it could be replaced after a severe seismic event. This implies that the braces and all other elements composing the bracing system beside the shear panel have to be designed so that they don’t experience plastic strains; therefore energy dissipation is concentrated only in the shear panel. The need to replace a damaged panel implies a bolted connection between the braces and the panel. This connection is carried out with doubler plates on both flanges and webs.

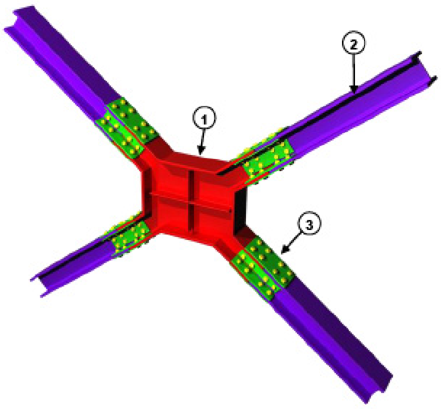

Figure 1. Schematic overview of the dissipative bracing system: (1) ductile shear panel, (2) braces, (3) bolted connection.

3 Multi-storey RC frame and numerical modelling

The seismic performance of a non-ductile five-storey three-bay RC frame was investigated through nonlinear static and dynamic analyses. The RC frame was designed to withstand only vertical loads without capacity-design concept or ductility detailing. The inter-storey height was 3 m for all the storeys, while the bay width was 4.5 m. The geometric configuration of the RC frame and details of typical column and beam cross-sections are shown in Figure 2. The materials used were normal concrete of grade C20/25 and steel of grade S400 for longitudinal and transversal reinforcement. Storey masses were evaluated by taking into account dead loads and a percentage of live loads according to Eurocode 8 for common residential buildings. The internal columns of the first storey present square cross-sections of 35cm x 35cm, while all the other columns have square cross-sections of 30 cm x 30 cm. The beam cross-section dimensions were 30cm x 50cm.

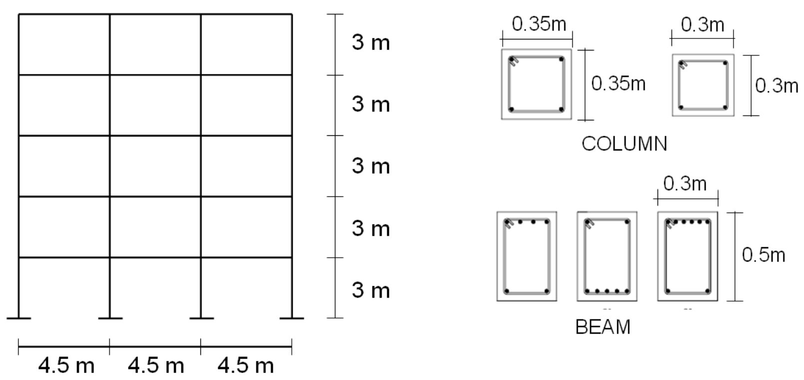

Figure 2. Elevation view of the RC frame and details of typical column and beam cross sections.

The finite element code Ruaumoko (Carr, 2006) was used to perform nonlinear static and dynamic analyses. Beams and columns were modelled by one-dimensional elastic elements with inelastic behaviour concentrated at the edges in plastic hinge regions (Giberson model) and defined by appropriate moment-curvature hysteresis rules available in Ruaumoko. The plastic hinge length was computed using the expression reported in Paulay and Priestley (1992). The Modified Takeda hysteresis model (Otani, 1974), widely used for RC sections, was used to represent the moment-curvature behaviour in the hinge region of the member. Bending moment-axial force interaction diagrams were used to account for the variation of moment capacity due to the axial force. Strength degradation curves were associated to the selected hysteresis behaviour to represent possible strength reduction due to number of cycles and ductility demand.

The braced ductile shear panels were inserted in the middle bay of all the storeys of the frame and the elevation view of the protected frame is shown in Figure 3. In the protected frame, horizontal (plates) and vertical (C-shaped cross-section) steel elements were anchored to the existing RC members in order to assist beams and columns in resisting loads transferred by diagonal braces. The BDSP system was included in the model using a pair of nonlinear link elements connected to the nodes of the rectangular frame to be braced, as shown in Figure 4. The hysteretic behaviour of the BDSP system was reproduced using an elastic-plastic hysteresis rule, (Valente et al., 2011).

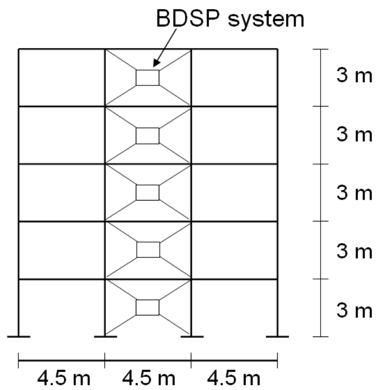

Figure 3. Elevation view of the RC frame equipped with braced ductile shear panels.

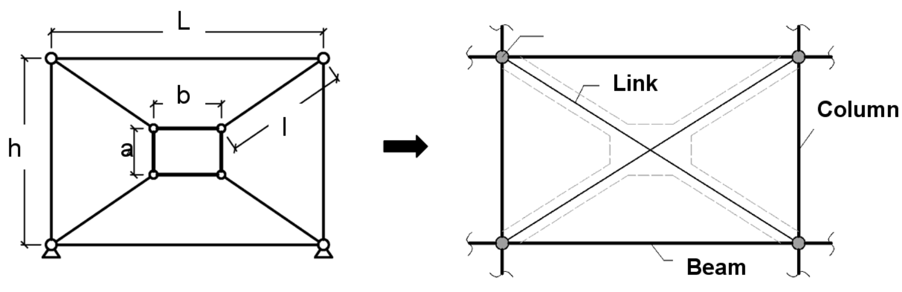

Figure 4. Geometric dimensions and schematic model of the BDSP system.

4 Displacement-based design procedure

A displacement-based design procedure for RC frames equipped with BDSP system was applied to meet a given target displacement selected according to a prescribed performance objective. The maximum top storey displacement was taken as the target performance point. The seismic demand was computed with reference to Eurocode 8 response spectrum (Type 1, subsoil class C, a_g=0.3g). The base shear - top storey displacement relationship (capacity curve) was obtained by gradually increasing the lateral forces appropriately distributed over the storeys. According to Eurocode 8 provisions, nonlinear static analyses were performed considering two lateral load distributions. The base shear - top storey displacement curve was transformed into the capacity curve of the equivalent SDOF system and it was idealized as a bilinear curve on the basis of the "equal-energy" concept. The performance point was obtained from the cross-point of the demand and the capacity curves plotted in the acceleration-displacement (AD) format. The graphical representation of the procedure is illustrated in Figure 5: the performance point for the SDOF system amounted to 14.2 cm (17.7 cm for the MDOF system).

The vulnerability assessment in terms of performance levels was carried out according to Eurocode 8. The target displacement was set to be equal to the top storey displacement corresponding to the attainment of performance levels, referred as Limit States. A Limit Sate is achieved by the structure when the first of its members attains the corresponding deformation capacity. The target displacement at the top storey of the frame amounted to 9.25 cm (7.4 cm for the SDOF system). This displacement corresponded to the attainment of the Limit State of Significant Damage according to Eurocode 8.

In order to determine the appropriate size of the BDSP system to meet the given target displacement, the method was applied to the retrofitted model. The geometric dimensions (length *b*, width *a*, thickness t_w) of the ductile shear panel were taken as the primary design variables. The proper size of the BDSP system was determined in order to satisfy the desired displacement limit state of the frame. In this study the size of the BDSP system in each storey was determined considering a distribution pattern proportional to storey shear. The storey-wise BDSP distribution pattern resulted a fundamental design parameter in the procedure because it affected the values of the characteristics of the BDSP system throughout the frame. It can be noted that the retrofitting intervention eliminates the irregularity of the frame and the global response of regular structures may be more accurately captured by procedures based on nonlinear static analyses.

Figure 5 shows the demand spectra, the capacity curves and the performance point in AD format for the retrofitted frame. The effective damping allowed to reduce the spectral acceleration to take into account the damping supplied by the BDSP system. The performance point of the retrofitted frame was defined as the intersection of the demand spectrum curve, reduced by means of the effective damping, with the equivalent bilinear capacity curve. The performance point coincided with the target displacement (7.4 cm for the SDOF system). Table 1 shows the geometric and mechanical characteristics of the ductile shear panel required in the model to achieve the target displacement.

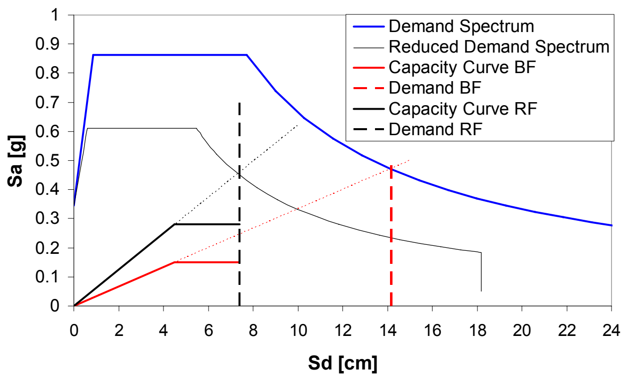

Figure 5. Demand spectra and capacity curves in AD format for the bare (BF) and retrofitted (RF) models.

Storey	b x a [mm]	t_w [mm]	steel
1	1000 x 600	3	S235
2	950 x 550	3	S235
3	850 x 450	3	S235
4	750 x 450	3	S235
5	600 x 400	3	S235

Table 1. Geometric and mechanical characteristics of the ductile shear panel at each storey.

5 Nonlinear dynamic analyses

The assessment of the seismic response of the RC frame in the unprotected (BF) and retrofitted (RF) configurations was carried out by means of nonlinear dynamic analyses using a set of artificial accelerograms with different values of peak ground accelerations a_g. The artificial accelerograms were generated so as to match the Eurocode 8 response spectrum (Type 1, subsoil class C) through the computer code SIMQKE. The aims of the nonlinear dynamic analyses were: 1) to verify the validity of the displacement-based design procedure; 2) to assess the effectiveness of the new dissipative bracing system.

Figure 6 presents the maximum top displacements registered for the bare and retrofitted RC frames at different seismic intensity levels (a_g ranges from 0.2g to 0.4g). A considerable reduction of the maximum top displacements was observed in case of frame equipped with BDSP system. The difference between the maximum top displacements of the two frames increased for severe seismic actions. The maximum top displacement registered for the frame retrofitted with BDSP system under earthquake motion was similar to the target displacement obtained in accordance with the simplified design procedure. The bare frame became highly vulnerable under ground motion intensity of 0.3g, corresponding to significant damage to structural elements and to the development of a soft-storey mechanism at the second level. Figure 7 shows the maximum inter-storey drift profiles for the bare and retrofitted frames for different seismic intensity levels. The retrofitted model exhibited more uniform lateral displacement profiles compared to the bare counterpart. In particular, a significant drift reduction was registered at the second level, preventing the development of a soft-storey behaviour. The introduction of the BDSP system changed the damage distribution throughout the frame. The maximum drift demand on the bare model was registered at the second storey; on the contrary, the drift demand on the retrofitted model concentrated in the third storey.

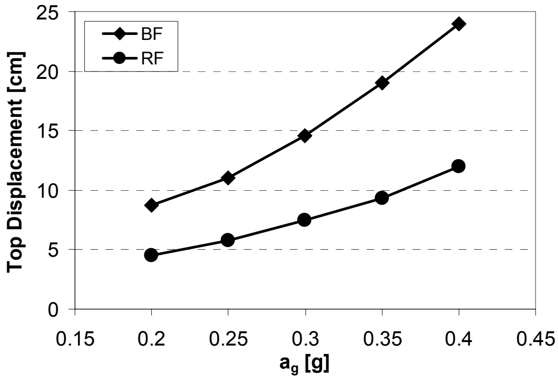

Figure 6. Maximum top displacement of the bare and retrofitted frames for different seismic intensity levels.

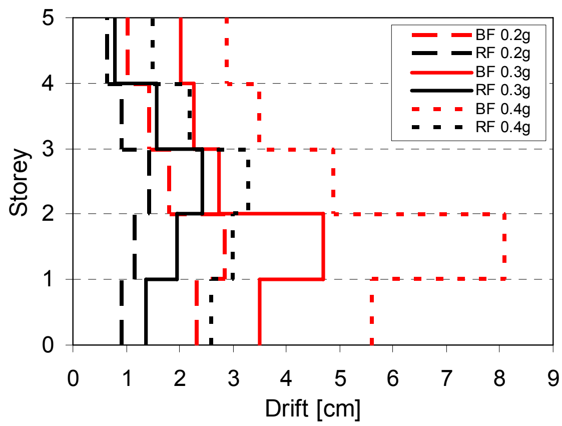

Figure 7. Storey drift profiles for the bare and retrofitted frames for different seismic intensity levels.

A comparison of the seismic response of the BF and RF models was carried out in terms of dissipated energy too. Figure 8 shows the energy dissipated by the bare and protected frames (primary structural elements and BDSP system) for different seismic intensity levels. The addition of the BDSP system reduced the energy dissipated by the primary structural elements of the frame, giving a significant contribution to the energy dissipation capacity of the whole system for severe seismic actions. The energy dissipation mostly concentrated in the dissipative steel panels, decreasing the maximum displacements of the retrofitted frame and the plastic demand on the structural elements. The total energy dissipated by the retrofitted model was larger than the bare model.

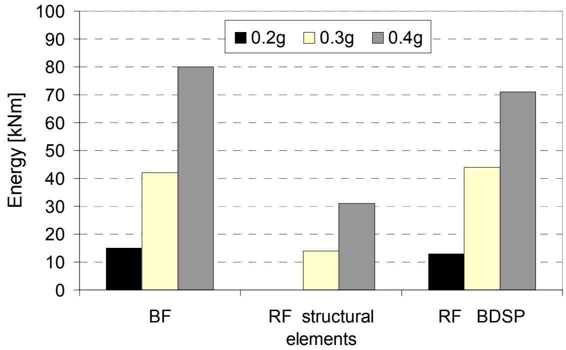

Figure 8. Energy dissipated by the bare frame and by the retrofitted frame (structural elements and BDSP system) for different seismic intensity levels.

Figure 9 reports the energy dissipated by the structural elements and by the BDSP system at each storey of the retrofitted frame subjected to ground motion intensity of 0.3g and 0.4g. The contribution of the second storey to the total dissipated energy was prevalent, associated with the extensive damage registered at this level for the bare frame. The percentage of the total energy dissipated by the two upper storeys was very small.

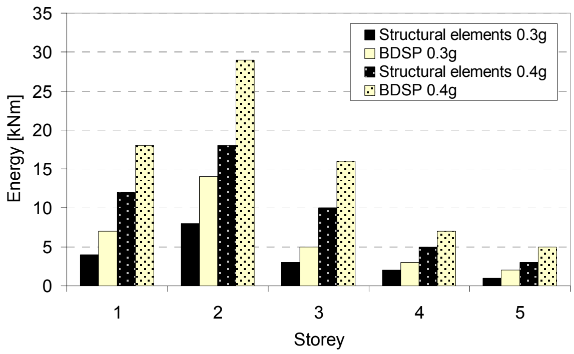

Figure 9. Energy dissipated by the structural elements and by the BDSP system at each storey of the retrofitted frame for different seismic intensity levels.

The seismic performance of the two frames was assessed at member level using the Demand-to-Capacity Ratio (DCR), that is the ratio of the chord rotation demand at the member ends to the corresponding capacity. The maximum chord rotation demand was derived from nonlinear dynamic analyses and the corresponding capacity was evaluated according to Eurocode 8 Part 3.

Figure 10 provides the maximum DCR values registered at each storey for all the columns of the two frames subjected to different ground motion intensity levels. The DCR values reproduced quite well the behaviour observed in terms of inter-storey drifts. In case of bare frame, DCR values greater than unity were registered for the first three storeys under ground motion intensity of 0.4g. The internal columns of the first levels presented the maximum DCR values as subjected to high axial load. A significant decrease of the maximum DCR values at the second storey was registered in the strengthened frame. This reduction confirms the effectiveness of the BDSP system in increasing stiffness and strength of the frame and preventing the formation of the soft-storey mechanism at the second level. The insertion of the BDSP system along the height of the frame produced DCR values smaller than 0.8 under ground motion intensity of 0.4g, even at the second storey where high values of deformation demand were computed. Maximum DCR values smaller than 0.7 were computed for all the other storeys. The maximum values of the axial force induced in the columns connected to braces at each storey of the retrofitted model were also checked.

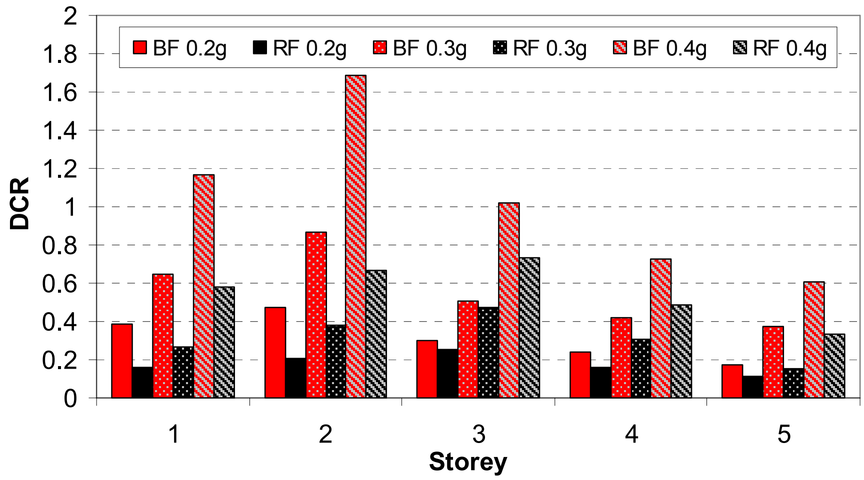

Figure 10. Maximum DCR values registered for the columns of each storey of the bare and retrofitted frames at different seismic intensity levels.

6 Conclusions

A new dissipative bracing system for seismic performance improvement of RC frames designed for gravity loads was investigated through numerical analyses. A simplified model of the bracing system was developed for global analyses of multi-storey frames. A displacement-based design procedure for the BDSP system was applied with the aim of seismic upgrading a non-ductile five-storey RC frame. The procedure was able to satisfactorily achieve the target displacement and was validated against earthquake records. The effects of the application of the dissipative bracing system on the seismic response of the multi-storey RC frame were assessed.

The results of the numerical investigations showed a considerable reduction of the maximum top displacements of the RC frame protected by the BDSP system. The energy dissipated by the structural elements was significantly reduced in case of severe seismic actions. A more uniform distribution of inter-storey drifts was observed for the retrofitted frame, preventing the development of a soft-storey mechanism at the second level. The energy dissipation concentrated in the ductile shear panels and resulted uniform over the height of the frame, reducing the plastic demand on the structural members of the second storey, along with the potential for structural damage.

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