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Seismic Protection of R/C Structures by a New Dissipative Bracing System

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Abstract

This study presents the results of numerical investigations carried out on a new alternative dissipative bracing system for improving the seismic performance of R/C frames. The proposed system is composed of ductile shear panel and concentric X-braces, and can be used to provide both ductility and stiffness to existing structures. Under seismic actions the braces are expected to remain elastic, while the panel dissipates significant amount of energy by yielding. A simplified model of the bracing system is developed for global analyses of frames. An energy based design procedure for seismic upgrading of frames with ductile shear panel and concentric X-braces is presented. This simplified procedure, based on energy balance concept and nonlinear static analyses, can represent an advantageous approach in preliminary analysis and design stage. Results of nonlinear dynamic analyses performed on a four-story R/C frame designed only for gravity loads show that the proposed bracing system can protect the primary structural elements of the frame preventing them from damage under severe seismic actions.

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Keywords: dissipative bracing system; seismic protection; R/C frames; design procedure.

1. Introduction

Among the new seismic design approaches for seismic protection of R/C structures, there are those based on the passive structural control systems. The main aim is to reduce the damage of the primary structural elements through the use of special devices. This study presents the results of numerical investigations carried out on a new alternative dissipative bracing system for seismic upgrading of R/C frames. The proposed system, named as braced ductile shear panel (BDSP) system, is composed of

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ductile shear panel and concentric X-braces, and can be used as a primary lateral load resisting system for steel frames. Previous numerical investigations, (Valente et al, 2011), showed that BDSP systems have high stiffness, excellent energy absorption capacity and stable hysteresis characteristics. This paper concerned the evaluation of the favourable effects of the BDSP system on non-ductile R/C frames subjected to seismic excitation. An energy based design procedure for R/C frames equipped with BDSP system is presented. A simplified model of the bracing system was developed for global analyses of multi-story frames. Nonlinear dynamic analyses were performed on a four-story R/C frame designed only for gravity loads and upgraded by the insertion of the dissipative bracing system. The effects of the BDSP system used as retrofit measure on R/C frames were assessed.

2. Description of the Bracing System

The proposed bracing system is composed of four concentric X-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. The device is also 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.

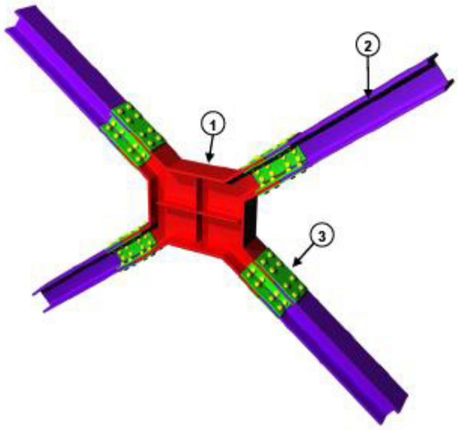

Figure 1. Schematic overview of the dissipative bracing system: (1) ductile shear panel, (2) braces, (3) bolted connection.

3. Multi-Story R/C Frame

The seismic performance of a non-ductile R/C frame equipped with braced ductile shear panels was investigated through nonlinear dynamic analyses. The frame was designed to withstand only vertical loads without capacity-design concept or ductility detailing and was tested using the pseudo-dynamic approach at the JRC ELSA laboratory at Ispra. A detailed description of the test structure can be found in a JRC ELSA Report, Pinto (2002).

The finite element code Ruaumoko, (Carr, 2006), was used to perform nonlinear dynamic analyses, which were conducted adopting the seismic input motion used for the experimental tests. 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 expression given in Paulay and Priestley (1992) was used for the definition of the plastic hinge length:

$$L_p = (0.08L) + \left(\xi f_y \emptyset_{max}\right) \qquad (1)$$

where L is the length of the element, $\phi_{\max}$ is the diameter of the main longitudinal reinforcing bars, f_y is the yielding strength of the reinforcement and $\xi = 0.022$.

The Modified Takeda hysteresis model (Otani, 1974), widely used for R/C sections, was used to represent the moment-curvature behaviour in the hinge region of the member. The elastic stiffness of the elements was computed according to the cracked section approach. 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 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 2. The hysteretic behaviour was reproduced using an elastic-plastic hysteresis rule with hardening.

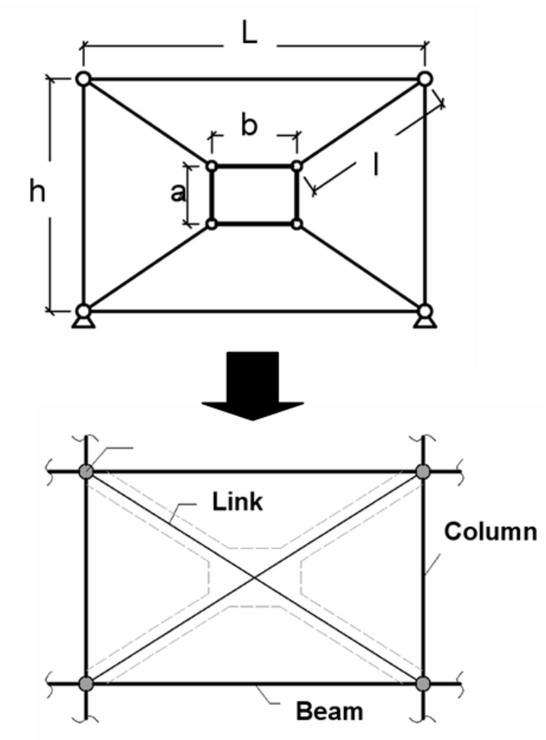

Figure 2. Schematic model of the BDSP system.

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 model vertical steel straps connected to the columns adjacent to the bracing system were taken into account.

For the validation of the numerical models, the bare frame was subjected to the same artificial accelerograms with increasing intensity adopted in the pseudo-dynamic tests. The numerical analyses were performed sequentially, according to the various steps of the experimental campaign, in order to better reproduce the laboratory tests. The comparison with the test results made it possible to calibrate and improve analytical modelling and to check the accuracy of the numerical models. Figure 4 shows the maximum inter-story drift profiles under Acc-975 record (a_g=0.29g) for the bare frame. A good agreement between numerical and experimental results can be observed, even if a small underestimation of the story drift at the third level was registered. It is apparent that the deformation demands concentrated at the third story, as confirmed by the experimental tests. The experimental values of the maximum story shear profile derived from the pseudo-dynamic tests on the bare frame were compared to the results obtained for the numerical model, exhibiting a satisfactory match, as shown in Figure 5.

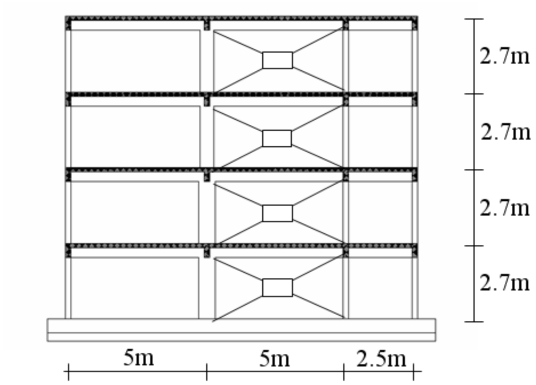

Figure 3. Elevation view of the R/C frame equipped with braced ductile shear panels.

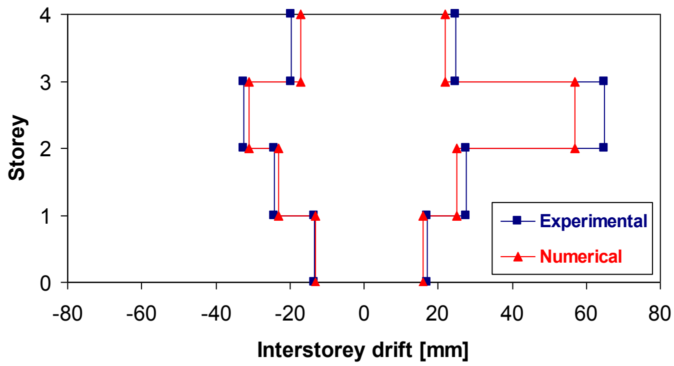

Figure 4. Inter-story drift profiles of the bare frame under Acc-975 input motion.

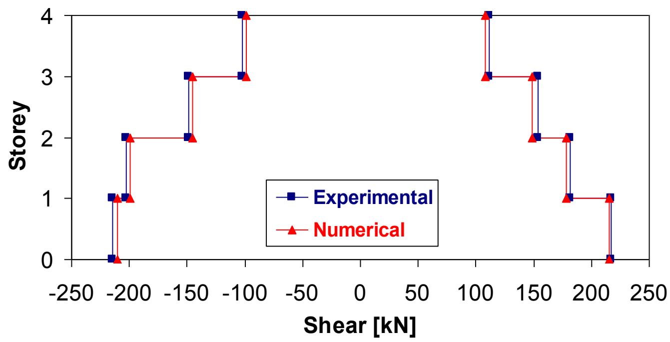

Figure 5. Story shear profiles of the bare frame under Acc-975 input motion.

4. Energy Based Design Procedure

A simplified energy based design procedure for seismic retrofitting of multi-story R/C frames with BDSP is presented based on the energy balance concept and nonlinear static analyses. The equation proposed by Housner (1956) is used for estimation of the input seismic energy. This approach may be advantageous in preliminary analysis and design stage and may represent a convenient tool for determining the seismic energy demand of a structure without carrying out nonlinear dynamic time-history analyses. The basic steps of the design procedure are schematized briefly in the following.

a) Pushover analysis and determination of the target displacement

Pushover analyses are performed by subjecting the structure to a monotonically increasing pattern of lateral forces, representing the inertial forces which would be experienced by the structure when subjected to ground shaking. The selection of an appropriate lateral load distribution is an important step within the pushover analysis. The base shear-top displacement curve of the structure is obtained and the target displacement is determined so that a given performance objective is satisfied.

b) Transformation to an equivalent single-degree-of-freedom (SDOF) system

The target displacement of the structure is converted into the corresponding value of the equivalent SDOF system. A bilinear idealization of the pushover curve is performed at the target displacement on the basis of the “equal-energy” concept (the areas underneath the actual and bilinear curves are approximately the same, within the range of interest).

c) Estimation of the input seismic energy and determination of the energy stored by BDSP

The input seismic energy was estimated from the response spectrum and the elastic and hysteretic energy were computed using energy balance concept. The input seismic energy E_i of the system can be estimated as:

$$E_i = \frac{1}{2} M \left(\frac{S_a}{\omega_p}\right)^2 \quad (2)$$

where M is the mass, S_a is the pseudo-acceleration and ω_p is the fundamental natural frequency. The pseudo-acceleration S_a is determined from the response spectrum using the fundamental natural period of the system. The input seismic energy is equal to the energy stored by an equivalent elastic system, which is composed of the elastic energy E_e and the plastic energy E_p in the original elastic-plastic system. E_{BDSP} is the energy stored by BDSP at the target displacement and it is equal to the difference between the seismic input energy and the energy stored by the system.

The energy stored by BDSP can be expressed as:

$$E_{BDSP} = 2.\sum_{j=1}^{n} N_{j,y} cos\theta . \left[d_{j,so} - \frac{1}{2} d_{j,y} + \frac{\beta}{d_{j,y}} \frac{\left(d_{j,so} - d_{j,y}\right)^2}{2} \right] \quad (3)$$

where $d_{j,y}$ is the lateral yield displacement at the j^{th} story, $d_{j,so}$ is the lateral target displacement at the j^{th} story, $N_{j,y}$ is the lateral yield force at the j^{th} story, β is the post-yield stiffness ratio of the system, θ is the slope of the link elements used to represent the BDSP system.

d) Check of convergence

In the first step the required energy and the size of BDSP are obtained on the basis of the natural period assumed for the bare structure. Once the first values of BDSP size are determined and introduced into the models, new values of the natural period and of required energy can be computed. Moreover, the introduction of BDSP changes the capacity curve of the frame. The design procedure needs iteration and the process is repeated until the plastic energy dissipated by BDSP converges to the required energy.

The proposed procedure was applied to the four-story R/C building tested at the JRC ELSA laboratory to determine appropriate size of BDSP to meet a given target displacement. The seismic demand was evaluated with reference to Eurocode 8 response spectrum (Type 1, soil class A) for a peak ground acceleration a_g=0.3g. 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 story 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 achieves the corresponding deformation capacity. The target displacement at the top story of the frame amounted to 6.9 cm, corresponding to the attainment of the Limit State of Significant Damage according to Eurocode 8. Table 1 presents the final values of the characteristics of the BDSP device obtained from the application of the design procedure.

Table 1. Characteristics of the BDSP device.

b x a [mm]	t_w [mm]	steel
900 x 600	3	S235

5. Nonlinear Dynamic Analyses

Nonlinear dynamic analyses were performed on the original and protected models of the R/C frame using seven artificial accelerograms with different values of peak ground accelerations a_g. The suite of artificial accelerograms was generated so as to match the Eurocode 8 response spectrum (Type 1, soil class A, 5% viscous damping) through the computer code SIMQKE, (Gasparini 1976). Time-history analyses were carried out to verify the validity of the simplified design procedure and to assess the effectiveness of the new dissipative system. Mean values of the seven analyses results are reported. The introduction of the bracing system significantly reduced the top displacement compared with the bare frame and the difference was more evident for high levels of seismic actions, Figure 6. The maximum top displacement of the frame retrofitted with BDSP under earthquake motion was similar to the target displacement obtained in accordance with the simplified design procedure. The slight discrepancy resulted from the fact that the same size of the BDSP was adopted for all the storeys of the frame. The bare frame became highly vulnerable under 0.3g ground motion intensity, corresponding to significant damage to structural elements and to the development of a soft story mechanism at the third floor, Figure 7. The frame protected with braced ductile shear panels showed a smaller sensitivity to increases of the seismic intensity levels. A more uniform distribution of inter-story drifts was observed for the protected model, preventing the development of a soft-story mechanism at the third floor. The trend of the top displacement curve showed that the upgrading intervention with braced ductile shear panels provided the structure with sufficient stiffness and ductility to withstand the a_g=0.3g seismic intensity level without approaching the failure mechanism and improving the global structural behaviour.

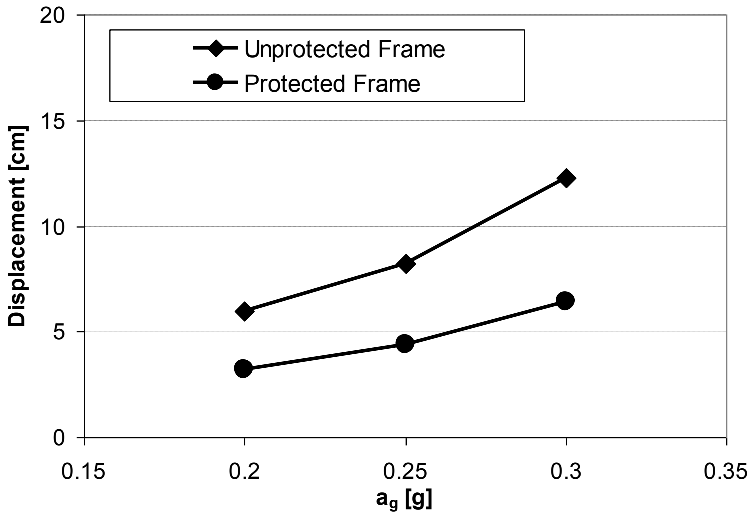

Figure 6. Maximum top displacement for the unprotected and protected frames for different seismic intensity levels.

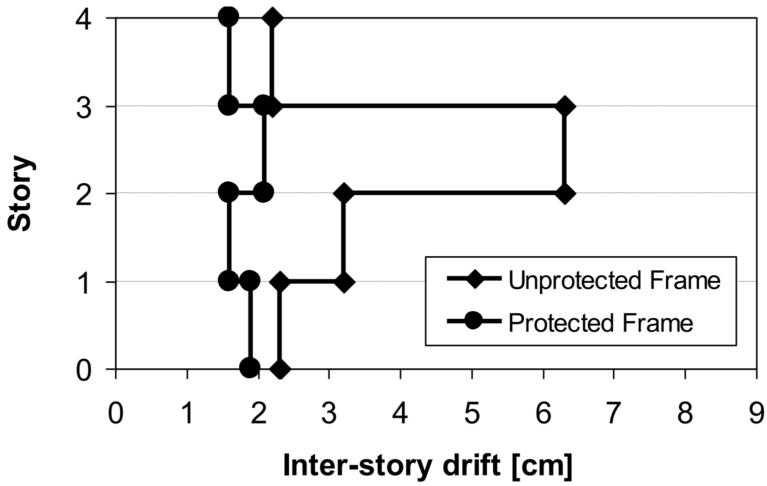

Figure 7. Inter-story drift for the unprotected and protected frames under 0.3g ground motion intensity.

The energy dissipated by the structural elements of the protected frame showed a considerable decrease compared to the original frame, Figure 8. The energy dissipation concentrated in the ductile shear panels and resulted uniform over the height of the frame, even under 0.3g ground motion intensity. The plastic demand on the structural members of the third story was drastically reduced, along with the potential for structural damage. The maximum values of the axial force induced in the columns connected to braces at each story of the model were also checked.

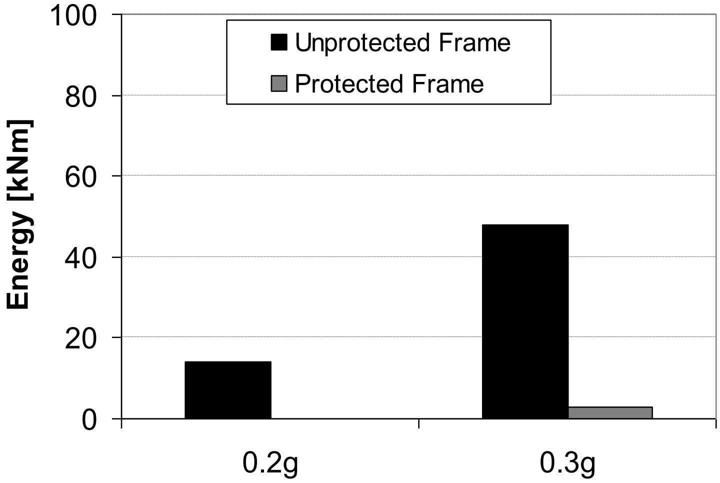

Figure 8. Energy dissipated by the structural elements for the unprotected and protected frames for different seismic intensity levels.

6. Conclusion

A new dissipative bracing system for seismic performance improvement of R/C frames designed only for gravity loads was investigated through numerical analyses. An energy based design procedure for the BDSP system was applied to the seismic upgrading of a four-story non-ductile R/C frame structure. The method was able to achieve the target displacement satisfactorily and was validated against earthquake records. The primary advantage of the proposed procedure was that it provided a simple solution for obtaining a design of the BDSP system. A simplified model of the bracing system was developed for global analyses of multi-story frames. The effects of the application of the dissipative bracing system on the seismic response of the multi-story R/C frame were assessed. The results of the numerical investigations showed a considerable reduction of the maximum top displacements in case of frames 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-story drifts was observed for the protected R/C frame, preventing the development of a soft-story mechanism at the third floor. 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 third story, along with the potential for structural damage.

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