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SEISMIC DESIGN OF FRAME STRUCTURES EQUIPPED WITH INNOVATIVE HYSTERETIC DISSIPATIVE DEVICES

MICHELE PALERMO, VITTORIA LAGHI, STEFANO SILVESTRI, GIADA GASPARINI, and TOMASO TROMBETTI

Dept of Civil, Chemical, Environmental and Materials Engineering, University of Bologna, Bologna, Italy

In the present work, a Performance-Based Seismic Design procedure applied to multi-storey frame structures with innovative hysteretic diagonal steel devices (called Crescent Shaped Braces or CSB) is introduced. CSBs are steel elements of peculiar geometrical shapes that can be adopted in frame buildings as enhanced hysteretic diagonal braces. Based on their "boomerang" configuration and placement inside the frame structure, they are characterized by a lateral stiffness uncoupled from the yield strength and, if properly inserted, by an overall symmetric hysteretic behavior with hardening response at large drifts, thus preventing from global structural instability due to second-order effects. The procedure here presented is intended to guide the structural engineer through all the steps of the design process, from the selection of the performance objectives to the preliminary sizing of the CSB devices, up to the final design configuration. The steps are described in detail through the development of an applicative example.

Keywords: Design procedure, Performance-based seismic design, Viscous dampers, Crescent shaped braces.

1 INTRODUCTION

Most of current force based seismic code design procedures are based on the accomplishment of prescriptive rules leading to a "passive" design, since the designer often obtains a solution without having a clear and complete understanding/control of the structural performances under different earthquake intensities.

A change of paradigm has been postulated since the end of the 20th century with the conceptual framework of Performance Based Seismic Design (PBSD) first proposed by SEAOC (1995), which encompasses the full range of seismic engineering issues toward predictable and controlled seismic performances under established multiple earthquake intensity levels (Bozorgnia and Bertero 2004). PBSD principles would therefore permit to shift from a "passive" to an "active" overarching design approach, in which the designer (i) first selects and identifies multiple performance objectives (the coupling of a building performance level with a given earthquake intensity level) (Bertero and Bertero 2002), (ii) then conceives a conceptual design and a preliminary sizing of structural and non-structural elements (member size, reinforcements) and (iii) finally develops the detailed design.

Among various design approaches proposed in the literature, some of the authors proposed in 2009 a conceptual approach based on the full exploitation of stiffness, strength, ductility, and energy dissipation properties of a structural system (stiffness-strength-ductility design approach, Trombetti *et al.* 2009). It was soon realized that conventional diagonal bracing systems do not permit the required freedom in the design, so that a novel steel hysteretic dissipative brace, called Crescent Shaped Brace (CSB), was introduced (Palermo *et al.* 2015). Up to now, the mechanical properties of CSBs have been through analytical, numerical and experimental investigations (Palermo *et al.* 2017), while design procedures have been developed only for the particular case of CSBs inserted at the ground floor only (Palermo *et al.* 2014) or for shear-type frames with CSBs inserted at all stories (Kammouh *et al.* 2018), so that the structure stiffness matrix can be easily computed. In the present work a general PBSD design procedure for multi-stories frames equipped with CSB devices is presented.

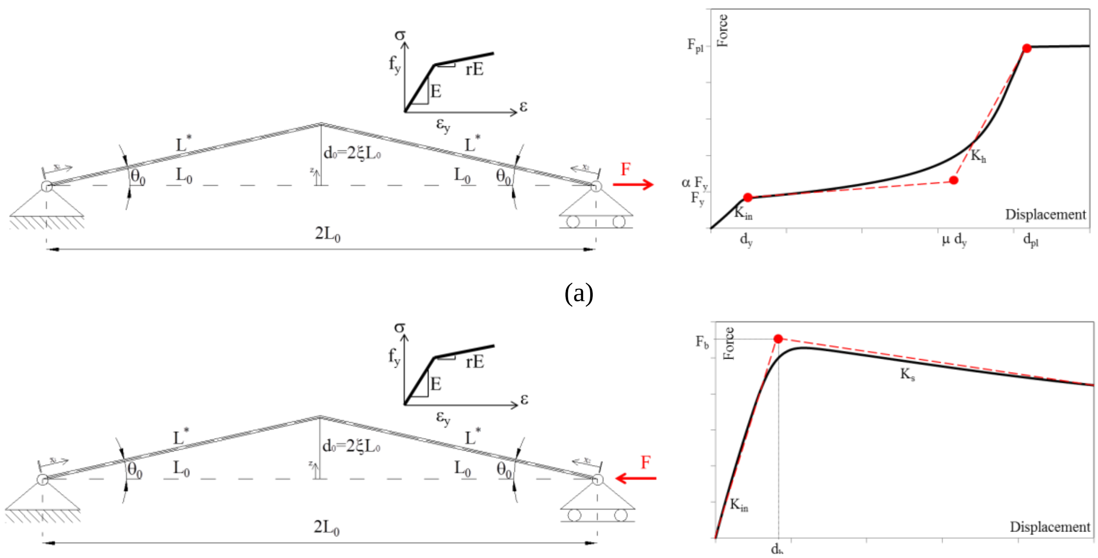


Figure 1. The bilinear symmetric configuration of the CSB and its lateral force-displacement behavior: (a) in tension; (b) in compression (Adapted from Palermo *et al.* 2017).

2 CRESCENT-SHAPED BRACES

A CSB is a hysteretic steel device connecting two points of the structure, either members of two adjacent stories (like diagonal braces) or slabs of the same floor. In its symmetric configuration (Figure 1) the device is composed by a continuous element made by two equal straight segments each one inclined of an angle θ_0 with respect to the horizontal direction. A characteristic dimension of the device is the so-called "initial arm" d_0. When subjected to a lateral force F, the two straight segments react through both internal axial force and bending moment whose signs and relative magnitudes (compression/ tension plus bending) depend on the initial lever arm value and on the direction and sign of the applied force. For instance, the qualitative graphical representation of the lateral force vs lateral displacement behavior of a bilinear symmetric CSB device is represented in Figure 1. Let us first focus the attention on the behavior under lateral forces inducing tensile/bending (Figure 1a). A first linear-elastic behavior is observed until the first yielding of the knee point, followed by a pseudo-plastic range (kind of plateau) and the final hardening range until the device reaches the straight configuration (e.g., the arm reduces to zero). The behavior under lateral forces inducing compression/bending is characterized by a first linear-elastic branch until the yielding of the knee point, followed by a softening branch (Figure 1b). The resulting force-displacement curves can be described in terms of the following parameters: initial stiffness k_{in}, first yielding point (F_y, d_y), ductility capacity (δ), hardening stiffness in tension (k_h), plastic tensile capacity (F_{pl}, d_{pl}), compression capacity (F_b, d_b), softening slope under compression (k_s). These "behavior" parameters can be related to the specific geometrical and mechanical properties of the device (details can be found in Palermo *et al.* 2017).

3 THE DESIGN PROCEDURE

The proposed design procedure allows to obtain a structure, which will follow a so-called objective curve that represents the desirable structural response in a Force-displacement graph, to satisfy multiple performance objectives POs (see Figure 2). It consists of the following phases:

- **PHASE 0. Identification of the POs**. It consists in the identification of the performance objectives. For a frame structure equipped with CSB devices placed as diagonal braces, the following four POs are envisaged:

  PO1: The building has to remain fully operational (no damage) under frequent earthquakes (characterized by minor intensity, EQ1). It is achieved by imposing a target initial stiffness to each CSB device.

  PO2: The building has to remain in operational conditions (limited and repairable damage) under occasional earthquakes (characterized by moderate intensity, EQ2). It is achieved by imposing a target yielding force to each CSB device.

  PO3: The safety of the occupants has to be guaranteed under rare earthquakes (characterized by major intensity, EQ3). It is achieved by ensuring a minimum ductility to each CSB device.

  PO4: The collapse of the building has to be prevented under very rare earthquakes (characterized by extreme intensity, EQ4). It is achieved by ensuring the building stability (no collapse due to P-D effects).

- **PHASE 1. HRS design: linear elastic behavior and yielding point.** It consists in (i) calibrating the initial elastic stiffness of each CSB through a straightforward iterative procedure (based on the one proposed by Lavan and Levy 2006) in order to satisfy inter-storey drifts limitations (as prescribed by most current seismic codes) under occasional earthquakes (EQ1); (ii) calibrating the yielding point of each CSB so that the structure will reach it under frequent earthquakes (EQ2).
- **PHASE 2. HRS design: non-linear behavior.** It consists in: (i) calibrating the ductility of each CSB device, so that they will respond within the "plateau" range under rare earthquakes (EQ3); (ii) evaluation of the final hardening stiffness of each CSB device, so that they will provide additional stiffness under very rare earthquake in order to prevent from P-Delta induced collapse (EQ4).
- **PHASE 3. Final design/verifications through non-linear TH analyses.** It consists in the development of the final design/verifications by means of non-linear time history (TH) analyses considering the actual non-linear characteristics of the CSB devices as obtained from the preliminary design (Phases 1-3).

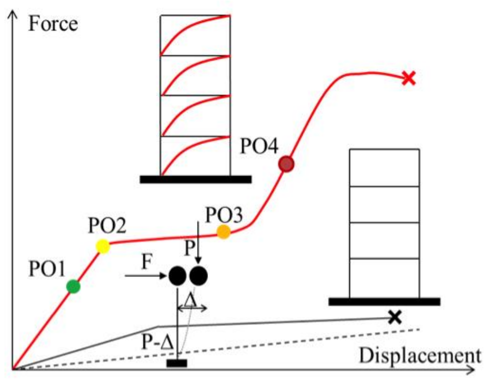
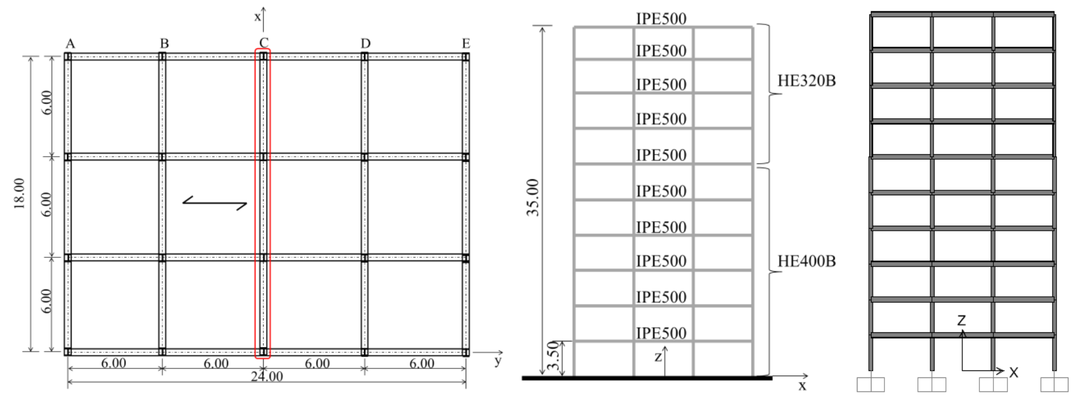


Figure 2. Graphical representation of the "Objective curve" and performance objectives (POs).

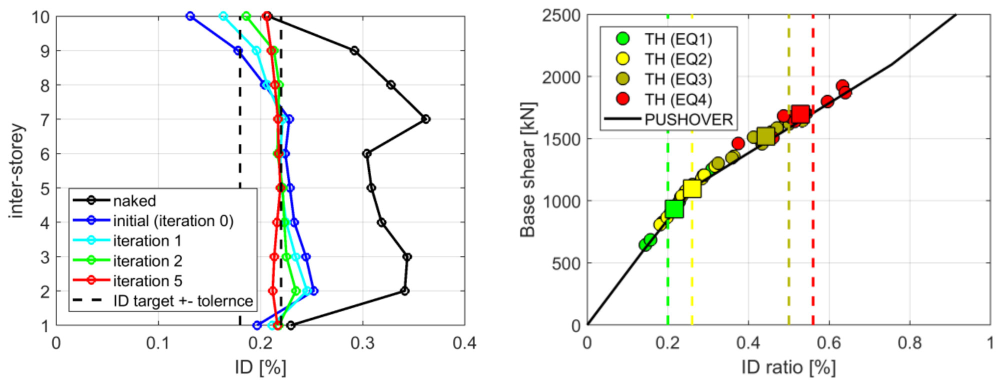
4 APPLICATIVE EXAMPLE

The design procedure is here applied to an example case that is a 10-story steel regular MRF located in a high seismic risk region of Southern Italy. The building has a rectangular plan (24 m x 18 m) with equal span width of 6.00m. The building height is 35 m with a constant inter-storey height H= 3.5 m. The moment-resisting frames are composed by columns and beams with European HE and IPE cross section profiles, respectively. Rigid beam-column connections are considered. The seismic design load is equal to 10 kN/mq. Figure 3 provides a plan view and a frame elevation view with the corresponding SAP2000 finite element model. The non-linear behavior of frame elements and CSB devices is modelled through M-θ plastic hinges. The four POs used for the seismic design can be summarized as follows. Under EQ1 intensity level (frequent events) all peak inter-storey drifts are limited to $\overline{ID}$=0.2%. Under the EQ2 intensity level (occasional events) all the CSB devices reach the first yielding. Under EQ3 intensity level (rare events) the ductility demand of all CSB devices is limited to $\lambda \cdot \frac{a_{g,EQ3}}{a_{g,EQ2}}$ (being $a_{g,EQ2}$ and $a_{g,EQ3}$ the design PGA values at EQ2 and EQ3, respectively, the λ value is chosen by the designer). Under EQ4 intensity level all the devices should have enough lateral strength to prevent from P-D collapses. The values of the design PGA are equal to $a_{g,EQ1}$=0.1 g, $a_{g,EQ2}$=0.13 g, $a_{g,EQ3}$= 0.359 g and $a_{g,EQ4}$= 0.469. For the sake of conciseness, the detailed calculations to impose each PO are not here reported (they will be provided in a journal paper). Some selected results are, instead, shown in Figure 4a and b. In particular, Figure 4a graphically displays the iterative procedure to reach the PO1. It can be noted that the algorithm (adapted from Lavan and Levy 2006) converges in few iterations. Figure 4b displays the Force-Displacement structural global response (in terms of base shear vs first storey ID ratio). The colored circles indicate the response under a particular accelerogram (seven artificial accelerograms, generated using the software SIMQKE, and scaled to the four different seismic design intensities have been used to perform the non-linear TH analyses). The squares indicate the average responses from T-H analyses. The graph includes also the pushover curve obtained using a uniform along-the-height distribution of lateral forces. It can be noted that the seismic response of the building is quite close to the pushover curves.



(a) (b) (c)

Figure 3. (a) Plan view. (b) Elevation view. (c) SAP2000 bare frame FE model.



(a) (b)

Figure 4. (a) Graphical representation of the iterative procedure to find the CSB initial stiffness. (b) Global response in terms of base shear vs ID ratio.

5 CONCLUSIONS

In the present work a general procedure for the seismic design of frame structures equipped with CSB devises has been presented. The procedure is framed in the context of PBSD. It is composed of four main phases going from the definition of the seismic performance objectives to the definition of the linear and non-linear properties of the CSB devices, up to the final verification of the actual behavior of the building with the added CSB devices through the development of fully non-linear time history analyses. The procedure has been finally applied to a 10-story example frame, considering both cases of moment resisting frame and pendular frame. The results have shown that the procedure efficiently achieved the proposed performance objectives.

Acknowledgments

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