How to Promote Self-Centering Behavior of Buildings Having a System of Buckling-Restrained Braces and Gravitational Frames

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SUMMARY
Buckling-restrained braces have been found to be an efficient and adequate way to provide seismic-resistance to buildings. In spite of the many structural advantages they offer, several studies have found a lack of ability of buckling-restrained braces to promote a self-centering behavior. Under this circumstance, it has been suggested that the use of this type of braces should be complemented with stiff moment-resisting frames with the purpose of reducing permanent drifts, and thus, the vulnerability of braced frames to aftershocks. Design strategies can be developed to achieve adequate self-centering behavior of buildings whose structural system is composed of light gravitational moment-resisting frames and buckling-restrained braces. Independently of the level of lateral stiffness provided by the gravitational frames, a buckling-restrained braced frame will exhibit adequate self-centering behavior provided its lateral displacement is controlled in such a manner as to prevent nonlinear behavior in the frames.

Keywords: Displacement-based design, Buckling-restrained braces, Dual system, Self-centering behavior

1. INTRODUCTION

In recent decades, practicing engineers have developed innovative design tools and structural systems aimed at improving the seismic performance of their earthquake-resistant structural systems. Within this context, several studies have shown that the use of buckling-restrained braces represents, from technical and economical points of view, an attractive option in terms of seismic resistance. Nevertheless, it has also been observed that buckling-restrained braces tend to develop significant permanent deformations after intense ground motions, and this has resulted in recommendations in terms of complementing them with heavy and stiff moment-resisting frames that can provide self-centering capabilities to the braced frames. The studies presented herein suggest that light and flexible gravitational frames can result in adequate self-centering behavior of buckling-restrained braced buildings provided they are designed under the consideration of a damage-tolerant approach.

2. DISPLACEMENT-BASED DESIGN

After analyzing the reasons why several recent seismic events have resulted in excessive losses, the international community of seismic engineering has concluded that the levels of structural and nonstructural damage, as well as that in the contents of a building, is a direct consequence of excessive levels of motion. Innovation in earthquake-resistant design implies the design and construction of structural systems, either traditional or innovative, that can control the level of damage in the different sub-systems of a building through adequately controlling its dynamic response during seismic excitations of different intensity. Within this context, the structural properties that should be supplied to a building, independently of the structural material and structural system being used, should be such that its earthquake-resistant system is able to control its dynamic response within thresholds that are consistent with the level of damage or performance required from the different sub-systems. Limiting structural and nonstructural damage implies the control of the maximum inter-story drift index demand, which in turn implies controlling the roof displacement of a building within acceptable thresholds. The use of displacement-based approaches in conjunction with innovative structural systems can result in highly efficient earthquake-resistance. In the particular case of buckling-restrained braces, Montiel and Teran (2011) report improved reliability and significant reduction in the weight of a twenty-four-story building when its structural system is stiffened with braces sized according to a displacement-based format.

3. DAMAGE-TOLERANT STRUCTURES

A promising approach to achieve safer and lighter buildings through the use of displacement-based design is that of *damage-tolerant structural systems* (Wada et al. 2003). In one such system, structural damage induced by earthquake concentrates in specific structural devices, known as sacrificial elements. Their role is to act as structural fuses that protect the main or gravitational sub-system of the building, as well as the nonstructural sub-system against excessive damage. Because of this, the structural rehabilitation of the earthquake-resistant system after severe ground motion is reduced to substituting the damaged fuses. The use of this type of system in Japan has not only resulted in lighter buildings, but promises large savings in terms of cost and time of structural rehabilitation. Research carried at the Universidad Autonoma Metropolitana (UAM) has resulted in the proposal, within the context of displacement-based design and damage-tolerant structure, of a performance-based methodology for the conception and preliminary design of buildings laterally stiffened with buckling-restrained braces (Teran and Virto 2009, Teran and Coeto 2011). The UAM approach considers that under the effect of a low intensity ground motion a building with standard occupation exhibits adequate performance if it satisfies the *Operational* performance level. This implies that the gravitational and bracing systems should not exhibit significant structural damage, and that the nonstructural system should remain undamaged. Regarding performance for severe ground motion (associated to an earthquake hazard level characterized through a probability of exceedance of 5% in 50 years), the building exhibits adequate performance if it satisfies the *Life Safety* performance level and it can be easily repaired. This implies that while the gravitational system should remain practically elastic and thus, undamaged; the bracing system develops significant plastic behavior that allows it to dissipate a large percentage of the input energy. Once the integrated system deforms beyond its elastic limit, structural damage practically concentrates in the braces. An undamaged gravitational system is capable of providing the braced building with positive post-yield system stiffness.

Figure 1 schematically illustrates the structural behavior of a damage-tolerant building. Because both the gravitational and bracing systems provide lateral stiffness to the building, it is possible to schematically model their behavior through two parallel springs. According to what is shown, the gravitational system should be flexible, in such a manner that it can deform laterally without increasing in a substantial manner its internal state of stress, and thus, its level of structural damage. Contrary to this, the bracing system provides the building with a high lateral stiffness, in such manner that it yields at relatively low levels of lateral displacement. Through their lateral stiffness and plastic energy dissipation capacity, the braces constitute themselves in a reliable and stable source of earthquake-resistance that controls the dynamic lateral response of the building within the displacement thresholds imposed by the required performance of the gravitational systems. After a severe seismic excitation, structural damage translates into residual deformation in the building due to yielding in the buckling-restrained braces. Because the gravitational system should remain essentially elastic, the residual deformation should be eliminated once the yielded braces are substituted. It should be noted that in terms of what is shown in Figure 1, the structural skeleton of the earthquake-resistant building is composed by two independent and highly specialized structural systems, one to carry the gravitational loads, and the other one to provide lateral vibration control. Within this context, each system can be conceived and designed to achieve its structural role with high efficiency, and this has the potential to result in great savings in terms of structural materials (Teran 2012).

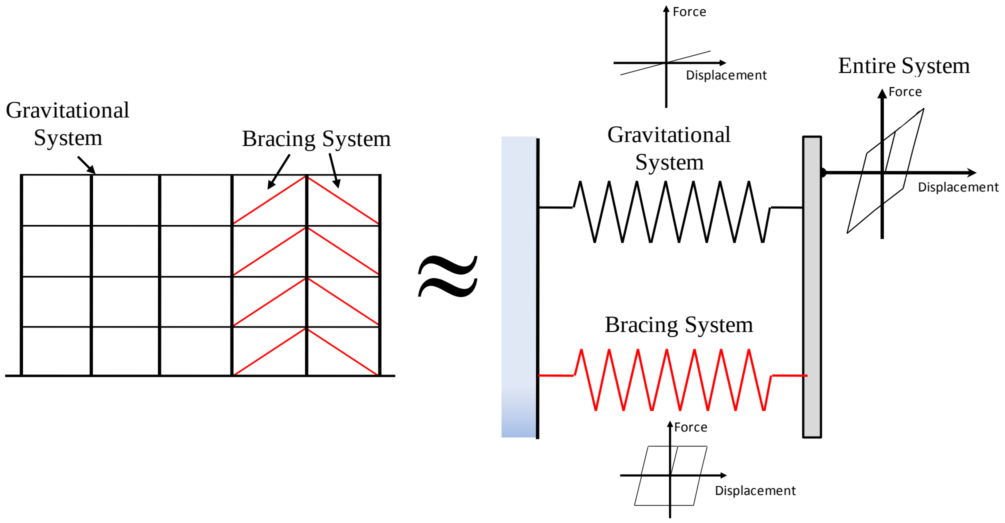

Figure 1. Behavior of a damage-tolerant building conceived according to the UAM approach

Figure 1 neglects the *global flexural drift mode* of the bracing system produced by the axial deformation of the columns that support the braces; that is, the model that is shown only considers the *global shear drift mode* associated to the axial deformation of the braces (the global shear drift mode is characterized by racking deformations). For the case of a tall building, the model can still assume that the total lateral stiffness of the building can be estimated by adding the lateral stiffnesses provided by the gravitational and bracing sub-systems. Nevertheless, now it is necessary to consider that the drifts due to global shear and flexural modes of the bracing sub-system are independent and produced, respectively, by the axial deformation of its braces and support columns (Teran and Coeto 2011, Coeto and Teran 2012). Under these circumstances, the model shown in Figure 1 should be modified according to what is shown in Figure 2, to consider that the structural system of the building can be modeled by means of two parallel sub-systems. In turn, the bracing sub-system can be modeled as two sub-systems working in series: one that represents the global shear stiffness provided by the braces, and another one that represents the global flexural stiffness provided by their support columns. The application of displacement-based methodologies that consider a damage-tolerant approach through the conceptual models shown in Figures 1 and 2, has resulted in reliable and efficient buckling-restrained braced frames that provide adequate seismic resistance to buildings having a number of stories ranging from four to twenty-four (Teran and Virto 2009, Teran and Ruiz 2010, Teran and Coeto 2011).

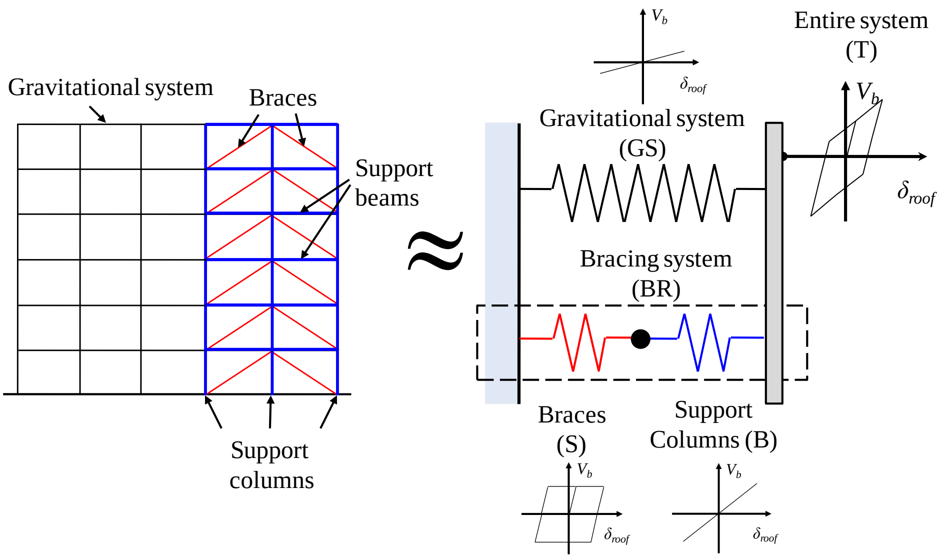

Figure 2. Modeling assumptions for tall buildings stiffened with a bracing system

Previous studies have highlighted the fact that framed buildings having non-degrading hysteretic behaviour in their structural elements can experience significant lateral residual (permanent) deformations after an earthquake ground motion (Pampanin et al. 2003, Ruiz-Garcia and Miranda 2006). Particulary, experimental and analytical studies have shown that steel buildings incorporating buckling-restrained braced frames can experience significant permanent drift demands (Kiggins and Uang 2006, Fahnestock et al. 2007). However, it should be noted that those studies based their results in a one-bay buckling-restrained brace frame, which neglects the contribution of the gravitational frames. Further studies observed that permanent drifts are constrained when a one-bay back-up frame is added to the buckling-restrained brace frame or when beam-to-column moment connections within the one-bay buckling-restrained frame are allowed (Kiggins and Uang 2006, Ariyaratana and Fahnestock 2010). However, no specific recommendation to provide additional lateral stiffness and strength was offered.

In spite of the advantages offered by buckling-restrained braced frames in terms of earthquake-resistance, concerns still linger in terms of their ability to survive intense aftershocks. Particularly, the large permanent drifts observed in the experimental and analytical studies of various buckling-restrained braced frames have created uneasiness about their apparent vulnerability to aftershocks, and this has resulted in recommendations that consider the use of heavy and stiff frames to provide them with a self-centering ability (Maley et al. 2010). Within this context, the advantages and large savings in terms of structural materials that result from the use of light and flexible gravitational frames are lost, and the weight of the buckling-restrained brace is comparable to that of any traditional structural system.

In spite of the apparent disadvantages associated to the use of gravitational frames to complement a buckling-restrained bracing system, it can be argued that a damage-tolerant approach does not only provide adequate seismic resistance against the main shock, but results in braced frames that, independently of the lateral stiffness provided by the frames, can exhibit small permanent drifts. A key consideration within this setting is that the gravitational system should remain practically undamaged (operational) while the bracing system develops significant plastic behavior (see Figures 1 and 2). An elastic gravitational system, no matter how low its lateral stiffness, is capable of providing the braced building with enough post-yield system stiffness that stabilizes its dynamic response and reduces its residual deformations (Teran-Gilmore and Ruiz-Garcia 2010). Note in the case of Figure 2, that in a tall building not only do the elastic frames promote self-centering behavior, but that the elastic behavior assigned to the columns that support the braces create an overall flexural behavior that provides further self-centering capabilities to the dual system.

4. SAMPLE BRACING SYSTEMS

The five braced frames shown in Figures 3 and 5 are taken into consideration herein to illustrate the high self-centering capabilities provided by flexible steel moment-resisting frames. In terms of low and medium height buildings, four regular three-bay frame models having two different numbers of stories are considered. The frames are representative of exterior moment-resisting steel frames found in typical office buildings in California, and were designed by Santa-Ana and Miranda (2000) according to the lateral load distribution along height of the 1997 Uniform Building Code (UBC). The flexural stiffness of the beams and columns of the frames was tuned to obtain two families of frames: one that comprises stiff frames; and a second one that includes flexible frames. While the family of stiff frames was intended to provide a realistic upper bound in terms of lateral stiffness; the flexible frames aimed at providing a realistic lower bound. All frames satisfy the maximum inter-story drift limitations of the 1997 UBC when subjected to the design lateral loads corresponding to Zone 4. The frames were stiffened through braces having the configuration shown in Figure 4, and sized according to a damage-tolerant approach. Within this context, the displacement-based methodology discussed by Teran and Virto (2009) was used to provide lateral control so that under the effect of the design earthquake, the maximum inter-story drift index demand is controlled within a 0.01 threshold required to keep elastic the frames.

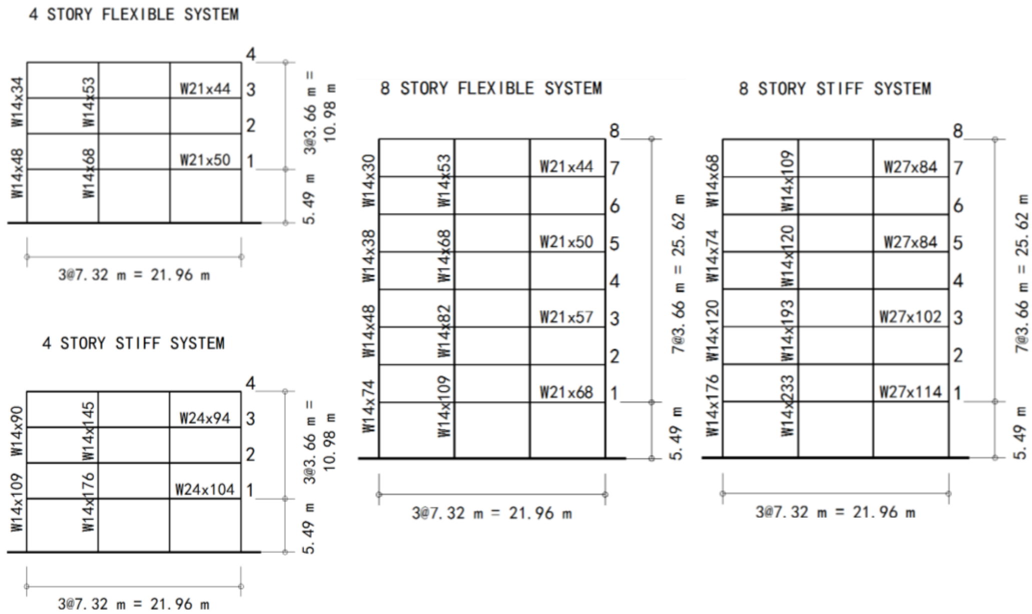

Figure 3. Steel moment-resisting frames under consideration (Santa Ana and Miranda 2000)

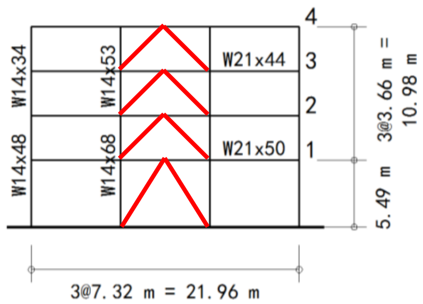

Figure 4. Configuration of bracing system for the four and eight-story frames

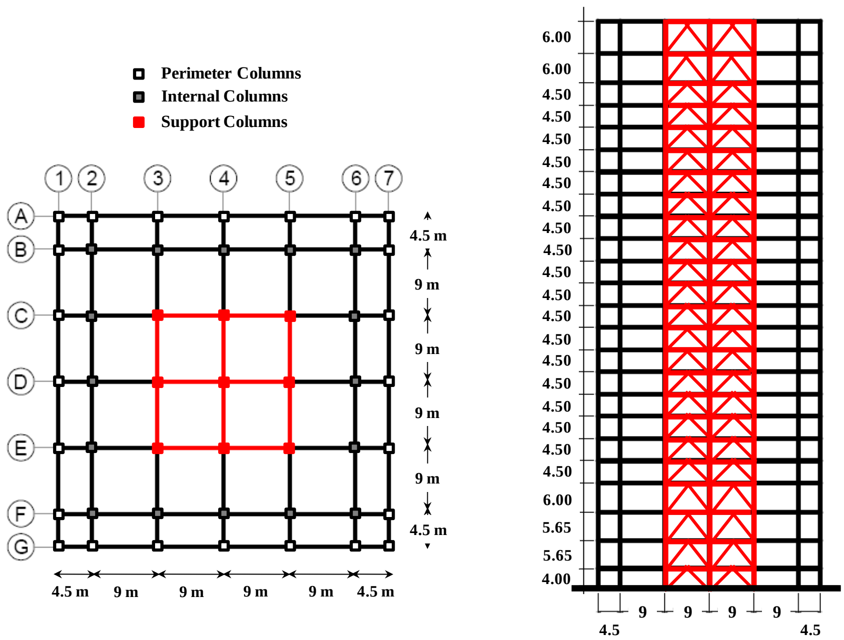

Figure 5. Geometry and structural layout of twenty four-story building

In terms of a tall building, a similar displacement-based methodology was used to design the twenty four-story steel building shown in Figure 5 (Teran and Coeto 2011). Overall, the building has a total height of 114.8 meters. The building has four central bays of 9 meters, two lateral bays of 4.5 meters and seven frames in each one of its principal directions. With the exception of the first three stories and the roof story, whose weights are equal to 1916 and 1355 tons, respectively, the stories of the building exhibit a weight of 1340 tons. As shown, the sample building requires for earthquake-resistance a steel bracing sub-system that includes the two central bays of the three central frames in each direction of analysis. Again and in order to keep the steel frames operational after the occurrence of the design ground motion, a maximum interstory drift index threshold of 0.01 was used. Tables 1 and 2 summarize the sizes of the braces used to provide seismic resistance to the frames.

Table 1. Dynamic properties and core area of braces for the four and eight-story frames

Frame	*T* (sec)	Area (cm$^{2)}$							
		1	2	3	4	5	6	7	8
four-story stiff	0.45	21	12	9	5	-	-	-	-
four-story flexible	0.48	29	19	14	8	-	-	-	-
eight-story stiff	0.74	36	22	20	18	16	13	9	5
eight-story flexible	0.77	43	30	28	25	22	18	13	7

Table 2. Dynamic properties and core area of braces for the twenty-four-story building

Frame	*T* (sec)	Area (cm$^{2)}$					
		1-4	5-8	9-12	13-16	17-20	24-21
Twenty-four story	3.0	120	89	86	77	62	37

One set of twenty ground motions, corresponding to the Los Angeles urban area, was considered for the design of the bracing systems of the four and eight-story frames. The ground motions were established for the FEMA/SAC Steel Project (Somerville et al. 1997), and correspond to the design earthquake for firm soil with 10% exceedance probability in fifty years. Figure 6 shows the elastic mean plus one standard deviation (σ) pseudo-acceleration and displacement spectra corresponding to the set of motions. Note that the strength spectrum has a corner period close to 0.4 sec, and that the displacement spectrum shows a practically linear increase of displacement with period. A series of synthetic motions were generated for the design of the twenty-four-story building. The motions, which intend to reflect the characteristics of the SCT85-EW motion, were generated through a two-stage simulation algorithm that is based on the stochastic sum of small motions (Kohrs-Sansorny et al. 2005). The seed motion used for this purpose was recorded during 1989 at the SCT site. The design spectra shown in Figure 7 correspond to ductilities of 1 and 2, and a percentage of critical damping of 5%. The inelastic spectrum was build from an elasto-perfectly-plastic model.

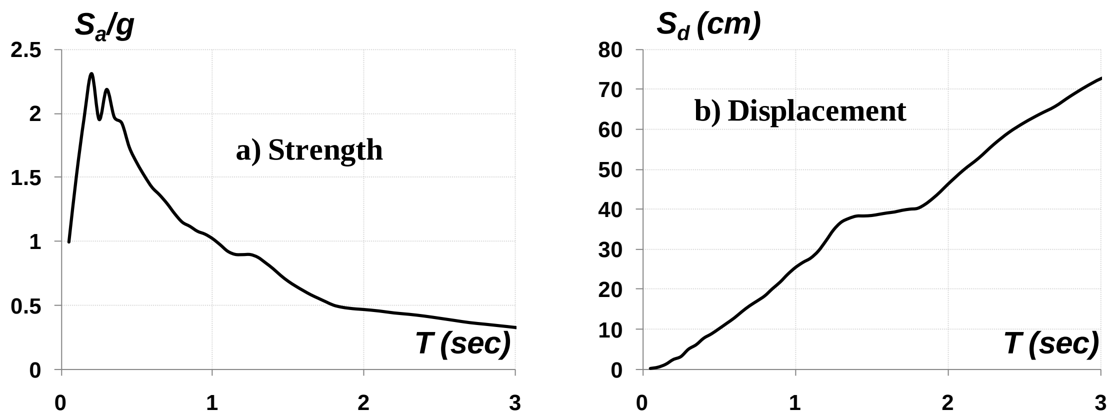

Figure 6. Design spectra for the four and eight-story frames

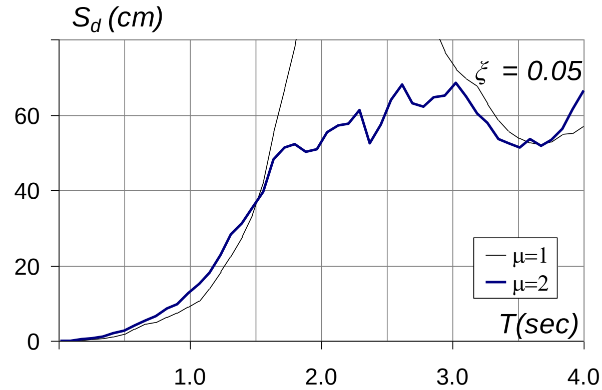

Figure 7. Design spectra for the twenty-four-story building

5. MAXIMUM AND PERMANENT DRIFTS

Nonlinear step-by-step dynamic analyses were carried for all braced frames to estimate their maximum and permanent drifts when subjected to the action of the design ground motion. The same motions used to establish the design spectra for the braced frames were considered for the nonlinear analyses, and in consistency with the statistical measure used to formulate these spectra, the mean + σ drift demands are considered in the discussion to follow.

For the nonlinear dynamic analyses, the frames were modeled as two-dimensional centerline nonlinear models. Rayleigh damping equal to 5% of critical was assigned to the first and second modes for all the frame models. While global P-Δ effects were considered during the analyses, local P-δ effects were neglected. Beams and columns were modeled as frame elements that concentrate their inelastic response in plastic hinges located at their ends. An elasto-plastic moment-curvature relationship was assigned at each end. In addition, axial load-flexural bending interaction was considered to model the hysteretic behavior of the steel columns. The flexural moment capacity of beams and columns was determined using actual yield strengths. The buckling-restrained braces were modelled as truss elements or axial springs with elasto-plastic *axial force-displacement* behaviour. Since experimental research has shown that buckling-restrained braces exhibit larger compressive strength than tensile strength, it was assumed the yield compressive strength of each brace is 2% larger than its corresponding yield tensile strength. In this study, the yield stress associated to the braces was assumed to be 10% larger than the corresponding nominal stress of 248.1 MPa. A detailed discussion of the modelling assumptions under consideration herein can be found in Teran and Ruiz (2010) and Teran and Coeto (2011).

Figure 8 shows that the maximum interstory drift index demands suffered by the four and eight-story frames are very close to their design threshold of 0.01. Permanent inter-story drift demands over height for these braced frames are shown in Figure 9. The displacement-based approach has given place to braced frames that exhibit a fairly uniform distribution along height of permanent drifts, and that have the ability to adequately control their residual deformations. A clear tendency can be observed for the peak residual inter-story drift demands: while a value of 0.001 or less is observed for the stiff braced frames, demands around 0.002 are observed for the flexible braced frames. In any case, the four and eight-story frames are in good shape to undertake any possible aftershock. In spite that the braces develop inter-story ductility demands close to five (they yield at an interstory drift index close to 0.002), the braced frames are able to adequately control their permanent deformation. This can be explained by the fact that the steel frames remain fully operational (elastic), thus providing an elastic component that mitigates residual displacements. Although the larger elastic component provided by the stiff frames results in smaller permanent drifts, the flexible frames provide adequate control of permanent drifts.

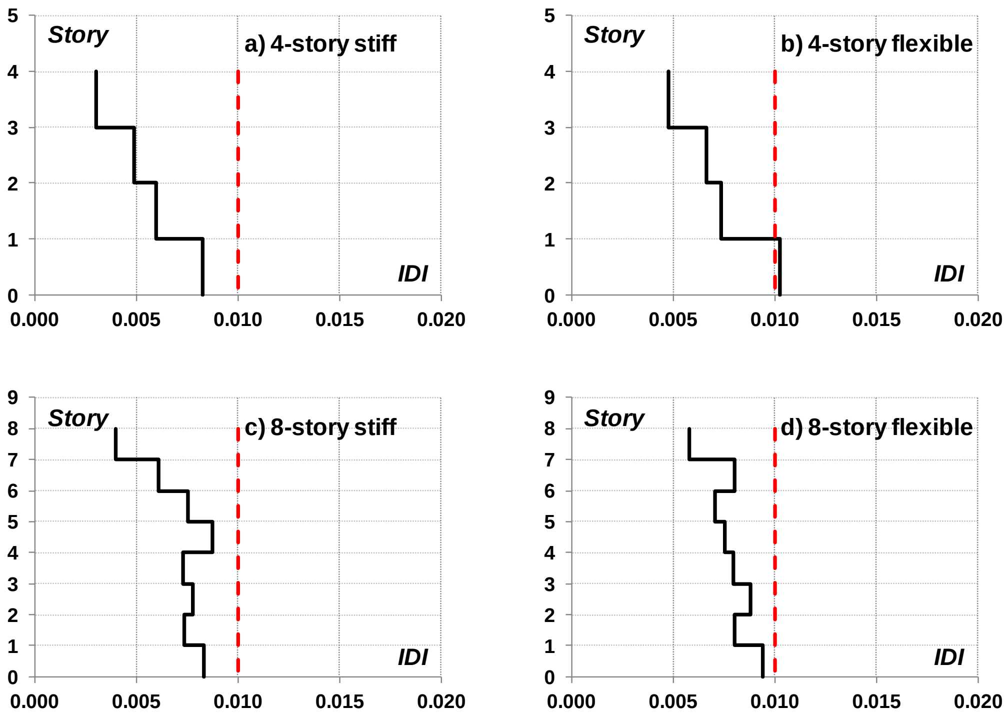

Figure 8. Maximum interstory drift index demands for the four and eight-story frames

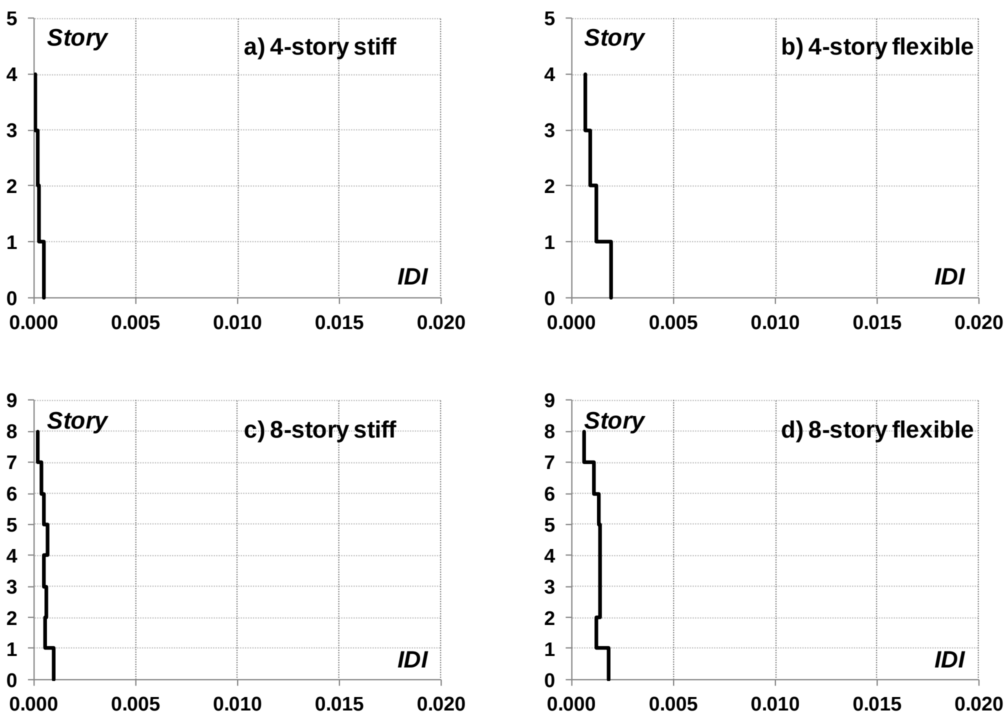

Figure 9. Permanent interstory drift index demands for the four and eight-story frames

Similar conclusions can be derived from the maximum and permanent interstory drift index demands shown in Figure 10 for the twenty-four-story building. In spite that the relative lateral stiffness provided by its gravitational frames is significantly smaller than that provided by the frames of the four and eight-story frames, the twenty-four-story building exhibits a noticeable self-centering behaviour characterized by permanent drifts close to 0.0005 along the entire height of the building. In part, this is a consequence of the enhanced self-centering capacity provided by the elastic behaviour of the columns that support the braces.

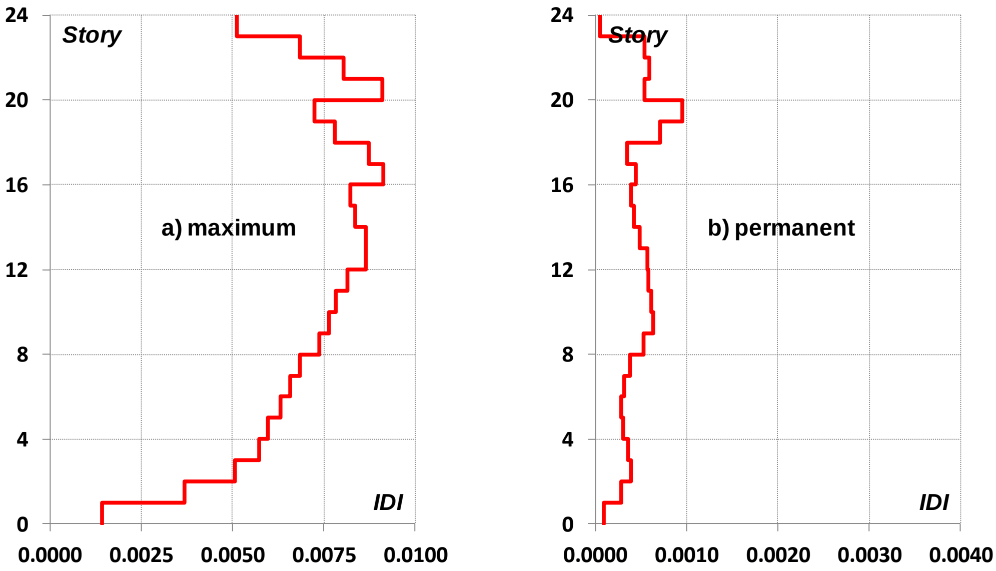

Figure 10. Interstory drift index demands for twenty-four-story frames

6. DISCUSSION

It is interesting to note that due to their large deformation capacity, it has been suggested that dual systems composed by steel frames and buckling-restrained braces can and should undergo significant nonlinear behaviour during severe ground motion. Under these circumstances, the residual deformations in the dual system need to be controlled either by hinging the ends of the structural members of the frame (Kim and Seo 2004, Choi and Kim 2009), or by contemplating the use of strong frames to provide adequate self-centering capacity. For example, Maley et al. (2010) considered dual systems in which the steel frames provide 40 to 50% of the lateral strength, and estimated residual inter-story drifts of 0.004 and 0.003, respectively, when these systems undergo maximum inter-story drifts close to 0.02 during the design ground motion. The results summarized in this paper allow for the formulation of a design approach that differs from that offered in previous publications. To explain this, the weight and inter-story drift index demands obtained for the different four-story buildings will be considered. In first place, the original (unbraced) four-story stiff frame weighs 25.8 ton and exhibits maximum and residual inter-story drifts of 0.02 and 0.006, respectively. Second, the braced version of this building weighs 27.1 ton, and has drift demands of 0.01 and 0.001, respectively. A first comparison between these two cases allows for the following conclusion: while the buckling-restrained braces adequately and efficiently control the maximum lateral response of the dual system, the stiff frames (which contribute close to 40% of the lateral stiffness of the system) allow for efficient control of the residual displacements. Nevertheless, note that no benefits are obtained in terms of structural efficiency by using stiff frames, because no significant reduction in weight can be achieved. Consider now the case of the braced four-story flexible frame, which weighs 13.1 tons and exhibits inter-story drifts of 0.01 and 0.002, respectively. Adequate performance is achieved in terms of maximum and residual displacements with a frame that contributes about 15% of the lateral stiffness of the dual system. The fact to be outlined within this context is that the braced four-story flexible frame is able to achieve this with about half the structural steel required by the two cases in which the stiff frame was considered. It can be concluded that in terms of performance and structural efficiency, a dual system with a flexible gravitational system can outperform similar systems in which the steel frames are assigned a larger role in terms of seismic resistance. A key element within this context is the need to carefully control the maximum inter-story drift in such a way as to achieve a serviceable gravitational system. The very small permanent interstory drift index demands (around 0.0005) observed for the twenty-four-story building confirms the previous observations. Nevertheless, it is interesting to note that in the latter case, its gravitational frames provide less than 10% of the lateral stiffness of the structural system. In the case of tall buildings, an enhanced self-centering capacity is provided by the damage-tolerant approach through keeping elastic the columns that support the braces.

The results obtained in this paper strongly suggest that although the use of heavy moment-resisting frames to provide self-centering capabilities to buckling-restrained braces may lead to adequate seismic performance, the end result of applying it is an inefficient use of structural steel. A dual system composed by a flexible gravitational system and buckling-restrained braces can outperform, particularly in terms of structural efficiency, similar systems in which the steel frames are assigned a larger role in terms of seismic resistance. A key element within this context is the need to carefully control the maximum interstory drift in such a way as to achieve a serviceable gravitational system.

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