Nonlinear Behaviour of Steel Braces Under Seismic Loading.

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Braced frames are a popular form of construction. It offers high strength for the weight of steel, and a stiff structure as well. However, greater stiffness does not necessarily translate to improved seismic performance because with greater stiffness the dynamic character of the structure is generally shifted to a more energetic regime of earthquake ground motions, which results in greater forces. Despite of this, braced frames can be an economical option in seismic regions.

The intended function of a braced frame is to resist lateral forces as axial actions in the structural members of the frame, and in seismic regions, ductile/dissipative behaviour can be achieved through buckling of braces in compression and yielding in tension. Inelastic hysteretic behaviour of braces has been tested in multiple component experiments, including in the testing programs carried out by Black et al. (1980) and Fell et al. (2008, 2009). In these studies a number of brace elements were put through dynamic loading time histories designed to mimic the effects of seismic events. A few examples hysteretic axial load-deformation responses brace members are presented in Fig. 1.

![Figure 1](image)

Figure 1. Measured and modelled brace axial load-deformation responses from (a) and (b) Black et al. testing program (Black et al. 1980), and (c) and (d) Fell et al. testing program (Fell et al. 2008, 2009). The measured brace responses are shown with a black line but modelled responses are shown with a red line. The ability to accurately model the brace responses formed a vital part in a study of retrofitting an existing steel moment-frame building by Björnsson (2013).
In compression, member buckling involves a lateral deflection and the formation of a plastic hinge at mid-length (and at two other locations towards the ends of the deflected shape). On reversing the load, elastic recovery occurs followed by loading in tension until yielding. In subsequent cycles the buckling load reduces due to residual deflections, the increase in length as well as the Bauschinger effect. Furthermore, tensile yielding occurs at increasing axial deformation with each cycle of loading, due to accumulated plastic elongation.

The observed hysteretic axial load-deformation responses reveals that relying on conventional brace elements to resist seismic lateral forces can be problematic. Namely, as anticipated, under strong ground motions the brace elements buckle in compression, resulting in a dramatic drop in stiffness and strength. Moreover, the buckling of brace elements in compression does not necessarily occur simultaneously over the entire height of a given structure. Hence, the braced-frame has a tendency to develop soft and weak stories in the most stressed portion of the structure, which can lead to concentration of deformations and formation of a collapse mechanism. Eurocodes attempt to address this issue by balancing the demand-to-capacity ratio over the height of the structure. EC8 limits the maximum difference in brace over-strength \( \Omega = \frac{N_{pl,Rd.i}}{N_{Ed.i}} \) over all the diagonals in a frame to within 25%. However, given the complexity of structural behaviour under seismic action, it is questionable whether this criteria is sufficient to ensure uniform behaviour over the height of the structure. Nevertheless, this limit has been shown to improve uniform behaviour under realistic seismic excitations (Elghazouli 2003, 2007).

Furthermore, the concentration of strains associated with the lateral deflection of the buckling mechanism builds up strain hysteresis in the cross section which limits the available ductility of the element upon reversal of the loading. If local buckling of the cross section occurs it further exaggerates the concentration of strains and may even lead to formations of cracks in the cross section and rapid deterioration of the element (Fell et al. 2008, 2009). In fact, in seismic situations, failure of brace elements is largely related to fracture of the cross-section following local buckling, provided that bracing connections are adequately designed and detailed. Eurocodes address the risk of connection failure prior to brace yielding through methodology of capacity design, i.e. designing connections and effected elements for the yield force of the brace elements, taking into account material overstrength \( (R_d > f, f_{ov,i}N_{pl,Rd(brace)}) \). Also, the risk local buckling of cross sections is addressed in Eurocodes by limiting the width-to-thickness of components depending on the expected ductility demand.

As an alternative to conventional braces, multiple devices have been developed in recent years to resist and dissipate seismic forces (Symans et al. 2008). One such device that is gaining increasing popularity in North America and in other seismically active regions is a special type of brace elements termed buckling-restrained braces. Buckling-restrained braces have been developed to avoid the pitfalls associated with lateral buckling of conventional braces. They are generally composed of a structural steel section that has a reduced cross-sectional area over a central portion of the element. The central portion is restrained from lateral and local buckling by an external mechanism, and is detailed such that the central yielding core can deform and yield longitudinally independently from the external mechanism. Conceptually the brace is intended to have equal properties in compression and in tension.

A number of experiments have been performed on the different types of buckling-restrained
elements, including Black et al. (2006), Newell et al. (2006), and Merrit et al. (2003a, 2003b). Interestingly, compressive strength of buckling-restrained braces has been reported to be greater than the tensile strength. This effect is commonly referred to as compressive overstrength. Compressive overstrength has been reported as great as 20% (Merrit et al. 2003b). Also, the braces have been demonstrated being capable of sustaining multiple cycles of highly nonlinear brace responses. A couple of examples hysteretic axial load-deformation responses buckling-restrained brace members are presented in Fig. 2.

Figure 2. Measured and modelled buckling-restrained brace axial load-deformation responses from (a) Newell et al. testing program (Newell et al. 2006), and (b) Merrit et al. testing program (Merrit et al. 2003). The measured brace responses are shown with a black line but modelled responses are shown with a red line. The ability to accurately model the brace responses formed a vital part in a study of retrofitting an existing steel moment-frame building by Bjornsson (2013).

The interested reader is directed towards Roader et al. (2011) and Elghazouli (2010) for a more in-depth discussion of brace behaviour and seismic design concepts for steel structures.

References
Newell, J., Uang, C., and Benzoni, G. Subassemblage testing of CoreBrace buckling-restrained braces (G-series). Tech. Rep. TR-2006/01, University of California, San Diego, La Jolla, California, USA, 2006.
