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Experimental investigation of behavior of steel frames with y-shaped concentric bracing

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ABSTRACT

Concentric bracings composed of three members arranged in y-shaped geometry have been traditionally used to provide openings in braced bays. However, using common single gusset plates in y-braced frames leads to single curvature flexure and out of plane buckling of braces accompanied by low hysteretic energy dissipation. In order to explore and improve the behavior of y-braced frames, a research program including experimental tests was conducted at BHRC[1] structural engineering laboratory. Specimens presented in this paper include four full-scale frames with y-bracings of different geometries and cross sections. Quasi-static cyclic loading was increasingly applied until yielding and failure occurred in the specimens. The results show that out-of-plane buckling with single curvature in braces can be replaced by in-plane, double curvature buckling through appropriate detailing of cross sections and connections. These sections have larger radius of gyration for out of plane buckling of bracing members. Hysteretic energy dissipation and damping of y-bracing are increased due to inelastic flexural deformation of brace members. Energy dissipation capacity of y-braced frames with new details is comparable with the traditional X bracing. Based on these findings, two-bay y-braced frames were designed to carry the same lateral load as X-braced frames. The seismic performance of these frames was compared using nonlinear static procedures and found to be similar.

1. Introduction

For nearly four decades, steel moment-resisting frames have been considered as one of the best structural systems for buildings in regions susceptible to severe seismic ground shaking. They also provide excellent compatibility between structure and open architecture of most office and residential buildings. However, experience and research show that severe earthquakes could produce very large interstory drifts in moment frames. Such large drifts could result in significant damage to structural and architectural components. As such, performance and economic considerations have lead many engineers to seek out simpler and more economical systems that promise good seismic performance with reduced interstory displacements. The most dramatic shift in construction appears to be a substantial increase in the use of concentrically braced steel frames (CBF) [1].

In spite of the increasing use of CBF as an earthquake load resisting system, there has been a growing concern to their ultimate deformation capacity because of observed damages in past earthquakes [2]. The major drawback of CBF is highly pinched inelastic load-drift cycles, which drastically decreases their seismic energy dissipation. This is more pronounced especially in configurations that provide architectural openings in braced bays, like chevron bracing [3].

y-shaped concentric bracing as typically shown in Fig. 1, has been devised as a compromise between architectural and structural requirements. The entire shaded area may be used for openings, which make it especially favorable in small building plans. However, increased axial forces in brace members accompany this advantage, which requires larger cross section for braces in comparison with X bracing. Basic geometrical parameters shown in Fig. 1 include the length of diagonal brace BR2, *l*, and the length of half-diagonal, *d*. The ratio *l*/*d*, which is practically less than 1.0, is a major factor in the fraction of bay area available for opening. Variation of *l*/*d* ratio also affects the stiffness and strength of y-braced frame.

A notable structural advantage of using symmetrical pairs of y-bracing is shown in Fig. 2.

It is evident from simple statics that the uplift on foundations is halved by using y-bracing in two bays of frame instead of X bracing. This point is of practical importance regarding technical and economical issues encountered in coping with uplift of foundations.

The y-braced frame has been briefly mentioned in technical literature. Taranath [4] introduces it as one of various forms of concentric bracings.

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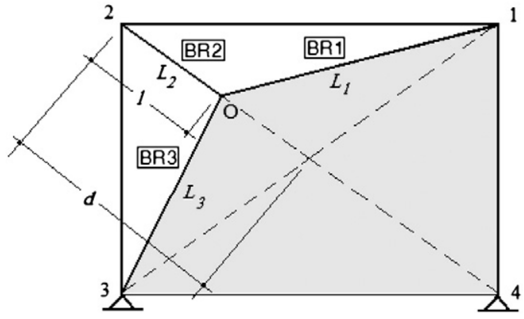

Fig. 1. General view of y-bracing.

Sontag [5] introduces this kind of bracing and shows its advantages in providing door and window openings in comparison with other bracing forms through perspective drawings.

Yaseri [6] mentions y-shaped bracing as an option for industrial steel buildings. He states that this type of bracing is not efficient under compression in its members. So it is advised to use symmetrical pairs of y-bracing in frames braced by this system.

This idea is also implied in Eurocode 8 [7] for design of buildings against earthquakes. Generally, it can be deduced from literature that y-bracing is not so reliable under compression in its members. This opinion may stem from observing the behavior of common connections of bracing members. These connections commonly include a single steel plate connecting the intersecting members. In this regard, Davaran and Hoveidae [8] noted the effect of mid-connection detail on the behavior of X-bracing systems and suggested a connection detail to improve continuity of braces. Also, Yoo et al. [9] noted the restraint provided by beam and column connections to gusset plates and its effect on behavior of multi-story X-braced frames. Specific guidelines have been presented in AISC [10] to design single gusset plates that facilitate inelastic rotations in ends of brace members. Further research by Lehman et al. [11] shows that AISC details can be further improved regarding rotational ductility of gusset connection. Even by adopting these details and proposals, it is obvious that the radius of gyration of common single plate gusset is very small, compared to that of braces. Such a connection is very weak against out of plane buckling and causes the brace to buckle at low critical load.

Under these conditions, lateral loads are naturally carried by the bays that have tensile bracings and are more stable.

If by some measures the load bearing capacity of y-bracing is increased up to acceptable levels, still it is necessary to use symmetrical pairs of this bracing. This is deduced from the code [10] requirement to resist the earthquake load by a combination of tension and compression in bracing members. In this regard, it should be noted that all three members of y-bracing go into tension or compression simultaneously. This is a direct result of having angles less than 180° between adjacent brace axes. In such geometry, balance of forces in convergence point stipulates the same sign for axial forces in three concentric brace members.

Several scientific documents exist on behavior of y-bracing under compression. Badpar [12] derived relations for computing the elastic buckling load. He assumed the connection of brace to frame to be fully fixed. Hinged connections were considered between brace members at convergence point. Brace members were modeled by prismatic frame elements that incorporate bending properties. The relation for computing the critical load is derived by setting the sum of the lateral stiffness of braces equal to zero. It has been shown that for frames of common dimensions having box section braces, critical load of y-bracing is comparable to its allowable tensile load.

Majidzamani and Rassouli [13] analyzed several one bay y-braced frames with various geometries using finite element models with shell elements. Box sections for braces and double plate gussets were incorporated in the models. Elastic and inelastic out of plane buckling of y-braced frames was studied. Cyclic inelastic analyses showed that the highest energy dissipation occurs in y-braced frames with l/d ratio from 0.54 to 0.6.

Majidzamani and Rassouli [14] conducted an experimental study on full-scale y-braced frame specimens. In this study, it is shown that using symmetrical box sections for brace members leads to out of plane buckling. In addition, the effect of location of the convergence point on the critical load and energy dissipation of frame is investigated.

Moghaddam and Estekanchi [15] analyzed y-braced frames regarding in-plane large deformations of bracing .Their research focused on the elastic behavior of y-bracing under tension in its members. They observed that low stiffness for small to moderate drifts reduces building accelerations and high stiffness under large lateral deflection, prevents building collapse.

In current paper, the results of a series of experimental tests conducted at Building and Housing Research Center (BHRC) are reported and elaborated. The main goal is to force the bracing to buckle inelastically in modes involving plastic hinges at mid-span and ends of brace members .It is hoped that significant decrease of compressive resistance after buckling is alleviated by enforcing higher buckling modes. This goal is achieved by intelligent detailing of the cross section of bracings and their connections. By limiting the buckling of bracing to in-plane mode, the effective buckling length of bracing members is based on individual member length rather than the full bay diagonal length. This provides a remarkable convenience in structural engineering computations.

2. Geometric design of specimens

Specimens discussed in this paper are destined to provide lateral support in one axis of plan for a one-story building as shown in Fig. 3. All specimens are one bay frames with 4.2 m span and 3.0 m height. These dimensions can be regarded as typical for low-rise buildings on small land lots.

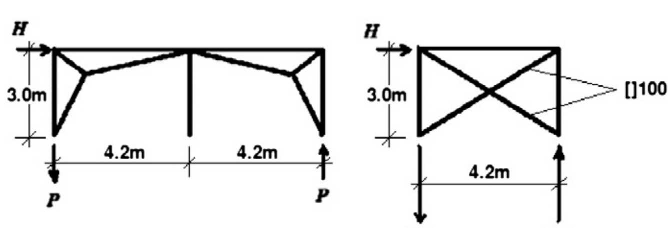

Fig. 2. Equivalent concentric bracings of two types.

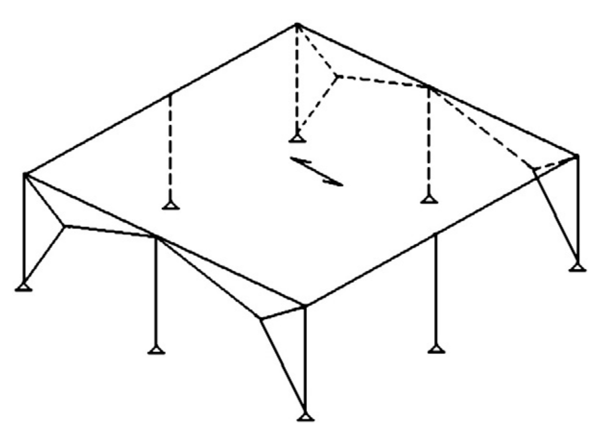

Fig. 3. General arrangement of y-braced frame.