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Three-segment steel brace for seismic design of concentrically braced frames

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ABSTRACT

A three-segment steel brace has been developed and investigated by means of numerical and experimental studies. The objective of the development was to develop a brace member that exhibits stable and symmetrical cyclic response under cyclic loading. The concept was conceived by extending a conventional elastic buckling of a column with variable sections to include post-buckling deformation. The concept was first examined using FEM-based simulations, and tested experimentally with an ensemble of small-scale brace specimens under cyclic loads. Seismic response of CBFs with conventional buckling braces and the three-segment braces were compared and results are discussed in terms of drift, brace and beam ductility demands. The results indicate that the tested three-segment braces specimens were capable of exhibiting stable and symmetrical hysteretic response, as well as dissipating a greater amount of energy compared to conventional buckling braces. Further, the dynamic analyses results point out that substituting the conventional buckling braces with the three-segment braces substantially mitigates the seismic demand on the braced frames.

1. Introduction

Seismic response of a concentrically braced frame (CBF) is highly dependent on the inelastic cyclic behavior of its braces. Due to the degradation in compressive strength subsequent to global buckling, conventional buckling braces exhibit an unstable and unsymmetrical cyclic behavior when subjected to an earthquake ground motion excitation. The potential issues arising from the unsymmetrical hysteretic response due to the post-buckling behavior can be summarized as follows:

(1) Strength loss due to the post-buckling behavior substantially reduces the overall energy dissipation capacity of a CBF.
(2) Substantial difference between the tensile and compressive strengths [1] would impose significant demands on the brace-intersected girders [2,3], columns and beam-to-column connections [4] during a seismic event.
(3) Isolated stories in a CBF that incorporates conventional buckling braces may be subjected to significant lateral stiffness and strength reduction due to the rapid stiffness and strength degradation in compression subsequent to global buckling. As a result of the non-uniform lateral stiffness and strength distribution along the building height, plastic deformations may accumulate in the relatively weak (or soft) stories as the demand increases [5].

The purpose of this study is to develop a steel brace member with conventional structural shapes that provides significant inelastic deformation capacity primarily through its yielding in tension and compression.

2. Buckling of a non-prismatic column

2.1. General remarks

Employing a uniform cross-section along the length (prismatic member) of an axially-loaded member (column member) might not be the most efficient way to resist compressive loads [6]. An investigation of a buckled simple column is given in Fig. 1. A compressed column member buckles globally when it reaches its critical load and begins to deform laterally (Fig. 1b). This lateral deformation induces second-order bending moments, which leads to plastic hinge formation at the mid-length of the brace. As indicated in Fig. 1(c), bending moment diagram for a buckled brace is not uniform, and thus the buckling load, as well as the hysteretic stability of a column member can be improved by increasing the steel material at the middle portion [6].

Ideally, such improvement can be achieved by utilizing a cross-

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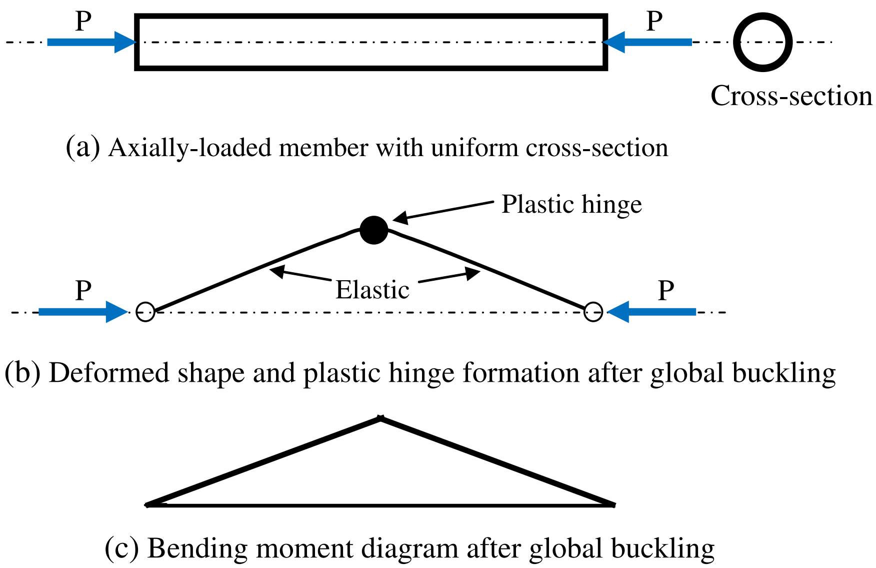

Fig. 1. Illustration of buckling of an axially-loaded member with uniform cross-section.

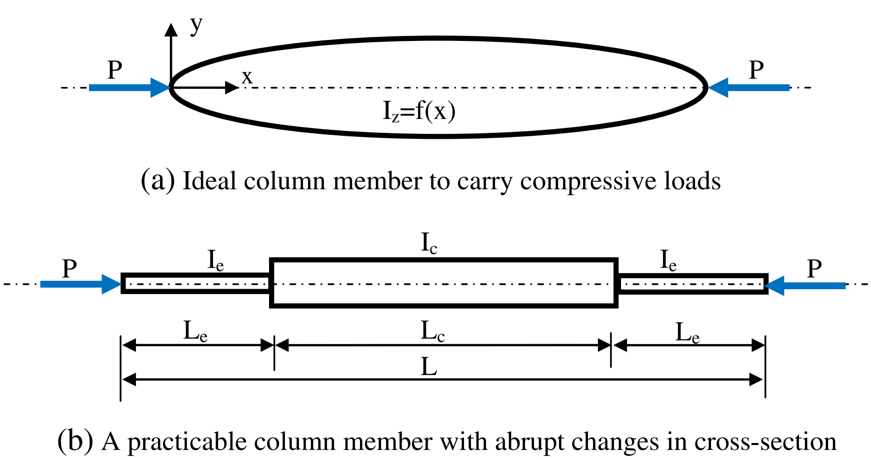

Fig. 2. Column members with non-uniform cross-sections.

section that is dependent on the bending-moment diagram, as shown in Fig. 2(a). However, a bar of parabolic non-prismatic cross-section is not practical for steel construction. As an alternative to the ideal case given in Fig. 2(a), a more practical steel brace model with sudden changes in cross-section can be used [6]. Fig. 2(b) illustrates a three-segment steel brace with hinged ends, which consists of two identical smaller end segments and a larger center section connected to the two end segments.

In steel structures such members can easily be fabricated by bolting or welding connector plates between the three segments. Several structural shapes with different combinations can be used interchangeably as end or center segments in order to increase inelastic deformation capability of the brace. Fig. 3 shows possible design options for the developed three-segment steel braces, employing square and round hollow structural sections (HSS). Considering the labor cost and ease of construction, either welded or bolted connection can be utilized to attach the end segments to the center segments.

An illustrative brace design with bolted attachment is given in Fig. 3(a). First, two identical end segments made of round or square HSS are pre-welded to gusset plates in a fabrication shop. Then, a larger HSS is connected to the two end segments following the erection of the columns and girders together with the gusset assemblies. With this attachment, the developed three-segment brace model has a high potential to speed up the construction process significantly by assembling beam-gusset-brace assemblages in a fabrication shop. In fact, construction of a CBF that incorporates the developed braces with bolted connectors might even be easier and faster than constructing a CBF with conventional braces owing to the shop-made brace-to-gusset connections in a three-segment CBF.

The second connector design option is similar to steel braced frame construction that incorporates conventional braces. End and center segments are welded to connector plates in a fabrication shop to form a three-segment brace (Fig. 3b). The end segments are to be fillet welded to the gusset plates subsequent to erection of the columns and girders. In the numerical and experimental portions of this study, the second connection option is investigated. In the numerical and experimental portions of this study, circular tubes with the welded connecter option are solely investigated. Further investigation is needed to extrapolate the findings of the present study to the braces with rectangular tubes or combination of circular and rectangular tubes utilizing bolted or welded connections as well as to the braces that incorporate circular tubes with bolted connection option.

2.2. Identification of design parameters

The essential design parameters have been identified and investigated through analytical and numerical studies prior to the experimental program. Determination of the design parameters began with the analytical solution to a simple case of a three-segment column given in Fig. 4. Note that the intended goal of the present study is to examine the inelastic cyclic behavior of the developed three-segment braces. However, identification of the key design parameters embarked