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Modeling of different bracing configurations in multi-storey concentrically braced frames using a fiber-beam based approach

K.K. Wijesundara [a], R. Nascimbene [b,*], G.A. Rassati [c]

[a] SAITM, Faculty of Engineering Malabe, Sri Lanka
[b] European Centre for Training and Research in Earthquake Engineering (EUCENTRE), Via Ferrata 1, 27100 Pavia, Italy
[c] Department of Civil and Architectural Engineering, University of Cincinnati, Cincinnati, OH, USA

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ABSTRACT

This study presents a modeling approach for concentrically braced frames to be used in multi-storey buildings. The model for an inelastic beam-column brace consists of two inelastic force-based beam-column elements, each of which having five integration points and a discretized fiber section. The hysteretic response of such elements can be derived by integration of uniaxial stress-strain relations.

To capture the effects of gusset end restraint, in addition to the two inelastic beam-column elements, this study uses an additional inelastic force-based beam-column element of length 2 t (where t is the thickness of the gusset plate) at each end of the brace. This study presents the correlation of the axial force–axial displacement and the axial force–lateral displacement responses obtained from the brace model with the available experimental results.

Based on the comparison of numerical hysteretic responses with the experimental results, it can be concluded that the brace model which includes two additional force-based beam-column elements at the ends of the brace can capture the hysteretic responses of axial force–axial displacement and axial force–lateral displacement more accurately. Finally, this study sets the limits of slenderness and the width-to-thickness ratio in which inelastic beam-column brace model can predict the hysteretic responses of a brace member with adequately accuracy.

1. Introduction

Concentrically braced frames are commonly used for seismic design in high seismic areas due to their high stiffness and strength when compared to moment resisting frames (Nascimbene et al. [23]). In current design practice, CBFs are designed and detailed to dissipate energy through brace yielding in tension and inelastic buckling in compression under the strong shaking of an earthquake. Therefore, the inelastic behavior of braces has been extensively studied in the past by a number of experimental programs (Black et al. [3], Lee and Goel [21], Archambault et al. [2], Walpole [35], Shaback [28]). These studies have identified the main influencing parameters for the hysteretic response of a bracing member as slenderness, which is a function of end conditions and section shapes, and width-to-thickness ratio, which governs the local buckling of a brace.

Depending on the slenderness ratio, braces can be classified into three categories as stocky, intermediate and slender braces (Fig. 1(a)). Stocky braces can be identified as braces for which yielding and local buckling dominate the response (Fig. 1(b)). The limiting value of the slenderness for the stocky braces could vary as a function of material stress–strain relationship, the width-to-thickness ratio of the brace, the residual strain in the brace, and the initial out-of-straightness of the brace. Bruneau et al. [4] proposed an approximate value for the slenderness ratio of 60 for compact braces made of A36 steel and 50 for compact braces made of Grade 50 steel.

Intermediate braces are identified as braces for which local buckling phenomena are less critical than global inelastic buckling (Fig. 1(c)). The range of slenderness ratios can be approximated to 60–130 for intermediate braces made of A36 steel to 50–110 for braces made of grade 50 steel.

Furthermore, different numerical models have been proposed in literature as an alternative to experimental tests to simulate the hysteretic response of a brace. Basically, these models can be classified into three main categories as: (a) phenomenological [19], (b) beam-column element [20,33,34] with different approaches for taking into account the interaction between second order bending moment and axial force, and (c) three-dimensional finite element models [10,15,27]. Phenomenological models represent a brace by a truss element with a hysteretic behavior that mimics the experimentally observed response (Ikeda et al. [19]). This approach has limited predictive capacity, since the hysteretic behavior can only represent the response of the individual specimen for which it was calibrated. Three-dimensional finite element models derive the hysteretic

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* Corresponding author.
E-mail address: roberto.nascimbene@eucentre.it (R. Nascimbene).

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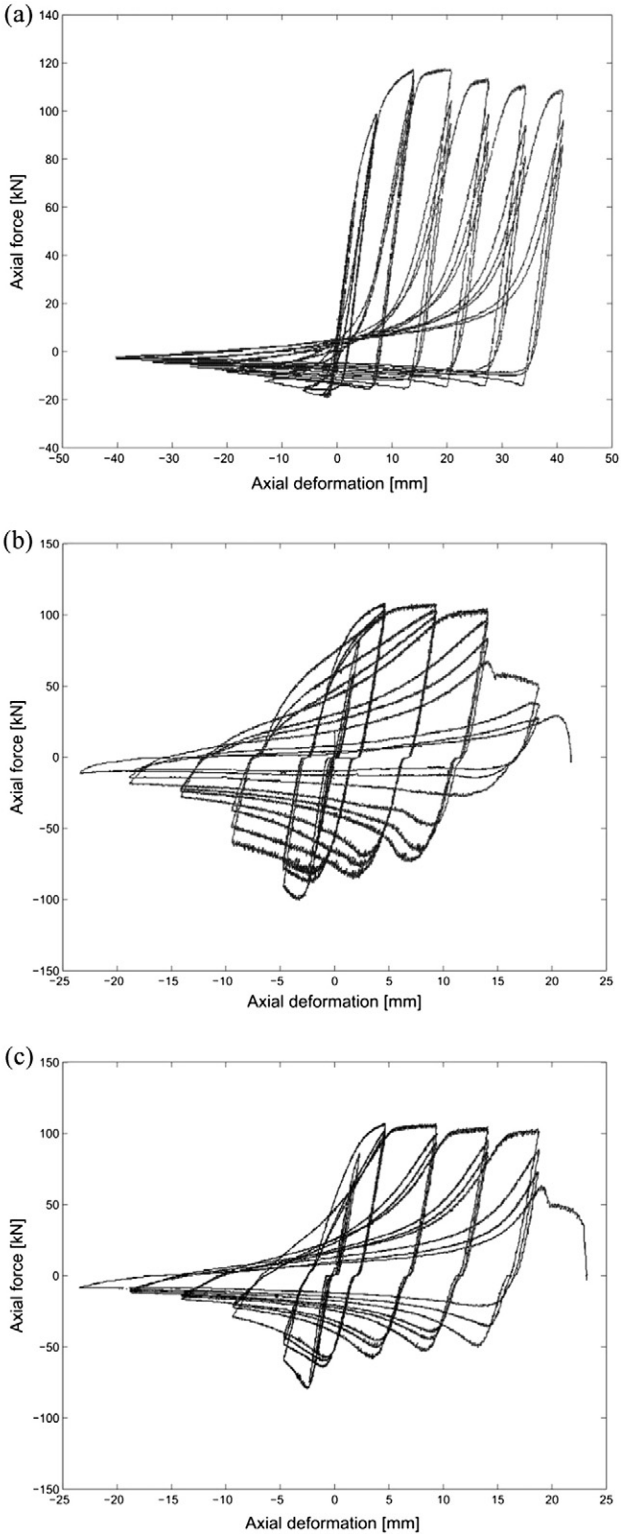

Fig. 1. Hysteretic behavior of slender brace (a), stocky brace (b), and intermediate brace (c) (adopted from Goggins et al. [16]).

response of the brace from the nonlinear material response of the system under large deformation theory [15,26,33]. Such models are not commonly used in structural engineering applications, because of their complexity and computational cost. Beam-column element models could be further subdivided into two subcategories: linear elastic beam-column elements with an inelastic hinge at mid length of the brace [38] and inelastic beam-column element models as proposed by Uriz [33] within the OpenSees computational framework [26].

This study investigates in detail the capabilities and the limitations of the inelastic beam-column element model proposed by Uriz [33] within the OpenSees computational framework [26] in simulating the hysteretic response of a brace with gusset end restraint in different bracing configurations. For this purpose, an additional inelastic force-based beam-column element of length $2t$ (where t is the thickness of the gusset plate) at each end of the brace model is included in the inelastic beam-column brace model to capture the effects of gusset end restraint on the hysteretic response more accurately. Furthermore, this study presents the correlation studies with the available experimental results of the axial force–axial displacement and the axial force–lateral displacement responses obtained from the brace model.

Based on the comparison of the numerical hysteretic responses with the experimental results, the brace model which includes an additional force-based beam-column element at the ends of the brace can capture the hysteretic responses of axial force–axial displacement and axial force–lateral displacement with adequate accuracy. Finally, this study proposes limits of slenderness ratios and width-to-thickness ratios within which the inelastic beam-column brace model can predict the hysteretic response of a brace member with adequate accuracy.

2. Nonlinear beam-column element brace model

Using an inelastic beam-column model, braces are modeled with fiber elements based on the force formulation (Spacone et al. [30]). The force formulation has many advantages over the typical displacement formulation such as [24,25,27,31,37]: (a) the force-interpolation functions are always exact in the absence of 2nd order effects, (b) a single element can be used to represent the curvature distribution along the entire member with sufficient accuracy through the selection of an adequate number of integration points and (c) the formulation has proven to be numerically robust and reliable, even in the presence of strength loss as it is seen in the inelastic brace buckling. Large displacement/rotation effects are taken into account through the use of the corotational theory [9,14], whereas the small deformation theory is used for the computation of local stresses and strains in the inelastic beam-column element.

Using this force-based approach, a brace must be modeled with at least two inelastic beam-column elements to represent the large in-plane and out-of-plane displacement of the brace. This model is capable to take into account the axial force and bending moment interaction by integrating the uniaxial hysteretic steel material model over the cross section of the brace. Therefore, a finer subdivision of the fibers is necessary to accurately represent local deformation. Furthermore, a minimum of three integration points must be assigned to each inelastic beam-column element to account for the interaction along the brace. As clearly explained by D'Aniello et al. [11], it is also essential to include an imperfection either to the geometry of the system in the form of an initial camber or to the properties of the member in the form of a residual stress distribution over the cross section to initiate the global buckling of a brace at realistic force levels.

The correlation studies conducted by Uriz [33] with the experimental results of the axial force–displacement response of brace specimens show that the model with two inelastic beam-column elements and each element with three integration points, predicts the buckling strength, post buckling behavior, and the hysteretic behavior of a brace with a compact cross section very well. Furthermore, it is recommended specifying the initial camber as 0.05–0.1% of the brace length. However, it is important to note that the end restraint conditions in the specimens used for the correlation studies are pinned–pinned and fixed–fixed, respectively. More studies have been performed and herein considered on the evaluation of the initial camber: Hu [18] used $L_s/1000$ and a parabolic distribution along the element; Nascimbene et al. [23] defined $L_s/700$ where the effects of the gusset plates at the restraint