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Review

A review of research on steel eccentrically braced frames

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ABSTRACT

This paper reviews the research conducted on steel eccentrically braced frames (EBFs). Both component level and system level responses for such braced frames are treated and discussed. For the component level response, a thorough review of the investigations on links, which are the primary sources of energy dissipation in EBFs, has been presented. The results of experimental and numerical studies on strength, rotation capacity, and overstrength of links are discussed. Furthermore, studies on the effects of axial force, the presence of a concrete slab, the loading history, compactness, link detailing, and the lateral bracing on link behavior are summarized. Relevant available research on link-to-column connections is revisited. Different approaches for the numerical modeling of links are also given. For the system level response, characteristics of EBF systems are discussed in light of the capacity design approach. Findings of numerical studies on the seismic performance of EBFs are discussed to provide insight into suitable response factors utilized in the design of these systems. Additionally, special topics and emerging applications of EBFs, such as replaceable links, are provided. The impact of research findings on the design of EBF systems is demonstrated considering the AISC Seismic Provisions for Structural Steel Buildings. Finally, future research needs for improvement of EBF design and application are identified and presented.

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1. Introduction

The main idea in the design of an eccentrically braced frame (EBF) is to integrate the advantages of both moment resisting frame (MRF) and concentrically braced frame (CBF) lateral load resisting systems into a single structural system. The EBF system originated from Japan in 1970s [1,2] with the aim of achieving a structure with high elastic stiffness as well as high energy dissipation during severe earthquakes.

There are several configurations for an EBF system, some of which are depicted in Fig. 1 along with their expected plastic mechanisms. Larger architectural openings can be used with EBF systems when compared to CBFs. The short segment of the frame generally designated by the length *e* (Fig. 1) is called the link. In EBF systems, yielding is concentrated only at link segments and all other members of the frame are proportioned to remain essentially elastic. Therefore, during severe earthquakes, links can be considered as structural fuses which will dissipate the seismic input energy through stable and controlled plastic deformations.

A comprehensive review is provided in this paper on the behavior and design of eccentrically braced frames. The review includes research conducted on links, as they comprise the most critical elements of an EBF. In addition, the research on EBF system response is elaborated. Areas of future research needs are also identified. The comparison of design provisions as presented in various design specifications is out of the scope of this work; however, the AISC Seismic Provisions for Structural Steel Buildings [3] are mentioned to illustrate relationships between research findings and design rules.

2. Characteristics of links

2.1. Yield behavior, shear capacity and overstrength

The length of a link segment (e) is one of the key parameters that controls the stiffness, strength, ductility, and behavior of an EBF system. The link length ratio, $\rho = e / (M_P / V_P)$, where M_P and V_P are the plastic moment and plastic shear capacities of the link, provides a convenient measure for the yield behavior. The free-body diagram of an isolated link is shown in Fig. 2. Based on equilibrium, considering equal end moments at the ultimate state, no moment-shear interaction, and an elastic-perfectly plastic material, the theoretical dividing link length ratio between shear dominated and flexure dominated behavior is $\rho^{theor} = 2.0$. In short (or shear) links, shear yielding of the web is found to be predominant (Fig. 3a). On the other hand, in long (or moment) links, flexural yielding controls the link behavior (Fig. 3c). An intermediate link, however, would experience a combination of both shear and flexural yielding (Fig. 3b).

There are substantial differences between the behavior of short and long links. Although longer links provide more architectural freedom for openings, early experimental studies by Roeder and Popov [4,5] and Hjelmstad and Popov [6,7] showed that the performance of short links is considerably better than that of long links under severe cyclic loadings in terms of strength and ductility. Over the years Popov and his colleagues [6,8–10] suggested different practical limiting lengths for shear dominated behavior, finally arriving at the limit of $\rho < 1.6$, which is still in use in many design specifications including AISC 341-10 [3].

The first comprehensive study on the behavior of intermediate and long links ($\rho > 1.6$) was conducted by Engelhardt and Popov [11] in 1989. A total of 14 tests were conducted on 12 two-third scale subassemblage specimens with ρ ranging from 1.45 to 4.25. Based on the experimental results it was concluded that a gradual transition from the shear-dominant behavior to the flexure-dominant behavior occurs as ρ is increased from 1.6 up to 3. Despite this, in most of the previous and current specifications (e.g. [3,12]), links with length ratios of $1.6 < \rho < 2.6$ are classified as intermediate links while links with $\rho > 2.6$ are generally referred to as long links. It is important to note that the presence of high axial force in a link may change this categorization, as discussed in Section 2.3. Engelhardt and Popov [11] also

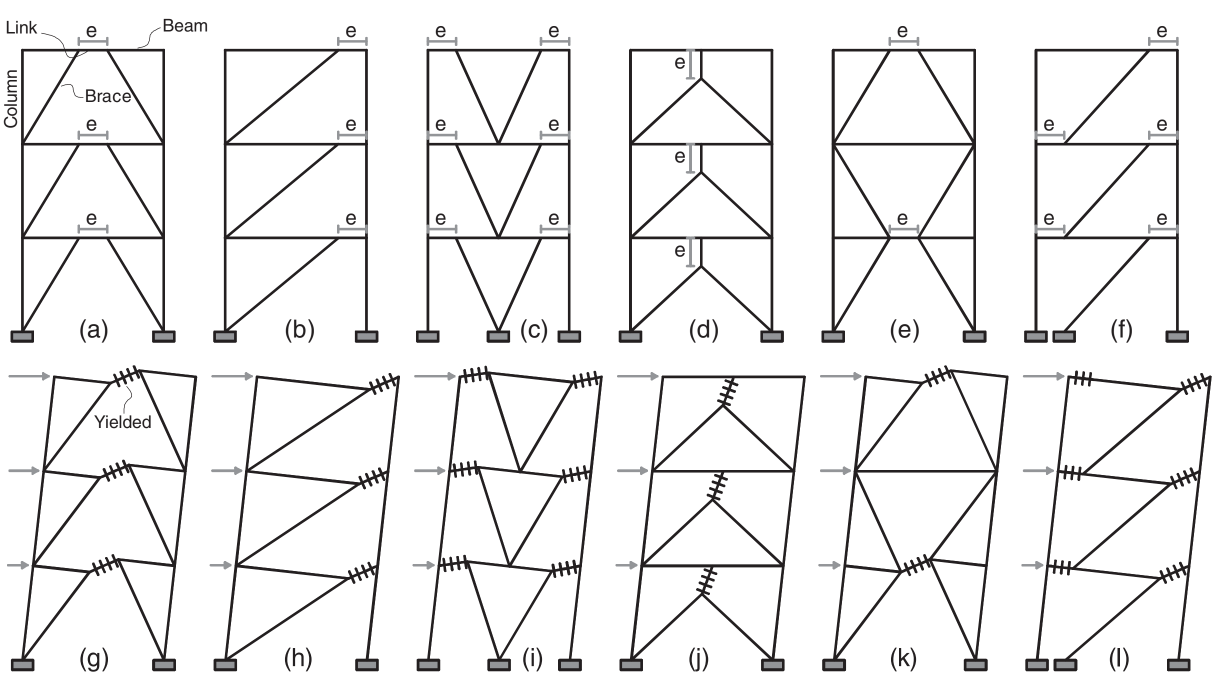

Fig. 1. EBF configurations and their corresponding plastic mechanisms.