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Development of Eccentrically Interconnected Braced Frame (EIC-BF) for seismic regions

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ABSTRACT

This study aims to develop an Eccentrically Braced Frame (EBF) system, which is so called Eccentrically Interconnected Braced Frame (EIC-BF), by proposing an innovative Structural Fuse (SF) using a very thin mid-height gusset plates with specified details for seismic regions. In the proposed structural system, as a low damage or repairable system, the mid-height gusset plate, as a replaceable centric shear link that connects four eccentric brace segments, behaves as a SF so concentrates most of large deformation and stress demand and dissipates the large amount of energy imposed by lateral loading. In order to investigate the effect of the proposed SF with the specified details, i.e. mid-height gusset plates with proposed details, on the seismic behavior of EIC-BF, nine three-fourth scale cyclic experiments were conducted. This research describes the results of the experiments elaborately and evaluates the cyclic responses of the studied EIC-BFs with respect to their utilized details. The results show that establishing the specified details and design parameters including eccentricity value of braces at mid-height gusset plate, mid-height gusset plate thickness and the stiffener configuration at mid-height gusset plate improves the seismic performance of EIC-BF in term of story drift angle by up to 32% as well as reduces the considerable pinching in cyclic response; while prevents main structural elements including beam, columns and braces from undergoing inelastic behavior.

1. Introduction

Eccentrically Braced Frames (EBFs) are widely used as the conventional lateral force resisting system for high seismic regions because they inherently provide both high stiffness and ductility required during strong earthquake due to the yielding of shear link [1]. In EBF systems, the link element is designed to act as structural ductile fuse and energy dissipater while the braces, beam and column material remain in elastic range of stress-strain curve of steel material and the maximum rotation of link element is controlled by vertical stiffeners and shear link mechanical specifications [2]. In order to concentrate the high stress demand at shear link, many researchers suggested different types of structural fuse as replaceable links of EBF system. For Example, Sabouri-ghomi and Roufegarinejad [3] proposed Yielding Damped Braced Frame (YDBF) as a structural fuse for the braced frame system to provide high ductility and prevent damage to the main structural elements such as columns. YDBF consisted of a box-shaped interior frame which is replaced with mid-height gusset plate and sustain high stress demand by tensile yielding of YDBF. The main result of this research indicated that YDBF can dissipate the energy due to strong ground motions sufficiently and control the lateral displacement adequately. Prinz and Richards [4] performed analytical study to consider the effect of drilled holes at EBF link web on reducing stress demand at EBF link flange as well as providing required connection rotation capacity for EBF link [5] by increasing the plastic strain demand around the drilled holes. They finally concluded that the reduced web section of EBF link is not a promising solution that assure achieving the required qualifications for EBF system as desired by AISC [5]. Chan et al. [6] developed Yielding Shear Panel Device (YSPD) as an energy dissipater device in the braces frame using a thin diaphragm steel plate welded inside a square hollow section (SHS). They indicated that the proposed device with specified geometric specifications is able to tolerate excessive plastic shear deformation through a stable cyclic response. In a follow-up study, Hossain et al. [7] developed the theoretical model for YSPD using experientially validated Finite Element Models (FEMs) to establish a design methodology.

Daneshmand and Hashemi [8] performed an extensive analytical study to consider the effect of geometric and mechanical specifications

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of EBF link such as slenderness ratio of the beam web as intermediate and long links on the seismic performance of EBF. The results of this study confirmed that the intermediate-length links with larger slenderness ratio of beam web do not satisfy the requirements as desired by AISC 341-05 [5]. Kuşyılmaz and Topkaya [9] investigated the influence of geometric parameters for EBF link on the overstrength factor of seismic response by developing a computational design algorithm to optimize the braced frame sections such as link beam section. The result of this research revealed that an increase in the EBF link length to bay width ratio leads to an increase in design overstrenght of EBF.

Gray et al. [10] proposed a new Yielding Brace System (YBS) that dissipates the energy by using the yielding steel fingers of a specially engineered cast steel connector. The results of their research indicated that ductile connector of YBS can enhance the dissipated energy and displacement capacity of braced frames. Mohebkhah and Chegeni [11] studied analytically the Overstrength and rotation capacity of EBF links made by European IPE sections. As a key finding of this research, it is exhibited that overstrength factor of short link made of European IPE sections with small distances between the web vertical stiffeners are considerably greater than the corresponding value suggested by the codes [5] while using the corresponding codified value [5] for design of intermediate and long link of EBF leads to conservative results. Hosseini Hashemi and Alirezaei [12] conducted experimental studies to develop an innovative structural system combining eccentric and knee bracing system which is so called Eccentrically Knee Brace (EKB). They showed that the proposed system is capable of providing the required stiffness and strength by adjusting two subsequent yielding of knee and diagonal brace elements. As the structural fuse concept adopted for this study, the knee element will yield first during a moderate earthquake; then both of them, i.e. knee and diagonal braces, contribute in dissipating energy in strong earthquakes. Zahrai [13] and Zahrai and Parsa [14] performed investigation on the cyclic behavior of Vertical Link Beam (VLB) with IPE shear panels, they indicated that stable hysteresis cycles will form when sufficient lateral support for VLP are provided and VLP can dissipate most of energy while the beam, braces and columns remain in elastic range of material properties. In a similar study, Tan and Christopoulos [15] carried out an extensive analytical study to develop an efficient replaceable cast steel link as a structural fuse for EBF by different structural fuse concept including Replaceable Link Benchmark (RLB), Simultaneous Flexural Yielding link Concept (SFYC), the Yielding Ring Concept (YRC) and Corrugated Web Concept (CWC). They concluded that the best performance is achieved by the replaceable cast steel link which employs the concept of SFYC using a rectangular, hollow cross section with varying widths. Ioan et al. [16] conducted experimental study on a full scale three-story braced frame to assess the seismic behavior of dual EBF with replaceable shear link. They exhibited that replaceable link provides excellent performance in dual EBF during strong earthquake; Also re-centring capability of dual EBF with replaceable link reduces the costs and manpower required for post-earthquake repair. Cheraghi and Zahrai [17] proposed a multi-level concentric pipe in pipe passive damper to establish two-level control structural system and then performed analytical study by Finite Element Method (FEM) to investigate the effect of the proposed passive damper on the seismic behavior of braced frame. The analytical results demonstrated that the proposed damper can sufficiently dissipate the energy considering different energy levels. Budiono et al. [18] experimentally studied the effect of residual stress on the performance of EBF link elements. The outcome of this research revealed that the distribution patterns of residual stress at the welded area close to both vertical and horizontal stiffeners added to shear link of EBF have the same values. In a review study, Azad and Topkaya [19] concluded the results of previous researches on EBF and they highlighted the effect of shortcoming of detailed spacing requirement for vertical stiffener added to intermediate and long shear link on seismic performance of EBF, which was not carefully addressed in previous researches, to come up with promising solutions for poor performance of this kind of shear

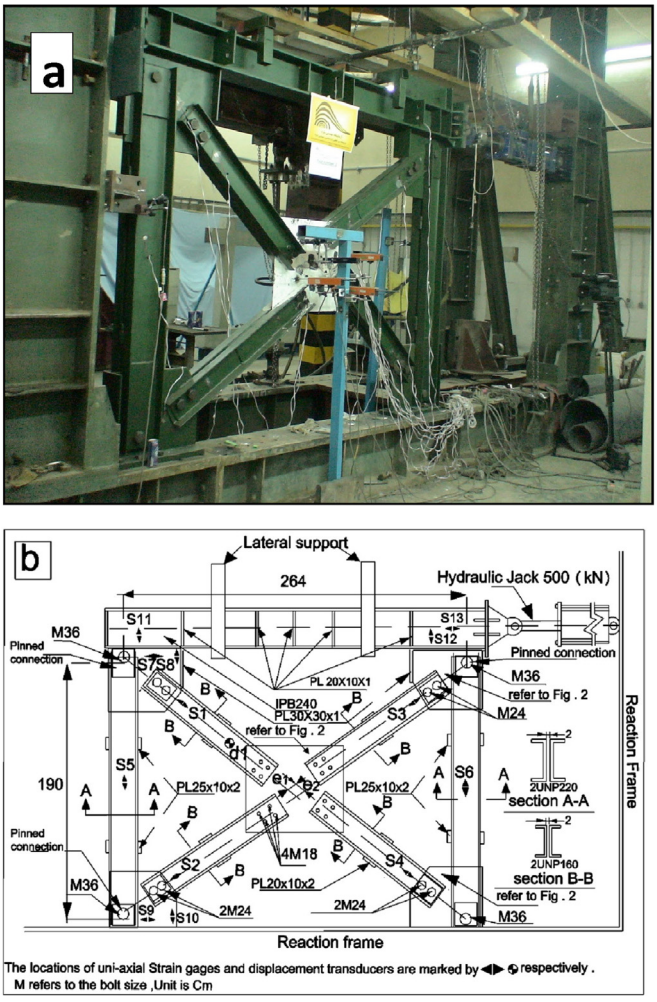

Fig. 1. (a) Side view of test set up and the reaction frame of this study (b) schematic view of test setup and typical test specimen.

links. In a more recent study, Rahnavard et al. [20] fulfilled analytical research to evaluate EBF seismic behavior with single and double shear panels in presence of concrete slab. The results illustrated that double shear panel provides superior advantages in terms of ductility, seismic performance and dissipated energy compared to single one.

This paper focuses on developing a structural fuse (SF) by providing the eccentricity between the two segments of a brace, which are connected by a very thin mid-height gusset plate with specified detailing. To examine the seismic behavior of the proposed structural system of this study, nine test specimens was conducted and the experimental results were compared, then final conclusions were made based on test observation and measured experimental data.

2. Description of the test setup

To develop the seismic behavior of Eccentrically Interconnected Braced Frame (EIC-BF), nine quasi-static lateral load experiments were conducted in three-fourth scale on a one-story single-bay braced frame. The experiments were carried out at IIEES (International Institute of Earthquake Engineering and Seismology). Fig. 1(a) illustrates front view of the typical test specimen and test up including reaction frame and lateral supports. Nine test specimens of this study, which are hereinafter so called EIC-BF1 to EIC-BF9, consisted of braced frame with X configuration and the specified mid-height gusset plate details; however brace segments of test specimens have the intentional eccentricity at mid-high gusset plate. All test specimens were equipped with