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Resilient welded steel moment connections by enhanced beam buckling resistance

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ABSTRACT

This study develops two (2) simple but effective techniques for enhancing buckling resistance of welded steel moment connections (WSMCs). The ANSI/AISC 358-10 prequalified connections satisfy the 4% interstory drift requirement, however experimental studies have shown that their strength degradation may initiate as early as 3% drift. This strength degradation has been observed to be initiated by buckling of the beam web which is followed by buckling of the beam flange and twisting of the beam. Consequently, buildings with the prequalified connections may sustain significant buckling damages under severe earthquakes and it is questionable as to whether these connections are capable of resisting gravity loads or lateral loads from strong aftershocks following a severe earthquake. To improve upon these shortcomings, two (2) performance enhancing techniques are proposed and investigated through finite element analysis (FEA). The more promising of the two involves reinforcing the beam web in the expected plastic hinge with a web reinforcement plate. Finite element analysis demonstrated that this reinforcement enhances the beam buckling resistance of WSMCs and thereby significantly reduces the beam buckling damages even at 5% interstory drift. The potential of this technique is analytically and experimentally demonstrated for the recently developed heat-treated beam section (HBS) WSMC. Test results confirm that the web reinforcement plate was effective in reducing local buckling damage and associated strength degradation, thereby improving the performance of HBS WSMCs. Areas for application and future development of the proposed techniques are identified.

1. Introduction

More than a decade of research activities after the Northridge and Kobe earthquakes has developed modified designs of welded steel moment connections (WSMCs) with improved ductility [1]. By eliminating premature weld or near weld failures the current moment connections prequalified for special and intermediate moment frames (SMF and IMF) by the ANSI/AISC 358-10 [2] have demonstrated the ability to attain at least 4% interstory drift while sustaining 80% of the nominal flexural strength (M_p). However, the ANSI/AISC 314-10 *Seismic Provisions* [3] notes that while connection qualification emphasizes plastic rotation capacity, the tendency for connections to experience strength degradation is of concern as this strength degradation can increase rotational demands from P-delta effects and adversely affect frame stability. In reported studies [4–8], prequalified connections such as the welded unreinforced flange–welded web (WUF-W), reduced beam section (RBS), extended end plate (EEP), bolted flange plate (BFP) and Kaiser bolted bracket (KBB) experience severe strength loss due to beam buckling prior to the termination of loading. Due to this rapid strength loss, frame stability may be jeopardized in a severe earthquake and it is questionable whether these connections are capable of resisting gravity loads or strong aftershocks following such an event.

The majority of research efforts on the seismic performance of WSMCs have focused on circumventing weld or near weld failures which limited the attainable plastic rotation of these connections during the Northridge Earthquake [1]. However some research has been conducted on local beam buckling failures and the associated strength loss during seismic loading [9–11,13,15–17]. The following is a brief review of the findings of research studies conducted to either improve understanding of the local buckling failure modes of WSMCs or to prescribe and evaluate techniques to improve the resistance of WSMCs to such failures.

Yu et al. [9] collected experimental data on the local buckling modes that result in strength loss in RBS connections. Selected results from their test of an all welded RBS connection with a W30 × 99 beam connected to a W14 × 176 column are shown in Fig. 1a. For details of the experimental setup, loading history, instrumentation etc. the reader is referred to the research report from the study [9]. In Fig. 1a, the envelope of the applied load and measured buckling amplitudes are shown to illustrate the progression of local beam buckling and its effect on connection strength loss. These results indicate that web local buckling (WLB) and lateral torsional buckling (LTB) are initiated early in the loading history (between 1 and 2% drift in the RBS region). It is noted

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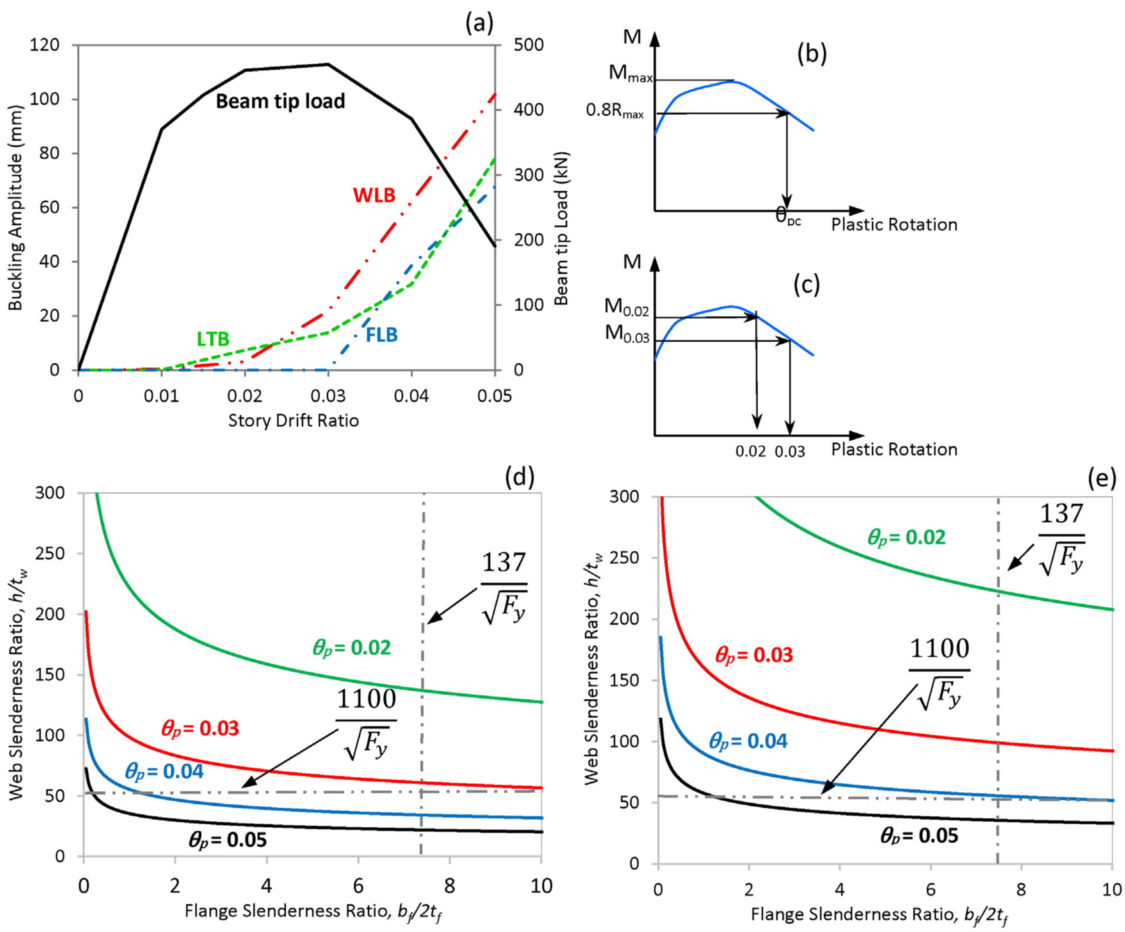

Fig. 1. (a) Measured local buckling modes and strength degradation of a RBS beam to column moment connection (Data from Yu et al. [9]) (b) Definition of plastic rotation capacity by Uang and Fan [10] (c) Definition of strength degradation ratio by Uang and Fan [10] (d) Limiting Slenderness Surfaces for RBS beam to column moment connections (F_y = 345 MPa) [10] (e) Limiting Slenderness Surfaces for RBS beam to column moment connections (F_y = 223 MPa) [10].

that in RBS connections, the beam flanges are trimmed to relocate plastic hinging of the beam away from the column face to the reduced section and as a result, the largest bending stresses in the beam web occur in the reduced section. In this region, the beam web experiences less rotational restraint along its vertical edge (adjacent to the column flange) and along its horizontal edge (adjacent to the beam flange). Therefore, although trimming of the beam flanges improves flange compactness at the center of the reduced section, it increases the susceptibility of the beam to WLB. Yu et al. [9] also evaluated the effect of a near fault loading history and the addition of lateral bracing near the reduced section on the response of RBS moment connections through full scale experiments. The study showed that additional lateral bracing near the RBS region did not delay the onset of strength degradation but did slow the rate of strength degradation. Finally, finite element analysis reported in this study showed that axial restraining effects from the columns in a frame system can also reduce strength degradation rates for RBS moment connections.

Uang and Fan [10,11] examined the stability criteria for steel moment connections with reduced beam sections through nonlinear regression based on the test results of 55 full-scale RBS moment connections. In their study, connection resistance to buckling induced strength degradation was quantified by

1. The plastic rotation capacity (θ_{pc}), defined as the total plastic rotation beyond which a connection starts to degrade below 80% of the peak strength (Fig. 1b). Plastic rotation is calculated by dividing the plastic component of the beam tip displacement by the distance from the beam tip to the column centerline.
2. The strength degradation rate (SDR) defined as the ratio of connection resistance (bending moment) at 0.03 and 0.02 rad plastic rotation (Fig. 1b).

By studying the statistical influence of flange slenderness ratio (b_f/$2t_f$), web slenderness ratio (h/t_w), slenderness associated with LTB (L_b/r_y), and yield strength (F_y) on connection plastic rotation capacity (θ_{pc}), the following equation was developed by Uang and Fan [10,11] to describe the relationship between these parameters:

$$\theta_{pc} = 5.8\left({b_f}/{2t_f}\right)^{1/8}\left({h}/{t_w}\right)^{1/2}\left(F_{ye}\right)^{1/2} \tag{1}$$

where b_f is the beam flange width, t_f is the beam flange thickness, h is the clear distance between beam flanges less the fillet radius for rolled shapes, t_w is the beam web thickness, L_b is the unbraced beam length, r_y is the radius of gyration about the y-axis, and F_{ye} is the expected yield stress defined as:

$$F_{ye} = R_y F_y \tag{2}$$

where R_y is the ratio of expected yield stress to specified minimum yield stress.

Eq. (1) was developed using the unreduced section properties. This equation does not include the LTB slenderness ratio (L_b/r_y), as LTB was not found to have much effect on the plastic rotation capacity of connections in the data set examined [10,11]. Note the relatively stronger influence of the web slenderness ratio (h/t_w), as compared to flange