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Seismic toughness and failure mechanisms of reduced web-section beams: Phase 1 tests

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ABSTRACT

Avoiding fracture in the beam-column connections of steel moment frames is critical to their seismic performance. Both Reduced Web Section (RWS) and Reduced Beam Section (RBS) methods apply the capacity design principle to shift the location of yielding into the beam and away from the beam-column connection. In the RWS approach, large openings are introduced into the web of the beam, so that the arrangement and configuration of the openings determine the mode of inelastic mechanism that develops within the beam. In this paper, experimental and numerical results are discussed for five RWS specimens that were subjected to reversed cyclic displacements. Also, the concept and potential inelastic modes of RWS beams are introduced, and beam shear equations corresponding to the assumed plastic mechanisms are derived. Of the five specimens, one had only two openings close to the beam-column connections, while the others had multiple openings distributed over the beam span. Most of the specimens exhibited stable hysteretic behavior up to approximately 6% story drift.

1. Introduction

The unexpected fracture of welded beam-column connections of steel moment frames in the Northridge and Hyogo-Ken Earthquakes in the mid-1990s has motivated the development of methods to improve the performance of the system [1,2]. Some methods focus on increasing the toughness of the beam-column connections [3,4], while other methods aim to limit the intensity of stress at the connections by shifting the location of plastic hinging away from the beam-column welds. Examples of the latter include the use of haunches [5–7] and the removal of portions of the beam flange near the connections (known as a “Reduced Beam Section”) [8,9]. These approaches enforce yielding to develop in flexure at critical (weaker) locations away from the beam-column connections.

In the present study, an innovative method of reducing the shear strength of a wide-flange beam is explored aiming at inducing yielding within the beam span due to beam shear; as a result of this mechanism, the intensity of stress at the beam-column welds is limited. Because steel beams of ordinary dimensions have ample shear strengths compared with the shear demands, relatively large openings must be introduced in the web to generate yielding due to beam shear. This approach to providing ductility to moment frames is termed the “Reduced Web Section” method [10].

Openings have been introduced into beam webs to facilitate the routing of utilities such as plumbing and electrical conduit, oftentimes necessitating reinforcement to ensure the opening is not a source of weakness [11]. In the case of castellated beams, flexural stiffness and strength are improved by longitudinally cutting the beam in two, offsetting the two parts, and welding the web in between the openings so formed. Such beams provide for passing utilities through the openings. Important phenomena that bear on the design of castellated beams have been described [12–14] and synthesized into design criteria [15,16]. Castellated beams made from IPE, UB, and other shapes sections are widely available [17].

The use of girders having rectangular web openings reinforced by diagonal members was suggested for providing inelastic response to seismic motions [18]. The emphasis herein is the use of unreinforced web openings to promote ductile mechanisms associated with beam shear. Ten beam-column frame specimens, each comprising a Reduced Web Section (RWS) beam, were tested under reversed cyclic lateral displacements. This paper introduces design concepts for RWS beams subjected to lateral loading, describes results from numerical studies, and discusses the seismic

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toughness and failure mechanisms of the first five specimens, tested in Phase 1 of the series. Test and analysis results of the Phase 2 specimens are discussed in the companion paper [19].

2. Concept of reduced web-section beams

A beam in a moment-resisting frame subjected to lateral loading (Fig. 1a) develops shear forces and bending moments along the span as shown in Fig. 1b and c, respectively. The bending moment is the highest at the beam-column connection and zero near the midspan, placing large stress (and strain) demands on the connection welds or bolts. Unlike the moment, the shear force is constant over the span of the beam if subjected to lateral loads only, and it is nearly constant when the shear forces due to gravity loads are relatively small.

Fig. 1d illustrates that the resultant tensile and compressive forces caused by the bending moment are developed primarily in the beam flanges. For the moment equilibrium, the development of the flange axial forces is greatly related to the development of transverse shear in the web. Fig. 1e shows free-body diagrams for the top and bottom halves of the beam. Considering horizontal equilibrium in the free-body diagram, it is seen that the flange axial forces at the beam end are also associated with the development of longitudinal shear in the web. Therefore, considering the free-body diagrams in Fig. 1d and e, the intensity of the flange forces and resulting stresses at the beam-column connection can be controlled by limiting the capacity of the web to carry transverse or longitudinal shear forces. Because typical steel beams have ample shear strengths compared with the shear demands, a relatively large portion of the web section must be removed to achieve this goal.

Openings (i.e., voids) can be introduced into the web of a wide-flange section beam to reduce the shear strength. By fabricating only one or two openings, the transverse shear strength of a beam may be reduced enough to form a mechanism involving relative vertical offsets that take place over the opening regions. This mechanism is designated as Mode-A in Fig. 2a, and is mainly caused by local plastic hinging (in flexure) of the T-section beams above and below the openings. In contrast, for a beam having many openings in the web over the span, a greater reduction in the longitudinal shear capacity may be achieved compared to the transverse shear capacity, and this can lead to the formation of a mechanism showing relative horizontal offsets of the top and bottom portions of the beam. This mechanism is designated as Mode-B in Fig. 2b, and is associated with local yielding and/or buckling of the "web posts" that exist between the adjacent openings. The web posts may be proportioned to deliver any desired level of stress to the beam-column connections, with the goal of limiting the stress in the connections to promote ductile behavior. Therefore, the mode of deformation of a RWS beam depends on the relative shear strengths and demands in the longitudinal and transverse directions.

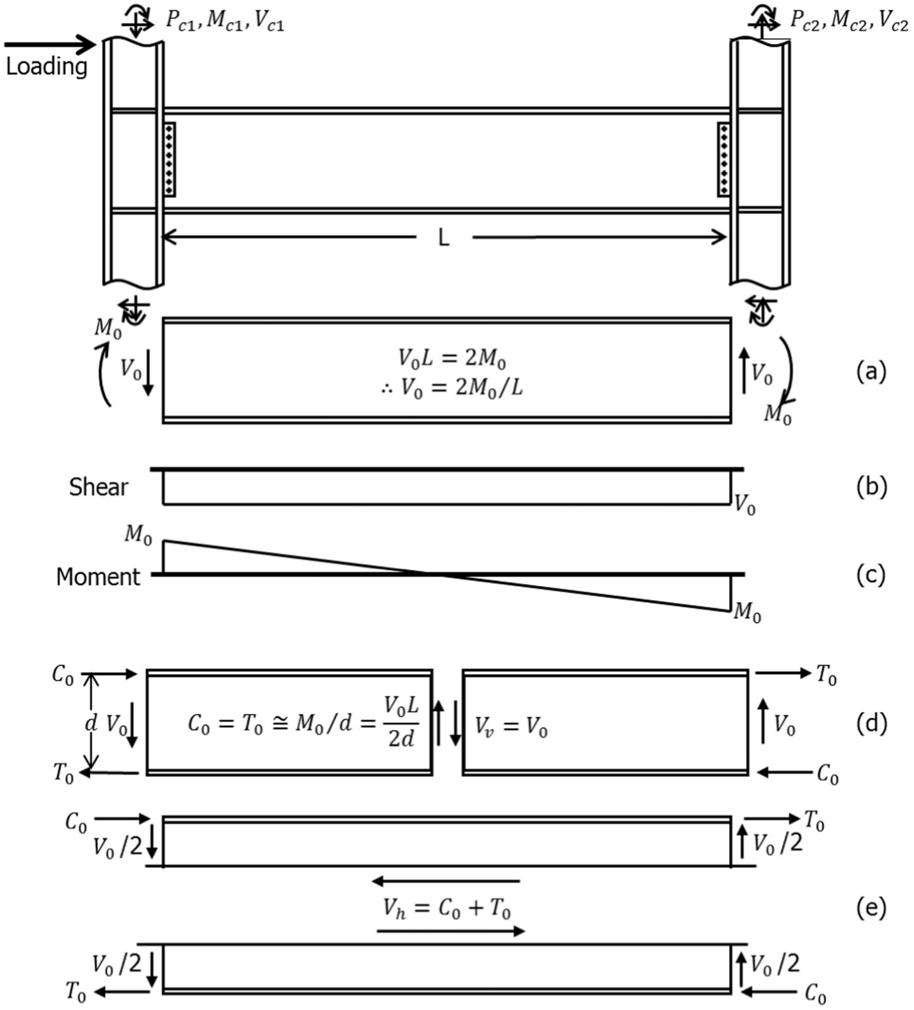

Fig. 1. Static equilibriums in a beam-column moment frame under lateral loading.