Journal of Constructional Steel Research 122 (2016) 190–197

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

Bending–shear interaction in short coupling steel beams with reduced beam section

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ARTICLE INFO

Article history:
Received 20 October 2015
Received in revised form 12 March 2016
Accepted 14 March 2016
Available online 28 March 2016

Keywords:
Reduced beam section (RBS)
Parametric study
M–V interaction
Beam FEA
Cyclic loading

ABSTRACT

In current design provisions, the plastic moment and rotation capacity of plastic hinges for beams must not be decrease due to compressive and/or shear forces. For the majority of moment-resisting frames, the influence of shear and axial forces on the bending moment and rotational capacity of plastic hinges can be ignored, because the shear and axial forces typically observed are low relative to the shear and axial capacities. However, in some cases, the lateral force-resisting systems are composed of closely spaced columns rigidly connected by short steel beams. Each of these beams is long enough to allow the development of plastic moment hinges at the ends, but also short enough to develop significant shear forces that can influence the bending moment and rotational capacity of the beam.

This report presents a parametric study conducted using an experimentally calibrated numerical model, performed at the CEMSIG Research Centre (http://www.ct.upt.ro/en/centre/cemsig) at the Politehnica University of Timisoara. The study observes and characterizes the plastic mechanism of short steel beams with reduced beam sections (RBS) applied in moment-resisting frames. A simplified and reliable alternative allowing the use of beam finite element analysis (FEA) for bending–shear interactions is proposed.

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1. Introduction

1.1. General details

Moment-resisting frames are often used for seismic-resistant structures because the frames are inherently ductile. Plastic deformations in the frames are accommodated by the formation of so-called "plastic hinges" in beams near the beam-to-column connections and column bases. The Eurocodes [1] specify that, for good energy dissipation, beams used in moment-resisting systems should have fully developed plastic moments and also possess adequate rotational capacity. For typical moment-resisting frames, the influence of shear forces on the plastic moment and rotation capacity can be ignored. However, this influence must be considered in some cases, such as those in which the lateral force-resisting systems are composed of frames with closely spaced columns and short coupling beams. Although welded beam-to-column connections are considered to comply with Eurocode standards, such connections have experienced serious damage and even failure during strong seismic events. Failure mechanisms have included fractures in the beam flange-to-column groove welds, cracks in the beam flanges themselves, and cracks propagated through the column sections. In order to reduce the risk of failure by brittle fracture, the connections can be strengthened or the beams can be weakened. In the first approach, sufficient connection overstrength is provided by haunches and/or cover plates. In the second, the beam flanges are trimmed, resulting in a reduced beam section (RBS) [2]. Proper detailing of the RBS, including flange cutouts and beam-to-column welds, is needed to ensure the formation of plastic hinges in the reduced section zones. However, the existing qualification provisions by AISC [3] specify only the minimum span-to-depth ratios of beams, depending on the ductility class of the structure. When RBS beams are outside of these limits, as in the case with short coupling beams, project-specific qualification tests must be performed in order to permit realistic evaluations of the structural behavior and assessment of the acceptance criteria.

The usual approach for considering bending–shear interactions [4] is the reduction of the yield stress in shear area, which reduces the plastic bending moment resistance.

1.2. Material models for cyclic analyses

Modelling the elastic–plastic stress–strain response is necessary for the design and failure analyses of engineering components. With the goal of improving the representation of stress–strain responses under non-monotonic loadings, several models for cyclic plastic deformation have been developed recently. The phenomena of ratcheting and shakedown are central in designing components subjected to cyclic plastic

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http://dx.doi.org/10.1016/j.jcsr.2016.03.020
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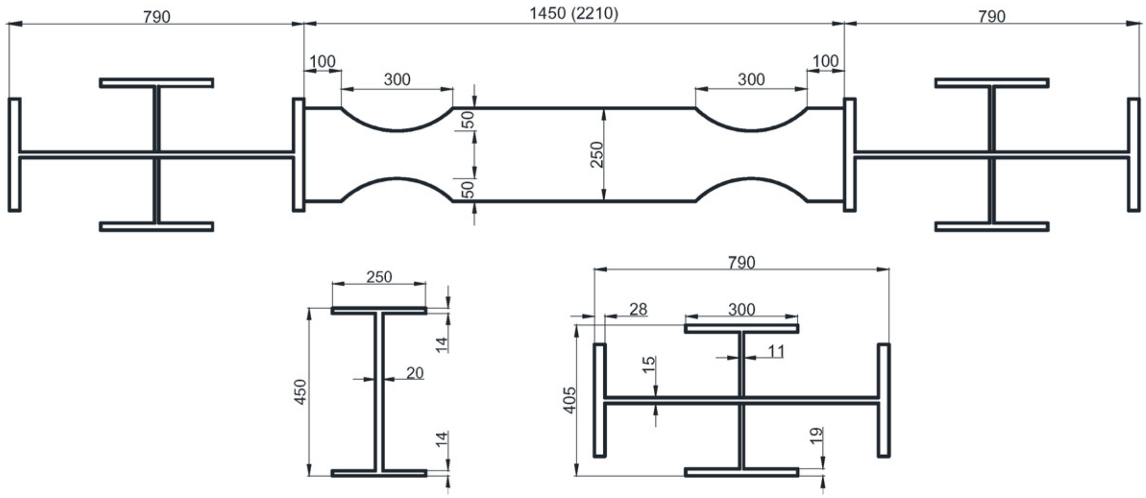

Fig. 1. Beam and columns details.

deformation. Following extensive research, many constitutive models are available to describe the material behaviors of metals under cyclic loading. The theories for these models are based on observations of some of the characteristic experimental behaviors in cyclic plasticity.

Initially, Prager [5] proposed a simple kinematic hardening rule to simulate the plastic responses of materials under cyclic loading. However, for a prescribed uniaxial stress cycle with a mean stress, the model cannot distinguish between the shapes of the loading and reverse-loading hysteresis curves and consequently produces a closed loop with no ratcheting. In 1958, Basseling [6] introduced a multilayer model, further improved by Mroz [7]. The model improves the linear kinematic hardening model by incorporating a multi-surface model, in which each surface represents a constant work-hardening modulus in the stress space.

Following this work, new concepts of uncoupled models were introduced by Dafalias and Popov [8]. In the model, they proposed the calculation of the plastic modulus that was not directly dependent on the yield-surface kinematic hardening rule.

Armstrong and Frederick [9] proposed a well-known nonlinear kinematic hardening model. The model introduced a kinematic hardening rule that contained a “recall” term, incorporating the fading memory effect of the strain path and essentially making the rule nonlinear. Chaboche [10,11] developed one of the most common material models for cyclic loading; it proposed a “decomposed” nonlinear kinematic hardening rule. The Chaboche rule is, in fact, a superposition of several Armstrong–Frederick hardening rules, each with a specific purpose. Later, Ohno and Wang [12] proposed a piecewise linear kinematic hardening rule. However, while extensive research [13,14] was performed to develop and improve the existing material models, no single material model is general enough to simulate both uniaxial and multiaxial ratcheting.

2. Numerical analyses

2.1. Experimental program

The complete description of the experimental program is presented by Dinu et al. [15] and summarized hereafter. The study is connected with the design of an 18-story office building, located in a high seismic area in Romania. The structure is 94 m in height and 43.3 m × 31.3 m in plan dimensions. The building site is characterized by a design peak-ground acceleration of 0.24g for a returning period of 225 years, and soft soil conditions with $T_C = 1.6$ s. The lateral force-resisting system consists of steel framing with closely spaced columns and short connecting steel beams.

The length-to-height ratio (L/h) of the connection beams varies from 3.2 to 7.4. Some beams are below the general accepted lower limit of L/h = 4. Notably, this condition originates from the limitations of the Euler–Bernoulli theory for beams. Unlike Timoshenko beam theory (a first-order shear deformation theory), Euler–Bernoulli beam theory neglects shear deformations.

In order to protect the beam-to-column connections, RBS were used. To avoid the development of stress concentrations, circular-radius cuts were used in both the top and bottom flanges of the beam to reduce the flange width and concentrate the plastic deformation (see Fig. 1). The detailing followed the recommendations of FEMA 350 [16]. The welds of the beam flanges and web-to-column flange are complete-joint-penetration groove welds.

Two types of beams were selected for the experimental program, as presented in Table 1.

Both beams and columns were made from S355-grade steel. The base material characteristics were evaluated experimentally and presented in [5]. The measured yield strength of the plates and profiles exceeds the nominal values.

The experimental setup is presented in Fig. 2.

The proposed cyclic loading protocol was based on the ECCS Recommendations [17] and adapted to the testing facility limitations. According to the ECCS procedure, the yielding displacement D_y and the corresponding yielding force F_y are obtained from the monotonic force vs. displacement curve. Notably, D_y was determined using a numerical model in order to limit the amount of necessary experimental testing.

Laboratory tests clearly demonstrate that the plastic hinges, which are developed in the RBS zone, are affected by shear. In Fig. 3, the envelope curves are presented comparatively, together with the shear deformation at the end of each cycle for the RBS–S and RBS–L test specimens.

In Fig. 3a, at point 4, the inclined pattern of the strain can be considered a direct consequence of high shear stresses. Further, in Fig. 3b, the deformation field is almost vertical, indicating the reduction of shear deformations.

Table 1
Characteristics of beams tested experimentally.

Name	h [mm]	b [mm]	L [mm]	L/h	M_{pl} [kNm]	V_{pl} [kN]
RBS–S	450	250	1450	3.2	641	1845
RBS–L	450	250	2210	4.9	641	1845

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