Thin-Walled Structures 72 (2013) 88–101

Contents lists available at ScienceDirect

Thin-Walled Structures

journal homepage: www.elsevier.com/locate/tws

Ultimate behaviour of steel beams with discrete lateral restraints

A.S.J. Foster, L. Gardner*

Imperial College London, London, UK

ARTICLE INFO

Article history:
Received 30 May 2013
Accepted 15 June 2013
Available online 20 July 2013

Keywords:
Bending
Experiments
Lateral torsional buckling
Steel structures
Strain hardening
Testing

ABSTRACT

Through a programme of experiments, numerical modelling and parametric studies, the implications of allowing for strain-hardening in the design of laterally restrained steel beams is investigated with particular emphasis on the performance of the bracing elements. A total of twelve tests were performed on simply supported beams considering two basic scenarios: discrete rigid restraints and discrete elastic restraints of varying stiffness. In the latter case, the forces developed in the restraints were measured and compared to the design forces specified in EN 1993-1-1 (2005). Two different restraint spacings were considered in the tests to give non-dimensional lateral torsional slenderness values of 0.3 and 0.4 for the unrestrained lengths. In all tests, bending resistances in excess of the plastic moment capacity were observed, but for the considered restraint spacings, the resistances often fell short of that predicted by the deformation-based continuous strength method (CSM), which allows for strain-hardening. It was concluded that closer restraint spacing may be required to harness significant benefit from strain-hardening and to develop the full CSM bending resistance, though the forces generated in the restraints were within current code requirements.

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1. Introduction

The resistance of beams to lateral instability can be improved through the provision of effective lateral bracing, either continuously or at intervals along the length of the member. For discrete bracing systems, the spacing of the lateral restraints influences the bending resistance of the member. In order to be effective, the restraints should have adequate stiffness to limit the lateral displacements at the point of restraint and have sufficient strength to withstand the forces that arise as a consequence of these displacements as well as any initial imperfections. It was shown by Winter [1] that, provided the restraint is of adequate stiffness, these forces are small relative to the axial forces in the primary member.

Numerous studies of lateral restraint requirements have been carried out (Flint [2], Massey [3], Nethercot and Rockey [4], Mutton and Trahair [5], Mutton and Trahair [6], Wang and Nethercot [7], Wang and Nethercot [8], Yura [9], Al-Shawi [10], Trahair [11], Yura [12], McCann et al. [13]), typically considering elastic member behaviour. The present research is devoted to examining the lateral stability implications of allowing for plasticity and strain-hardening in the design of the primary members by means of a newly proposed, deformation-based design procedure that is referred to as the Continuous Strength Method (CSM) [14]. To this end, a series of experiments on simply supported beams with variations in restraint spacing and stiffness were conducted. Using a geometrically and materially non-linear finite element model, the test data were reproduced and extended in a parametric study which was then used to inform and develop some basic design equations.

2. Key design aspects

2.1. Lateral restraint spacing

EN 1993-1-1 (2005) defines a non-dimensional slenderness limit, or plateau length, $\bar{\lambda}_{LT}=0.4$, below which, the effects of lateral torsional buckling can be ignored and the design buckling resistance moment of the member $M_{b,Rd}$ may be taken as the design bending resistance $M_{c,Rd}$ of the cross-section, assuming $\gamma_{M0}=\gamma_{M1}$. $\bar{\lambda}_{LT}$ is defined in Eq. (1) as

$$\bar{\lambda}_{LT}=\sqrt{\frac{W_y f_y}{M_{cr}}} \tag{1}$$

in which W_y is the major axis plastic section modulus for Classes 1 and 2 cross-sections, the elastic section modulus for Class 3 cross-sections and an effective section modulus for Class 4 cross-sections, f_y is the material yield strength and M_{cr} is the elastic critical moment for lateral torsional buckling, which is a function of member length L. For a given set of cross-section and material properties and a fixed value of $\bar{\lambda}_{LT}$, Eq. (1) can be solved for L to define the maximum allowable

* Corresponding author. Tel.: +44 2075946058.
E-mail address: leroy.gardner@imperial.ac.uk (L. Gardner).

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http://dx.doi.org/10.1016/j.tws.2013.06.009

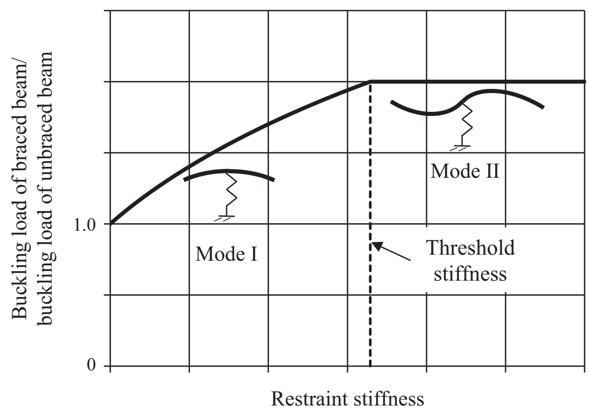

Fig. 1. Typical theoretical relationship between buckling load enhancement and restraint stiffness for a beam.

spacing between fully effective lateral restraints before reductions in resistance for lateral torsional buckling are required. For members containing plastic hinges, stable lengths below which lateral torsional buckling can be ignored are given in Annex BB-1 of EN-1993-1-1 (2005).

2.2. Restraint forces

Lateral restraints must be of sufficient stiffness to restrict lateral buckling deformations at the point of restraint, whilst also being of sufficient strength to resist the forces generated as a result of the restraining action. In the elastic range, it can be shown that, for a perfect system, there is a threshold level of brace stiffness that causes a beam to buckle into the second mode (i.e. between the brace points rather than in an overall mode) – see Fig. 1 [2].

For a beam of length L experiencing a force N_{Ed} in the compression flange, EN 1993-1-1 states that the restraint system should be capable of resisting an equivalent stabilising force per unit length q_d (Eq. (2)):

$$q_d = \sum N_{Ed} \frac{8e_0 + \delta_q}{L^2} \tag{2}$$

where the assumed initial imperfection amplitude of the restrained member, e_0, is defined as

$$e_0 = \alpha_m L/500 \tag{3}$$

in which α_m is reduction factor used for restraining multiple members and δ_q is the lateral deflection of the restrained member into the restraints. Assuming an infinitely stiff restraint system, $\delta_q = 0$, and Eq. (2) implies that a restraint must resist 1.6% of N_{Ed}. Eq. (2) is derived on the basis of elastic behaviour, but may also be applied when plasticity occurs in the restrained member, allowing for moments up to the full plastic bending capacity, M_{pl}, but not covering the demands of rotating plastic hinges.

2.3. The continuous strength method (CSM)

The continuous strength method is a deformation-based design approach for steel elements that allows for the beneficial influence of strain-hardening. To date, design equations for the CSM have been developed for cross-section resistance in bending and compression [15]. The CSM bending resistance function $M_{csm,Rd}$, which applies for $\bar{\lambda}_p \leq 0.68$ is defined in Eq. (4) as

$$M_{csm,Rd} = \frac{W_{pl} f_y}{\gamma_{M0}} \left(1 + \frac{E_{sh}}{E} \frac{W_{el}}{W_{pl}} \left(\frac{\epsilon_{csm}}{\epsilon_y} - 1 \right) - \left(1 - \frac{W_{el}}{W_{pl}} \right) \left(\frac{\epsilon_{csm}}{\epsilon_y} \right)^{-2} \right) \tag{4}$$

where E is the modulus of elasticity, E_{sh} is the strain-hardening slope taken equal to $E/100$ for structural steel, W_{el} and W_{pl} are the elastic and plastic section moduli and $\epsilon_{csm}/\epsilon_y$ is the strain ratio, defining the limiting strain in the cross-section as a multiple of the yield strain ϵ_y, and given by Eq. (5)

$$\frac{\epsilon_{csm}}{\epsilon_y} = \frac{0.25}{\bar{\lambda}_p^{3.6}} \quad \text{but} \quad \leq 15 \tag{5}$$

in which $\bar{\lambda}_p$ is the local cross-section slenderness, given by Eq. (6) as

$$\bar{\lambda}_p = \sqrt{(f_y/\sigma_{cr})} \tag{6}$$

with σ_{cr} being the elastic buckling stress of the cross-section, or conservatively its most slender constituent plate element.

This study will examine the implications of using the CSM resistance function where moments beyond M_{pl} can be sustained, on the forces developed in lateral restraints, following a series of experiments and numerical simulations.

3. Experimental programme

3.1. Introduction

A testing programme comprising tensile and compressive material coupon tests, stub column tests and tests on beams with discrete lateral restraints was carried out at the Building Research Establishment and Imperial College London on hot-rolled grade S355 steel I-sections. Two cross-section sizes were chosen: 305 × 127 × 48 UB, which had a Class 1 flange ($\bar{\lambda}_p = 0.31$) and a Class 1 web ($\bar{\lambda}_p = 0.30$), and 305 × 148 × 40 UB, which had a Class 2 flange ($\bar{\lambda}_p = 0.57$) and a Class 1 web ($\bar{\lambda}_p = 0.44$).

3.2. Material properties

Tensile and compressive coupon tests were used to determine the engineering stress–strain material response of the tested specimens; the tests were conducted in the Structures Laboratory of the Department of Civil and Environmental Engineering, Imperial College London.

Tensile and compressive coupons were cut and milled from the web and flanges of two representative UB sections in the longitudinal (rolling) direction only. Testing was carried out in accordance with the provisions of EN 10002-1 (2001). The nominal dimensions of the necked tensile coupons were 320 × 30 mm^2 and the nominal dimensions of the compressive coupons were 72 × 16 mm^2. Prior to testing, half gauge lengths were marked onto the tensile coupons to allow the final strain at fracture, ϵ_f, to be calculated, based on elongation over the standard gauge length

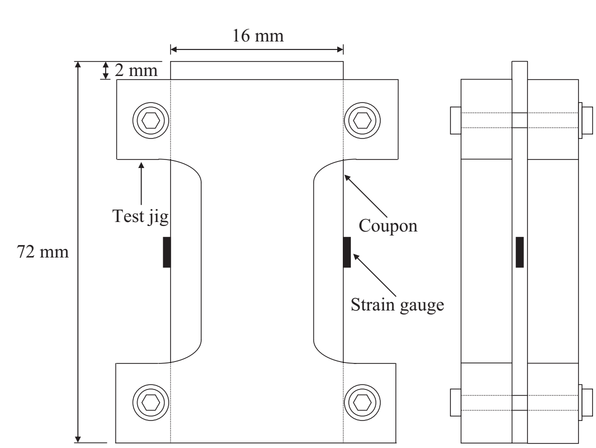

Fig. 2. Compressive coupon testing jig and nominal coupon dimensions.

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