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Engineering Structures 27 (2005) 977–989
ENGINEERING STRUCTURES
www.elsevier.com/locate/engstruct

Experimental cyclic response of cold-formed hollow steel bracing members

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Received 21 January 2004; received in revised form 29 November 2004; accepted 29 November 2004
Available online 26 April 2005

Abstract

This paper describes an experimental study on the response of rectangular and square hollow steel members to monotonic and cyclic axial loading. Tensile monotonic tests were first performed on short specimens in order to relate material strength to section resistance. The observed results are compared to European and North American design provisions. The cyclic tests included assessment of bracing specimens with various member lengths and cross-section sizes. The objective of these tests was to examine performance under idealised seismic loading conditions. In general, the steel hollow brace members exhibited stable hysteresis behaviour up to the on-set of local buckling, and then showed considerable degradation in strength and ductility depending on their slenderness. The tests provide information on key response parameters, including tensile and compressive strength and post-buckling capacity, as well as ductility and energy dissipation capabilities. Particular attention is given to the influence of member slenderness. The experimental findings are compared with the recommendations of a number of international codes of practice, and areas of agreement or discrepancy are highlighted.

Keywords: Bracing members; Hollow sections; Cold-formed steel; Cyclic loading; Buckling strength; Post-buckling capacity; Ductility; Energy dissipation

1. Introduction

Seismic resistance of building structures can be effectively provided through the utilisation of braced-frame configurations. Rectangular (RHS) and square (SHS) hollow sections are often employed as bracing members for structural as well as aesthetic reasons. For a severe seismic event, the main performance objective in design is generally to maintain the overall structural integrity without collapse. As part of this philosophy, energy is dissipated through critical members and components, which are expected to undergo inelastic cyclic deformations without suffering from significant loss of strength. Clearly, in the case of braced frames, these critical members are the diagonal braces, for which a detailed assessment of the cyclic response is fundamental to the seismic design process.

During the last few decades, several studies have been undertaken to examine the inelastic behaviour of bracing members. Earlier tests by Popov et al. [1] reported that once a member buckled during cyclic testing, its compressive capacity in subsequent cycles decreased and that the axial stiffness of a specimen during tension loading deteriorated with each cycle to larger displacement amplitudes. It was also noted that local buckling led to the development of tears in the steel. Fixed-ended specimens exhibited greater initial stiffness than pinned-ended specimens, and due to their smaller lateral deflections, local buckling was delayed and the strength of the steel during inelastic cycling was maintained. Thus, it was concluded that fixing the ends of the specimens resulted in superior energy dissipation characteristics.

Further work by Jain et al. [2] suggested that the post-buckling reduction in compressive strength during cyclic loading could be expressed as a function of the effective slenderness ratio of the member. More recently,

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0141-0296/$ - see front matter © 2005 Elsevier Ltd. All rights reserved.
doi:10.1016/j.engstruct.2004.11.017

Remennikov and Walpole [3] established that the post-buckling compression capacity of steel bracing members can vary between 20% and 100% of that in the first cycle depending upon the slenderness ratio of the brace, with slender braces suffering the greater reductions.

Tremblay [4] surveyed 9 experimental studies including 76 cyclic tests, during which it was found that the compressive strength of the braces at first buckling generally exceeded the value predicted using the Canadian (CSA) [5] and American (AISC LRFD) [6] column design curves. Fracture of rectangular hollow section bracing members was found to depend strongly on the slenderness ratio of the bracing members and, to a lesser extent, on the width-to-thickness ratio of the cross-section and the imposed displacement history. It was reported that slender braces sustained higher ductility levels prior to fracture, most likely because the strain demand in the plastic hinge reduces with brace slenderness. Tremblay's results suggest that slender braces perform well during dynamic testing, which agrees with the findings of Jain et al. [2].

Elchalakani et al. [7] subjected fixed ended tubular braces, with normalised slendernesses between 0.34 and 0.57, to cyclic concentric axial loading and found that the ductility capacities of the specimens were related to their slenderness and width-to-thickness ratio. It was recommended that further tests be conducted on specimens with normalised slenderness between 0.54 and 1.35.

Elghazouli [8] discussed the seismic design of concentrically braced frames, comparing compression-based and tension-based approaches. It was shown that the two approaches lead to very different member overstrengths and ductility demands, both of which are dependent on brace slenderness. Further, irrespective of which design approach is adopted, accurate predictions of yield, buckling and post-buckling capacity under cyclic loading are essential for reliable capacity design.

The present paper examines the results of a series of tests carried out on rectangular and square hollow sections. Fifteen specimens of different lengths and cross-section sizes with normalised slenderness ($\bar{\lambda}$), as defined by Eurocode 3 [9], between 0.4 and 3.2 were tested under cyclic axial displacements of increasing amplitude. The test set-up, specimen details and material properties are described, and the results are discussed. As well as a description of the overall hysteretic behaviour of the bracing specimens, emphasis is given to assessing buckling and post-buckling compressive capacity, tensile strength, and attained ductility and energy dissipation levels. In addition, 21 short specimens with a length-to-width ratio of three were tested under displacement-controlled monotonic tensile loading. The test programme was undertaken as part of an independent assessment of current developments within Eurocode 8 [17], and to this end, considers specimens with an especially wide range of member slendernesses.

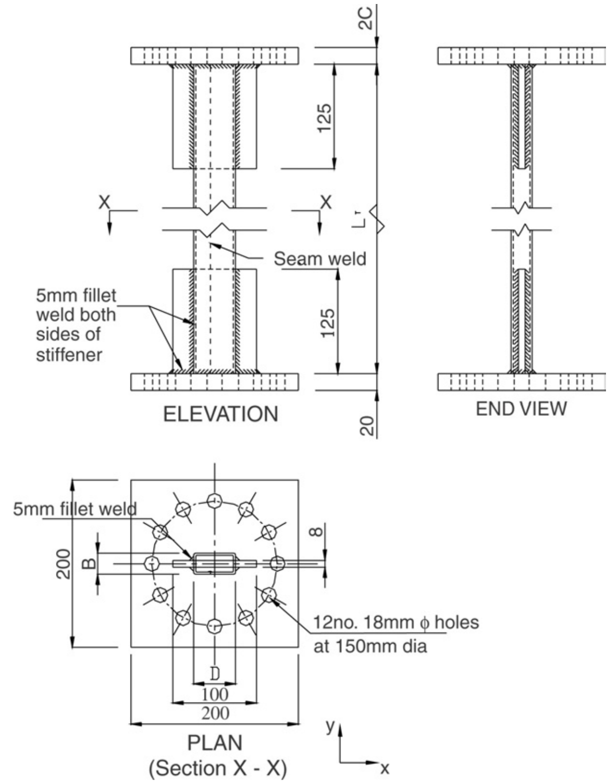

Fig. 1. Test specimen details.

2. Specimen details and test set-up

All specimens were rectangular hollow sections (RHS) or square hollow sections (SHS) manufactured from cold-formed steel S235JRH, with a nominal yield strength of 235 N/mm^2 and an ultimate strength of between 360 and 510 N/mm^2 [10].

Three cross-sectional geometries were considered, namely $50 \times 25 \times 2.5$RHS, $40 \times 40 \times 2.5$SHS and $20 \times 20 \times 2.0$SHS. Two specimen lengths (L_T) were examined in the cyclic tests—intermediate (1.1 m) and long (3.3 m). Fifteen cyclic tests were preformed in total—six intermediate and nine long. These are in addition to 21 tensile monotonic tests on relatively short specimens, which were carried out to compare section strength to that obtained from coupon tests, as discussed in the following section (material properties).

As shown in Fig. 1, fixed end restraints were employed for all test specimens and stiffener plates were placed to provide an adequate length of weld for the transfer of force between the brace and the supports and to encourage uniaxial flexural buckling. The specimens were manufactured in a rigid jig to ensure the base plates of the specimens were parallel, the holes aligned properly and all test specimens were of the same intended length within each group.

Two separate test rigs were employed, one for the monotonic tensile tests and cyclic tests of intermediate length (1100 mm) specimens, and another to test the long (3300 mm) specimens. Both test rigs comprised four solid