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Thin-Walled Structures 44 (2006) 677–691
THIN-WALLED STRUCTURES
www.elsevier.com/locate/tws

Experimental testing of joints for seismic design of lightweight structures. Part 2: Bolted joints in straps☆

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Received 30 November 2005; accepted 21 April 2006

Abstract

An experimental testing campaign on tensile bolted joints between straps is reported. Two dominant failure modes are identified: (1) tilting, bearing and tearing of the sheets (TS) and (2) tilting, bearing and net-section failure (NSF). The analysis in terms of ductility and strength shows that bolted connections are less adequate than screwed connections (reported in Part 1 of this paper) for the seismic design of X-braced shear walls in lightweight structures. NSF joints are more ductile than TS joints in the sense that they undergo larger displacements before failure. However, if washers are not used, both types of connections fail before energy dissipation through yielding of the diagonal straps can occur. Some design recommendations to improve the seismic performance of bolted joints, including the use of washers, are given. The accuracy of Eurocode 3 formulas to predict the ultimate load is also analyzed.

Keywords: Light gauge steel; Lightweight steel; Seismic design; Joints; Bolts; Experimental research; Ductility; Failure modes; Net-section failure; Bearing

1. Introduction

A growth in the application of lightweight steel technologies in residential construction has taken place in recent years, together with the development of a significant amount of investigations on the issue, mainly focused on structural questions concerning cold-formed steel members. The main current lines of research in this field can be seen in [1].

This research has allowed improving the existing design guides and standards, which are already giving solutions for the most common problems encountered in the project and construction of lightweight steel buildings. Questions such as materials for cold-formed steel construction, instability of compressed and bent members or connections and fasteners have been largely investigated, and they have already been included in codes for design. However, there are still some specific issues that clearly deserve more research. As pointed out in the first part of this paper [2], this is the case of the seismic performance of lightweight structures, which is also the object of study of the investigation presented herein.

Actually, the paper shows a part of a rather extensive experimental and numerical [3] research on the behavior of dissipative X-braced shear walls. The investigation comprises from the experimental study of strap-to-strap connections to tests of full X-braced frames. The seismic performance of these frames depends mainly on the strength of their components. Members and connections should be strong enough to allow the dissipative yielding of the X-bracings [4].

☆Research supported by the Research Fund for Coal and Steel (Grant 7210-PR-377) and the "Ministerio de Educación y Ciencia" (Grant DPI2002-12388-E).

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doi:10.1016/j.tws.2006.04.006

The investigation is focused on connections. The main objectives are, on the one side, to gain knowledge about their ductility and their behavior under cyclic loads; and, on the other side, to identify which type of joints are most suitable for seismic actions, i.e., to know which are the joints that have enough strength to allow the dissipative yielding of diagonal straps.

The initial steps of the investigation were presented in a previous paper [2], devoted to experimental testing of screwed connections subjected to shear loading. The main conclusion of the analysis of the experimental data is that the mode of failure is a key issue in seismic design of joints. It is verified that screwed connections should be designed to fail in the net-section failure (NSF) mode, because it is the most ductile type of failure and because it takes place after the yielding of the straps.

In view of this result, it seems that reliable equations to predict the mode of failure of a joint are needed to tackle the design of X-braced frames. That is the reason why part of the first paper is also devoted to verify de accuracy of the current Eurocode 3 Part 1-3 proposals for the calculation of joint resistance. It should be pointed out that the Eurocode 3 formulas for the net-section mode of failure showed to work satisfactory, while the bearing formulas gave rather conservative predictions for some of the screwed joints.

The second part of the investigation, presented in this paper, is focused on bolted connections subjected to shear loading. The analysis of the joint behavior is based on the results of a testing campaign performed in the framework of the RFCS research project "Seismic design of Light Gauge Steel Framed Buildings". Lap joints between two straps connected by means of two rows of bolts are tested under monotonic and cyclic load, see Fig. 1.

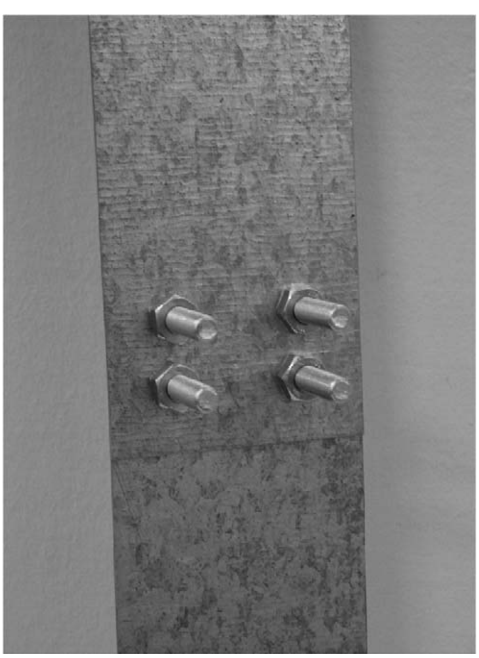

Fig. 1. Bolt joint.

The objectives and the scheme of the paper are similar to what was done for screwed connections. The goals of the experiments are:

1. Obtain parameters such as the initial stiffness, yielding load, ultimate load and maximum displacement.
2. Obtain complete force–displacement (*F–d*) curves, needed for the finite element modeling of X-braced frames [3].
3. Identify the failure modes.

After that, we analyze the experimental results in order to:

1. Classify the various failure modes in terms of their seismic suitability (strength and ductility).
2. Determine the relation between parameters in joint design (steel grade, strap thicknesses, number and diameter of bolts, etc.) and failure mode.
3. Compare experimental ultimate loads of the joints to the strengths calculated by means of the Eurocode 3 Part 1.3 design formulas.

It will also be very interesting to compare the behavior of screwed and bolted connections.

An outline of paper follows. The laboratory experiments are described in Section 2 (test specimens) and 3 (test procedure), and the results are summarized in Section 4 (monotonic tensile tests) and 5 (load–unload tensile tests). Three main features are studied: the modes of failure, the force–displacement curves, and the ductility and stiffness of the connections. The remainder of the paper is devoted to the analysis of the results. The seismic suitability of the joints is discussed in Section 6. Then, in Section 7, the ultimate loads are compared to the values predicted by the Eurocode. Recommendations for design and the concluding remarks of Sections 8 and 9 close the paper.

2. Test specimens

The bolt joints tested are similar to the screw joints of the investigation reported in the first part of the paper (Fig. 1) [2]. For example, the steel grade of the straps is the same, either S 350 GD + Z or S 250 GD + Z [5]. The nominal and mechanical properties of these steels are shown in Table 1. It should be noticed that the experimental f_{yt} and f_{ut} are rather higher than the nominal f_y and f_u.

Bolts of two different diameters are used to connect the straps: 8 and 10 mm. The heads of these bolts are hexagonal and the shafts are threaded all along their length. All the straps of steel grade S 350 GD + Z are connected with washers, while washers are only used in 4 out of the 38 S 250 GD + Z straps. When used, washers of 20 mm Φ are placed under the bolt head and nut.

The torque applied to the bolts is not measured. Bolts are tightened by hand using standard tools, so the torque should be small.