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Finite element investigation on the structural behaviour of cold-formed steel bolted connections

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Abstract

A finite element model with three-dimensional solid elements was established to investigate the bearing failure of cold-formed steel bolted connections under shear. It was demonstrated (Chung and Ip. Engineering Structures 2000;22:1271–1284) that the predicted load–extension curves of bolted connections in lap shear tests followed closely to the measured load–extension curves provided that measured steel strengths and geometrical dimensions were used in the analysis. Furthermore, it was shown (Chung and Ip. Proceedings of the Second European Conference on Steel Structures, Praha, May 1999, p. 503–506) that stress–strain curves, contact stiffnesses and frictional coefficients between element interfaces, and clamping forces developed in bolt shanks were important parameters for accurate prediction of the deformation characteristics of bolted connections. This paper presents an extension of the finite element investigation onto the structural behaviour of cold-formed steel bolted connections, and three distinctive failure modes (Ip and Chung. Proceeding of the Second International Conference on Advances in Steel Structures, Hong Kong, December 1999) as observed in lap shear tests are successfully modelled: bearing failure; shear-out failure; and net-section failure. Furthermore, a parametric study on bolted connections with different configurations is performed to provide bearing resistances for practical design, and the results of the finite element modelling are also compared with four codified design rules. It is found that the design rules are not applicable for bolted connections with high strength steels due to reduced ductility. Consequently, a semi-empirical design formula for bearing resistance of bolted connections is proposed after calibrating against finite element results. The proposed design rule relates the bearing resistances with the design yield and tensile strengths of steel strips through a strength coefficient. It is demonstrated that the design rule is applicable for bolted connections of both low strength and high strength steels with different ductility limits.

Keywords: Cold-formed steel; Bolted connections; Finite element modelling; Failure modes; Bearing resistance; Design rules

1. Introduction on cold-formed steel bolted connections

Galvanized cold-formed steel sections are found in various building applications, ranging from purlins and steel framings, to roof and wall cladding, and floor decking. The advantages of using cold-formed steel are derived from their long-term durability together with high yield strength and high buildability. In building construction, hot-rolled steel sections are commonly used as primary structural frames while cold-formed steel sections are used as secondary structural members to support claddings in forming external building envelopes. The most common cold-formed steel sections are C and Z sections, and the thickness of these sections typically ranges from 1.2 to 3.0 mm. Both steels with yield strength of 280 and 350 N/mm^2 are commonly used. Connections between hot-rolled steel and cold-formed steel members are commonly achieved with bolts and hot rolled angles as web-cleats.

At present, many design recommendations for cold-formed steel connections may be found in the literature which give design rules for the load carrying capacities of fasteners such as bolts, screws and rivets against bearing failure. However, they are empirical expressions developed from test data of specific ranges of material properties such as steel strength and ductility, and of geometrical dimensions such as steel thickness and bolt diameter. Most of the test data are derived from lap shear

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tests where deformations in the form of axial extensions are large, typically in the range of 3–10 mm, depending on deformation limits adopted during data analysis. These design rules are primarily developed for simple connections under lateral loads, and tension connections under axial forces where connection deformation is not critical to the structural performance of connected members. However, for bolted connections under moment, the bearing resistances of the connected parts in cold-formed steel sections may only be fully mobilized at large extensions together with large rotation, leading to moment connections of low stiffness and strength. In general, moment connections between cold-formed steel members are not commonly used in practice due to the lack of information on their structural behaviour and appropriate design guidance.

In recent years, due to advances in steel technology, cold-formed steel strips with high yield strength up to 550 N/mm^2 become available for building products. However, the ductility of high strength steels is found to be reduced significantly with an elongation limit typically <10%; the elongation limits in low strength cold-formed steels and hot-rolled steels are typically 15 and 25%, respectively. With reduced ductility, there is concern about the structural adequacy of high strength steels in term of deformation capacity, especially at connections where highly localized deformations are expected. Moreover, it is also important to recognize that codified design rules in most design recommendations may not be adequate for high strength low ductility steels as they are originally developed from test data with low strength high ductility steels at large deformations. Those design rules are unlikely to provide sufficient safety margin in assessing the connection resistances of high strength low ductility cold-formed steels. Furthermore, they may be inappropriate for moment connections where joint rotations between connected members are limited, and thus incapable of mobilizing the full bearing resistances as in simple connections.

2. Scope of work

Based on the finite element model established in Ref. [1], this paper presents an extension of the finite element investigation of the structural behaviour of cold-formed steel bolted connections, in particular, the three distinctive failure modes [2,3] as observed in lap shear tests:

1. bearing failure;
2. shear-out failure; and
3. net-section failure.

After calibrating against a number of test specimens with different steel grades and thicknesses, a parametric study over a practical range of connection configurations is also performed to reveal the effects of steel strengths and ductility limits on the bearing resistances of the connections. Comparison of the bearing resistances obtained from the finite element models and the design rules in AISI [4], AS/NZ4600 [5], BS5950: Part 5 [6], CSA:S136 [7], and Eurocode 3: Part 1.3 [8] is also presented to assess the applicability of codified design rules to high strength low ductility steels. In order to allow for reduced ductility in high strength steels, a semi-empirical design rule is proposed after calibrating against the finite element results. The proposed rule relates the bearing resistances of bolted connections directly with both the yield and the tensile strengths of cold-formed steel strips through a strength coefficient.

It should be noted that for all the connections reported in this paper, the bolts are 12 mm in diameter, and the design yield strengths of the steel strips are between 280 and 600 N/mm^2 while the steel thickness ranges from 1.2 to 3.0 mm.

3. Design and related research work on cold-formed steel connections

There are a number of codes of practice [4–8] and design recommendations [9,10] for the design of cold-formed steel structures together with complementary design guides and worked examples [11–14] to assist practising engineers. However, despite their simplicity, shear-resisting connections between cold-formed steel sections have received relatively little attention. Conventionally, connections between cold-formed steel sections comprising two bolts per member are considered as simple (or shear) connections, and hot-rolled steel angles of 6–8 mm thickness are often used as web cleats in practice. In order to provide rational design and construction of cold-formed steel web cleats as simple connections between cold-formed steel members, an extensive experimental investigation [15] was executed and a total of 24 connection tests with four different connection configurations in practical member orientations were carried out. It was demonstrated that cold-formed steel web cleats might be used with bolts or self-drilling self-tapping screws as practical shear resisting connections in building construction. A set of design rules was formulated in accordance with both BS5950: Part 5 and Eurocode 3: Part 1.3 after calibration against test data.

There has been much research work reported in the literature about the development of moment connections between cold-formed steel purlins in modern roof systems. A number of different connection configurations with sleeves or overlaps were found in various proprietary systems which offered partial continuity along the purlins. Bolted moment connections between cold-formed steel sections with connection configurations suitable for general application [16–21] were also pro-