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Effect of flange restraints on shear Tension Field Action in cold-formed C-sections

Cao Hung Pham *, Dmitry Zelenkin, Gregory J. Hancock

School of Civil Engineering, The Univ. of Sydney, NSW 2006, Australia

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ABSTRACT

The recently incorporated Direct Strength Method (DSM) rules for shear in the North American Specification for Cold-Formed Steel Structural Members (NAS S100:2012) consist of design equations for unperforated sections with and without Tension Field Action (TFA). The TFA is mobilised as a result of the development of diagonal tension due to the full depth bolt restraints. The design shear equations based on a reduction factor α to account for reduced TFA were proposed by Pham and Hancock in cases of partly bolted connections with lateral flange restraints. This paper presents an experimental program to further investigate the TFA of cold-formed C-sections in shear. A total of twelve tests were carried out at the University of Sydney. Three different bolted connection configurations were chosen with and without lateral restraints of the top flanges at the supports. Numerical simulations using the Finite Element Method (FEM) were also performed to validate test results and extend data range. For tests without lateral flange restraints, combined twisting and shear failure modes were observed. The lack of lateral flange restraint leads to a significant reduction of the ultimate load especially when more bolts were removed. Based on these experimental and FEM modelling data, a further reduction factor β dependent upon the slenderness of the sections is introduced in this paper to account for the lack of lateral flange restraint along with the previously proposed reduction factor α which accounts for bolt reduction.

1. Introduction

Cold-formed structural members in a floor system are shown in Fig. 1. The most commonly utilised beam shapes are C-sections and Z-sections used as intermediate members to transfer loads from the floor sheeting to the main structural frames (see Fig. 1). Shear and combined bending and shear are common design situations for beam design especially at or adjacent to supports. The connections at end supports and at some loading points often involve bolted or screwed connections where the bolts or screws extend over the full depth of the section or a portion of it. Tension Field Action (TFA) in shear may be utilised in cases where sufficient support is given to the web and flanges of the section to allow it to be mobilised. Fig. 2a and b shows examples of bridging members where load is transferred onto a short shear span where TFA may be mobilised. In an earlier paper, Pham and Hancock [1] investigated numerically the TFA for cases of reduced numbers of bolts at the loading and support points. A reduction factor α was proposed to allow for the reduced TFA. To further investigate and validate this approach, a test program and additional finite element analyses were conducted and described in this paper. As part of this program, it has been discovered that flange restraint also plays a significant part in mobilising TFA. Examples of beams attached to beams and columns without flange restraint are shown in Fig. 2c and e. Examples with lateral flange restraints are shown in Fig. 2d and f. End details are also shown in Fig. 2g and h.

The recent development of the Direct Strength Method (DSM) of design of cold-formed sections without holes in pure shear [2] has been extended in the North American Specification for Cold-Formed Steel Structural Members (AISI S100-2012) [3]. Proposed DSM design rules for sections with and without TFA and without holes were calibrated against a series of predominantly shear tests of both plain C- and SupaCee sections [2,4] performed at the University of Sydney. Two features researched are the effect of full-section shear buckling (as opposed to web-only shear buckling), and TFA.

In the above experimental programs [2,4], the vertically aligned bolts connecting the tested channel webs to the load and supports spanned the full depth of the section for both 150 mm and 200 mm depth tests. These vertical rows of bolts increased the restraints to the web panel and acted as web stiffeners. The increased restraints improved the post-buckling strength of the web especially for the predominantly shear tests. This post-buckling strength may occur as a result of the development of diagonal tension (TFA).

* Corresponding author.
E-mail addresses: caohung.pham@sydney.edu.au (C.H. Pham), dzel0743@uni.sydney.edu.au (D. Zelenkin), gregory.hancock@sydney.edu.au (G.J. Hancock).

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Fig. 1. Cold-formed framing system.
(Courtesy: ClarkDietrich Building Systems).

Pham and Hancock [1] extended the modelling and analysis of the experimental data using the Finite Element Method (FEM) program ABAQUS [5] to investigate the effect of reduced bolting on ultimate capacity of channel sections under predominantly shear including the TFA. To validate the performance of the model, they created reliable FEM models with full vertical bolts. These models were used to check the accuracy with the available test data from experimental programs from the University of Sydney [2,4] and the University of Missouri Rolla (UMR) tests in the 1970's [6]. Based on the reliable FEM models, three different bolted connection configurations, which represent different Patterns A, B and C of reduced bolting at both supports and loading points, were studied in Pham and Hancock [1]. Depending on the bolting configurations, when the bolts are removed, the shear capacities decrease due to reduced TFA. The failure mode shapes are a combination of shear buckling and web crippling at the locations of the missing bolts. A design proposal based on a reduction factor α to account for reduced TFA was calibrated against the FEM models.

This paper presents an extended experimental program also performed at the University of Sydney to further investigate the effect of reduced bolts at the connections on the TFA. A commercially available plain C-lipped channel section (C20015) of 1.5 mm thickness as tested in previous experimental programs [2,4] has been chosen. Initially, tests with full vertical bolts (5 bolts in each row) were conducted as a reference base to compare with the corresponding tests in [2,4]. The bolted connection configuration Pattern A in Pham and Hancock [1] has been chosen as it has the largest effect on the ultimate shear loads in comparison with those of Patterns A and B. The channel specimens were then tested with 1 Row-off and 2 Rows-off following Pattern A as shown in detail in the following section. In this experimental program, half of the tests were conducted with lateral flange restraints and these test results were validated against FEM models performed in Pham and Hancock [1]. The remaining tests were tested without lateral flange restraints. Although two tested channels were connected by the straps in each test, the premature failure caused by combined twisting and shear modes was observed in tests with bolts removed. This leads to significant drops in ultimate capacities of channel sections under predominantly shear loads due to lack of lateral flange restraints.

In order to validate these test results and obtain realistic failure modes as occurs in the tests in this study, the finite element nonlinear analysis using ABAQUS [5] was utilised to create FEM models for the whole test rig. The simulation results from FEM were then compared and calibrated against those from the testing series of this study for three bolted connection configurations with and without lateral flange restraints. For the cases of tests with lateral flange restraints, the FEM models for the whole test rig in this study were also compared with those in Pham and Hancock [1] where only half of the model had been modelled due to symmetry. For the cases without lateral flange restraints, the FEM models were subsequently utilised to simulate all sections in the Pham and Hancock testing programs [2,4] where the bolts were removed to avoid the need to perform these tests again. The FEM results from these cases without lateral flange restraints show further drops in ultimate shear strengths of the channel sections as more bolts were removed. Also, when the sections are more slender, further reductions are observed due to combined shear and twisting failure modes. New DSM design curves with TFA for channel sections in shear are therefore proposed in this paper with the introduction of a further reduction factor β where lateral flange restraints are not provided along with the reduction factor α which accounts for bolt reduction as proposed in Pham and Hancock [1].

2. Experiments on channel sections subject to predominantly shear loads

2.1. Test rig design

The experimental program [7] comprised a total of twelve tests conducted in the J. W. Roderick Laboratory for Materials and Structures at the University of Sydney. All tests were performed in the 2000 kN capacity DARTEC testing machine, using a servo-controlled hydraulic ram. A diagram of the test set-up configuration is shown in Fig. 3. At the loading point at mid-span, the DARTEC loading ram with spherical head moved downwards at a constant stroke rate of 1 mm/min during testing. The load was transferred uniformly to a T-shaped load transfer fabricated from an assembly of 2 steel plates of 20 mm thickness as shown in Fig. 3. Two C20015 channel sections were then bolted back to back through the webs by two vertical rows of M12 high tensile bolts. The distance between these two vertical rows of bolts is 50 mm. At each support, two channel beams were also bolted through the webs using another T-shaped load transfer by one vertical row of M12 high tensile bolts. For channel section C20015 with 200 mm depth in tests with full bolt configuration, five bolts were used at each support and ten at the loading point for tests. A nut was located between the channel web and the T-shaped load transfer in each bolt to minimize restraint to the web as seen in Fig. 3. The two T-shaped load transfers at supports rested on the half rounds of the DARTEC supports to simulate a set of simple supports.

The three T-shaped load transfers at the loading point and supports were introduced to prevent bearing failure which could be caused by using conventional bearing plates. Also, these T-shaped load transfers eliminated possible web crippling in the web and/or torsional loading of the tested channels. Further, the beams specimens were also connected by four $25 \times 25 \times 5$ EA (Equal Angle) steel straps on each top and bottom flanges adjacent to the loading point and supports as seen in Fig. 3. Self-tapping screws were used to attach these straps to the tested specimens. The object of these straps was to prevent section distortion of the flanges at loading point and supports. Two LVDTs (Linear Variable Displacement Transducers) were utilised as shown in Fig. 3 to measure vertical displacements at loading points. Four other LVDTs were also utilised to measure vertical displacements of top flanges at supports.

2.2. Tests with and without lateral flange restraints

In the total of twelve experiments, six tests were conducted with lateral flange restraints at supports and six remaining tests without lateral flange restraints. As shown in Fig. 4, two equal angle straps adjacent to the supports were bolted to the T-shaped load transfers. The purpose of this configuration is to prevent lateral displacements caused by the twisting mode. This premature failure mode may occur especially in cases where there are not enough bolts spanning the full depth of the sections.