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Tests and behavior of hot-rolled channel steel sections subjected to web crippling

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ABSTRACT

Web crippling failure of hot-rolled channel steel sections could be found due to localized concentrated loads or brace reactions. This paper reports the results of an investigation into web crippling behavior of channel sections subjected to end-one-flange (EOF), interior-one-flange (IOF), end-two-flange (ETF) and interior-two-flange (ITF) loading conditions. A total of 48 channel section tests subjected to web crippling were conducted. The investigation was mainly focused on the effects of bearing length and web slenderness ratio of channel sections on ultimate capacity against web crippling. The tests were performed on four different sizes of channel sections. The results obtained from these tests show that as the bearing length increases, the web crippling ultimate capacity increases significantly. When the bearing length was 50 and 100 mm, the web crippling ultimate capacity of channel sections with web slenderness ratio $(h_t/t) = 18$ reached its peak. When the bearing length was 150 mm, the web crippling ultimate capacity of channel sections with web slenderness ratio $(h_t/t) = 12.55$ reached its peak. The web crippling ultimate capacity of channel sections with web slenderness ratio $(h_t/t) = 24.67$ reached the minimum value. Plastic deformation developed near the mid-height of the web, and that a plastic hinge zone formed in the ultimate limit state. Finite element models have been developed and verified against the test results. The calculation equations of web crippling ultimate capacity put forward in the paper can accurately predict experimental value.

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1. Introduction

Structural steel is mainly used in two forms as hot-rolled and cold-formed sections. Hot-rolled members nowadays are more widely used than cold-formed steel members because hot-rolled steel members have various advantages, such as good welding performance and high ultimate capacity. The susceptibility of hot-rolled and cold-formed sections to buckle implies that instability phenomena such as web crippling, where the web locally buckles due to concentrated transverse forces, must be considered.

A considerable amount of research has been carried out on cold-formed sections subjected to web crippling over many years by numerous researchers, particularly to validate various design rules for web crippling, and the majority were based on experimental investigations. Holesapple and LaBoube [1] focused on the effects of bearing length on the web crippling capacity of cold-formed single web C-section and Z-section steel members. The current design requirements for end-one-flange web crippling capacity were found to be conservative. The web crippling strength was introduced in closed-form solution based on the parameters of the trained neural networks by Guzelbey et al. [2]. Extensive parametric studies were also performed and presented graphically to examine the effect of geometric and mechanical properties on web crippling strength. An experimental investigation of cold-formed stainless steel hollow sections subjected to web crippling was presented by Zhou and Young [3]. Tests were conducted on square and rectangular hollow sections of austenitic stainless steel type 304. A unified web crippling equation for cold-formed stainless steel sections with single web was proposed. A nonlinear finite-element analysis was based on element models of the test specimens and test set-up on cold-formed steel channels subjected to web crippling under end-one-flange and interior-one-flange loading conditions by Ren et al. [4]. It was found that the design strengths based on the numerical analysis and the tests calculated from the North American Specification [5] were generally unconservative for channel sections with unstiffened flanges having web slenderness ratio ranging from 7.8 to 108.5 subjected to web crippling under the end-one-flange and interior-one-flange loading conditions. A series of tests on cold-formed high-strength stainless steel square and rectangular hollow sections subjected to web crippling were performed by Zhou and Young [6]. The design strengths predicted by the ASCE Specification [7], the AS/NZS Standard [8], the EC3 Code [9], and the North American Specification [5] were either unconservative or very conservative. A unified web crippling equation with new coefficients for cold-formed high strength

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stainless steel square and rectangular hollow sections was proposed. Carden et al. [10] experimentally and numerically investigated the critical web limit states in unstiffened and unbraced steel beams used in bridge subjected to patch loads from timber or steel posts. Existing equations were appropriate for calculating the web yielding and crippling capacity. Islam and Young [11] experimentally and numerically investigated strengthening of ferritic stainless steel tubular members using externally bonded high modulus carbon fiber-reinforced polymer (CFRP) plate subjected to web crippling. Most of the strengthened specimens failed because of debonding of CFRP plate from the ferritic stainless steel tubes. Two different failure modes were observed in the tests of the strengthened specimens, namely the adhesion failure as well as the combination of adhesion and cohesion failure. Zhou and Young [12] numerically investigated cold-formed high strength stainless steel square and rectangular hollow sections subjected to web crippling at elevated temperatures. A unified web crippling equation for cold-formed high strength stainless steel square and rectangular hollow sections at elevated temperatures was proposed. A new unified web crippling resistance expression of ferritic stainless steel cold-formed sections based on numerical simulations validated with experimental results was proposed by Bock et al. [13]. Bock and Real [14] put forward a new design approach for web crippling design of stainless steel hat sections based on strength curves controlled by slenderness-based functions. The effects of web crippling on such cross-sections were studied numerically and the obtained results were used to derive the design expressions. The ABAQUS code was employed to implement purely static shell finite element models aimed at replicating a web crippling experimental test and quasi-static analyses with an explicit integration scheme were adopted by Natario et al. [15]. Wu and Bai [16] investigated the web crippling behavior of pultruded GFRP sections under concentrated loading, employing four square hollow sections of different sizes. A simple mechanism based design equation was proposed to estimate the strength of such pultruded GFRP sections subjected to web crippling.

There is little experimental and numerical research being carried out on the behavior of hot-rolled channel steel sections (channel sections) subjected to web crippling. Hence, the ultimate capacity, failure modes and ductility of channel sections subjected to web crippling need further investigation. In this paper, a series of web crippling tests of channel sections was performed. Reaction on the lower flange sometimes is considered a load condition (such as in the ETF and ITF cases) and reaction on ground sometimes is considered another boundary condition (such as in the EOF and IOF cases). The effects of bearing lengths, web slenderness ratio and boundary and loading conditions on the ultimate capacity and initial stiffness of channel sections subjected to web crippling were investigated. Furthermore, the comparison of experimental and finite element results revealed that the finite element models were very capable of closely simulating the web crippling failure behavior observed in the experiments. The design equations of ultimate capacity are also proposed for channel sections subjected to web crippling at the end of the paper.

2. Experimental investigation

2.1. Test specimens

To research web crippling property of channel sections, a total of 48 hot-rolled channel steel sections with different boundary condition, loading condition, section height, and bearing length was tested. The test specimens subjected to web crippling comprised four different section sizes, having a nominal height ranging from 80 to 140 mm. The web slenderness ratio (h_t/t) values ranged from 14.22 to 23.41, as shown in Fig. 1.

2.2. Load application and support conditions

The width of the rigid bearing plates was the same with the bearing plate length. The rigid bearing plates were fabricated by extrusion using Chinese Standard Q345 steel whose nominal yield strength is 345 MPa having the nominal thickness of 30 mm to evenly transfer concentration loading on the upper flange of channel section. Because the thickness of bearing plates is far larger than those of channel sections, the plates can be considered to be rigid. All bearing plates were machined to specified dimensions, and the length was 300 mm. The bearing plates were designed to act across the full flange widths of the specimen sections, so as to ensure the overall displacement loading.

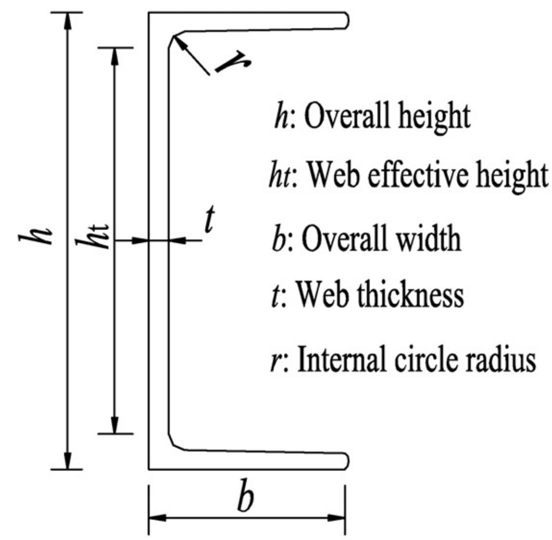

Fig. 1. Definition of symbols of channel sections.

In this paper, the specimens were tested in four loading and boundary conditions, namely, end-one-flange (EOF), interior-one-flange (IOF), end-two-flange (ETF) and interior-two-flange (ITF), as shown in Fig. 2. As an example, EOF supposedly covers the case in which the load is applied to the upper flange (through a bearing plate) at the end of the specimen, whose lower flange is resting on plane surface.

In order to remove the influence of the boundary condition, the distance from the edge of the bearing plate to the end of the member was set to be at least 1.5 times the overall depth of the web from the edge of the bearing plates. Schematic sketch of web crippling tests in four boundary and loading conditions were considered in Fig. 2. Fig. 3 shows photos of web crippling tests in four boundary and loading conditions.

The line of the hydraulic jack load goes through the shear centre of rigid plate. The bearing plate rotation is not controlled during testing. The bearing plates are fixed by spot welding to the specimen. For instance, in cases EOF and IOF, the specimens are presumably supported at the bottom on a plane foundation base, and the load is applied at the top through a bearing plate. In cases ETF and ITF, the specimens are supported on a reaction plate of the same dimension as the loading (bearing) plate through which the load is applied. In the ETF case, a reaction bearing plate is provided at the end opposite to that at which the load is applied.

2.3. Specimen labeling

In Table 1, the specimens were labeled so that the boundary condition, the loading condition, the nominal dimension of the specimens and the length of the bearing could be identified from the label. P_{cr} is experimental value of the web crippling ultimate capacity of channel sections in the test. For example, the label '[100-ETF-N100' defines the following specimen:

- The first letter '[' denotes hot-rolled channel steel sections.
- The following part of the label '100' denotes the section overall height of hot-rolled channel steel sections in mm with the nominal overall height of 100 mm.

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