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Experimental and finite element analysis research on cold-formed steel lipped channel beams under web crippling

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ABSTRACT

This article presents the results of an investigation into web crippling behavior of cold-formed steel lipped channel beams 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 cold-formed steel lipped channel beams with different boundary conditions, loading conditions, bearing lengths, and section heights were tested. The experimental scheme, failure modes, concentrated load-general vertical deformation and strain intensity distribution curves are presented in the article. The effect of boundary condition, loading condition, bearing length and section height on web crippling ultimate capacity and ductility of cold-formed steel lipped channel beams was also studied. Results of these tests show that the effect of bearing length on the web crippling ultimate capacity in EOF and ETF loading conditions is more obvious than those in IOF and ITF loading conditions. When bearing length is 50, 100, and 150 mm, web crippling ultimate capacity of cold-formed steel lipped channel beams with web slenderness = 78 reaches its peak. The middle web enters plasticity and form plastic hinge zone. The values of web crippling ultimate capacity in interior-flange loading conditions are larger than those in end-flange loading conditions. It is shown that the specimens in the interior-flange loading conditions have higher ultimate capacity, larger initial stiffness and better ductility than those of specimens in the end-flange loading conditions. Finite element analysis can simulate experimental failure mode and web crippling ultimate capacity. The calculation equations of web crippling ultimate capacity put forward in the article can accurately predict experimental value.

1. Introduction

Cold-formed steel lipped channel beams nowadays are widely used in stadiums, towers, and bridges due to their light weight, high strength, ease of transportation and construction, mass production, and fast installation. The webs of cold-formed steel lipped channel beams may buckle due to high slenderness and concentrated transverse forces. Therefore, web crippling needs to be considered in designing cold-formed steel lipped channel beams.

A considerable amount of research has been carried out on web crippling for many years by numerous researchers, particularly to validate various design rules for web crippling, and the majority was based on experimental investigations. Web crippling (crushing behavior) of hat section beams was experimentally investigated by Hofmeyer [1,2], who implemented the yield-line analysis (plastic mechanism analysis) to the investigation of the crushing behavior of top hat-section beams subjected to three-point bending-a similar approach was applied by Bakker and Stark [3]. A research program was initiated to investigate web crippling behavior of cold-formed thin-walled lipped channel beams in the four loading conditions. The results of the preliminary experimental investigations and the finite element analysis of lipped channel beams in IOF and ITF loading conditions were reported in previous publications [4,5]. Eighty-two web crippling tests of cold-formed steel sections, including 20 tests on channel sections without web openings and 62 tests on channel sections with web openings, were conducted by Uzzaman et al. [6,7]. The finite element model was shown to be able to closely predict the web crippling behavior of the channel sections, both with and without circular web hole. It was demonstrated that the main factors influencing the web crippling strength are the ratio of the hole depth to the flat depth of the web, and the ratio of the length of bearing plates to the flat depth of the web. A combination of experiments and non-linear finite element analysis was used to investigate the effect of offset web holes on the web crippling

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Nomenclature

EOF	End-one-flange
IOF	Interior-one-flange
ETF	End-two-flange
ITF	Interior-two-flange
P_{cr}	Experimental web crippling ultimate capacity
P_{crC}	Web crippling ultimate capacity obtained by using Chinese steel structures design code (GB50013-2003)
P_{crE}	Web crippling ultimate capacity obtained by using European design of steel structures (Eurocode 3)
P_{FEA}	Web crippling ultimate capacity obtained by using finite element analysis
P_{crRE}	Web crippling ultimate capacity obtained by using equations the article put forward
P_{EOF}	Web crippling ultimate capacity in EOF condition
P_{IOF}	Web crippling ultimate capacity in IOF condition
P_{ETF}	Web crippling ultimate capacity in ETF condition
P_{ITF}	Web crippling ultimate capacity in ITF condition
f_y	Tensile yield stress
f_u	Ultimate tensile stress
ν	Poisson's ratio
δ	elongation after fracture
E	Elastic modulus
h_t	Web height of cold-formed steel lipped channel beams
t	Web thickness of cold-formed steel lipped channel beams
a	Bearing length
h_t/t	web slenderness
ε_i	Strain intensity
ε_1	First principal strain
ε_2	Second principal strain
ε_3	Third principal Strain

strength of cold-formed steel channel sections in the end-two-flange (ETF) loading condition by Uzzaman et al. [8]. A series of tests on aluminum square and rectangular hollow sections under web crippling was presented by Zhou et al. [9,10]. The web crippling strength in ETF loading condition increases faster than those in ITF loading condition as the bearing length increases. The effect of the bearing length on the web crippling strength in ETF loading condition is more severe than those in ITF loading condition. The new web crippling test data presented in this article can be used to develop design rules for aluminum square and rectangular hollow sections. An experimental study was conducted at University of Missouri-Rolla by Stephens et al. [11] to establish the web crippling strength of both box and I-beam headers for an interior-one-flange (IOF) loading condition. The web crippling strength was greater than that for two independent, single web C-sections.

There is little experimental and numerical research being carried out on the behavior of cold-formed steel lipped channel beams in four loading and boundary conditions under web crippling. Therefore, the ultimate capacity, failure modes, and ductility of cold-formed steel lipped channel beams under web crippling need further investigation. In this article, the experimental work was conducted on cold-formed steel lipped channel beams under web crippling. The effects of bearing lengths, web slenderness, and boundary and loading conditions on the ultimate capacity and initial stiffness of cold-formed steel lipped channel beams under web crippling were investigated. Furthermore, using the calibrated finite element analysis, a parametric study was conducted to comprehensively investigate the effects of some important geometric parameters on the ultimate capacity of cold-formed steel lipped channel beams under web crippling. The design equations of ultimate capacity are also proposed for cold-formed steel lipped channel beams under web crippling at the end of the article.

2. Experimental investigation

2.1. Test specimens

To research web crippling property of cold-formed steel lipped channel beams, 48 cold-formed steel lipped channel beams with different boundary condition, loading condition, section height, and bearing length were tested. The bearing plates were fabricated with Chinese Standard Q345 steel having the nominal thickness of 30 mm. All the bearing plates were machined to specified dimensions whose 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.

The test specimens under web crippling comprised four different section sizes, having nominal heights ranging from 80 to 150 mm. The measured ratio of the height to the thickness (web slenderness) of the webs was 63, 75, 80, and 78, as shown in Fig. 1.

In the article, the specimens were tested in four loading conditions, namely, end-one-flange (EOF), interior-one-flange (IOF), end-two-flange (ETF), and interior-two-flange (ITF). 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. Schematic sketch of web crippling tests in four boundary and loading conditions was considered in Fig. 2. Fig. 3 shows photos of web crippling tests in four boundary and loading conditions.

2.2. Specimen labeling

In Table 1, the specimens were labeled so that the boundary condition, the loading condition, the nominal dimension of the specimen and the length of the bearing, as well as, web crippling ultimate capacity of cold-formed steel lipped channel beams (P_{cr}), could be identified from the label. For example, the label 'J[100-

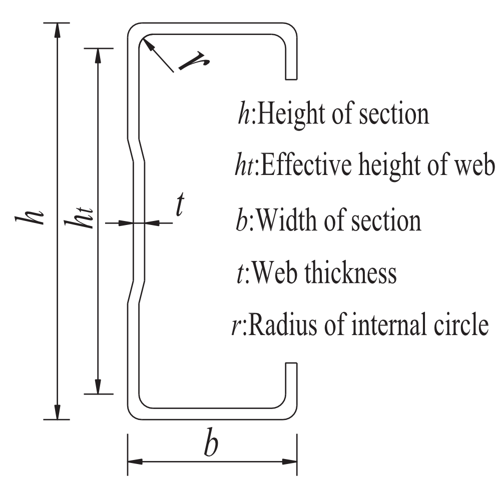

Fig. 1. Definition of symbols of cold-formed steel lipped channel beams.