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Web crippling behavior of grouted galvanized rectangular steel tube

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ABSTRACT

To research the web crippling behavior of welded galvanized steel tubes with square and rectangular hollow sections under concentrated load, SHS and RHS carbon welded galvanized steel tubes under four different loading conditions were tested. This paper also examined an approach to enhance web crippling strength of the tubes, by infilling the mortar as composite section. Although very relevant, the understanding about the web crippling behavior in carbon welded galvanized composite section is still very limited, as attested by the lack of information available in design codes and guidelines. End-two-flange (ETF) and interior-two-flange (ITF) loading conditions were adopted, with specimens seated on a bearing plate. Specimens were also placed on the ground with end (EG) or interior (IG) bearing load to simulate the loading conditions of floor joist members. The effects of the loading positions (end loading or interior loading) as well as the supporting conditions (on a bearing plate or on the ground) on the web crippling behavior are discussed and the enhancements of infilling mortar are evaluated. It was found that infilling the mortar in galvanized rectangular steel tube is a very effective approach to enhance the web crippling strength of the tubes, especially for specimens with end bearing with solid ground. Based on the results of the parametric study, a number of design formulas proposed in this paper can be successfully employed as a design rule for predicting web crippling ultimate capacity of grouted galvanized steel tubes under four loading and boundary conditions.

1. Introduction

Carbon welded galvanized steel tubes are widely used in industrial construction. Galvanized rectangular steel tubes are susceptible to web crippling at points of concentrated load or bearing reaction, particularly in galvanized steel beam. Infilling the mortar in galvanized rectangular steel tube is an effective approach to enhance web crippling strength of rectangular hollow section.

Web crippling behavior of cold-formed thin-walled steel lipped channel beams subjected to Interior-One-Flange(IOF), Interior-Two-Flange(ITF), End-One-Flange (EOF) and End-Two-Flange (ETF) loading conditions as defined by the American Iron and Steel Institute (AISI) was conducted by Macdonald et al. [1]. Based on the results of the parametric study, a design rule to predict the web crippling strength of cold-formed steel lipped channel beams was developed which is much more flexible to adapt for new types of sections and ranges of dimensions by Macdonald and Heiyantuduwa [2]. Cold-formed steel sections with web openings and without web openings subjected to web crippling under two-flange loading conditions were experimentally and numerically investigated by Uzzaman et al. [3]. Web crippling behavior of cold-formed steel beams was numerically investigated using quasi-static analyses with explicit integration by Natário et al. [4]. A new approach to predict the web crippling failure load of cold-formed steel beams under External Two Flange (ETF) loading using the Direct Strength Method (DSM) was proposed by Natário et al. [5]. A combination of tests and non-linear finite element analyses was used to investigate the effect of such holes on web crippling cold-formed steel channel section under end-one-flange (EOF) loading condition by Lian et al. [6].

Islam and Young [7] performed experimental and numerical investigation on strengthening of ferritic stainless steel tubular members using externally bonded high modulus carbon fiber reinforced polymer (CFRP) plate. A new unified web crippling resistance expression based on numerical simulations and there after validated with experimental results has been proposed by Bock et al. [8]. A numerical investigation of cold-formed high strength stainless steel square and rectangular hollow sections subjected to web crippling at elevated temperatures was performed by Zhou and Young [9]. The experimental and numerical investigations of lean duplex stainless steel hollow sections strengthened with different fiber reinforced polymer (FRP) subjected to web crippling were conducted by Islam and Young [10]. A new design approach for web crippling design of stainless steel hat sections based on strength curves controlled by slenderness-based functions was proposed by Bock and Real [11].

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Nomenclature

H	profile depth
B	profile width
t_f	the flange thickness
t_w	the wall thickness
r	radius at the web-flange junction
f_y	tensile yield stress of carbon welded galvanized steel tubes
f_{mu}	measured mortar cube strength
b	bearing length
N	test strength
Δ	vertical displacement
N_p	predicted strength obtained from proposed formulas
N_{EGS}	predicted strength for steel specimen in EG loading conditions
N_{IGS}	predicted strength for steel specimen in IG loading conditions
N_{ETFS}	predicted strength for steel specimen in ETF loading conditions
N_{ITFS}	predicted strength for steel specimen in ITF loading conditions
N_{EGC}	predicted strength for composite specimen in EG loading conditions
N_{IGC}	predicted strength for composite specimen in IG loading conditions
N_{ETFC}	predicted strength for composite specimen in ETF loading conditions
N_{ITFC}	predicted strength for composite specimen in ITF loading conditions
α	transverse confinement coefficient
μ	influence coefficient of depth to width ratio on mortar strength
A	nominal local compressive area $A = b \times B$
σ	nominal local compressive stress $\sigma = N / A$

A series of tests was performed on fiber reinforced polymer (FRP) strengthening of aluminium tubular structural members subjected to End-Two-Flange and Interior-Two-Flange loading conditions by Islam and Young [12]. Web crippling behavior of GFRP pultruded profiles with I-section was experimentally investigated by Fernandes et al. [13]. Chen and Wang [14] conducted experimental investigation on the web crippling behavior in glass fiber reinforced polymer (GFRP) pultruded profiles with rectangular hollow section.

A total of 48 hot-rolled channel steel sections subjected to web crippling were conducted by Chen et al. [15]. Plastic deformation developed near the mid-height of the web, and that a plastic hinge zone formed in the ultimate limit state. The calculation equations of web crippling ultimate capacity put forward in the paper can accurately predict experimental value.

There is no published report on web crippling behavior of grouted galvanized rectangular steel tube under four loading and boundary conditions. The paper describes a comprehensive experimental study, numerical study and design recommendation of grouted galvanized rectangular steel tube. Firstly, the ultimate capacity, failure modes and ductility of grouted galvanized rectangular steel tube under web crippling need further investigation. Secondly, the effect of slenderness ratio, depth to width ratio, infilling the mortar in tube and loading condition on web crippling behavior could be investigated. Specimens were also placed on a solid foundation with end or interior concentrated loading to simulate the supporting condition of floor joist members. The web crippling failure mechanisms of grouted galvanized rectangular steel tube were revealed by load-displacement curves as well as by the progressive failure process. Finally, The general purpose finite element analysis (FEA) program ABAQUS was used for the numerical investigation. The finite element model (FEM) included geometric and material nonlinearities; the results of the finite element analysis were verified against laboratory test results. Ultimate capacity as well as the modes of failure predicted from the finite element analyses were in good agreement with the laboratory test results. Upon validation of the finite element models, a series of parametric studies are carried out. The design formulas of ultimate capacity were also proposed for grouted galvanized rectangular steel tube under web crippling in the paper.

2. Test program

2.1. Test specimens

The web crippling tests were conducted on empty and mortar-filled carbon welded galvanized steel tubes with square and rectangular hollow section. A total of 16 specimens were tested by applying transverse compressive loads as listed in Table 1. The specimens were fabricated by carbon welded galvanized steel tube with identical cross-section of SHS 100 mm × 100 mm × 1.2 mm and RHS 100 mm × 50 mm × 1.5 mm (height × width × thickness), as shown in Fig. 1. The length of the specimen (L), was chosen to be much longer than the length required (1.5 times the total height of the web) in ASCE

Table 1
Details of test specimens.

Specimens	Height H (mm)	Width B (mm)	Thickness of flange t_f (mm)	Thickness of web t_w (mm)	Slenderness ratio of web $\lambda = (H - 2t_f - 2r)/t_w$	Mortar strength f_{cu} (MPa)
100 × 50-EG	100	50	1.5	1.5	62	0
100 × 50-ETF	100	50	1.5	1.5	62	0
100 × 50-IG	100	50	1.5	1.5	62	0
100 × 50-ITF	100	50	1.5	1.5	62	0
100 × 100-EG	100	100	1.2	1.2	78	0
100 × 100-ETF	100	100	1.2	1.2	78	0
100 × 100-IG	100	100	1.2	1.2	78	0
100 × 100-ITF	100	100	1.2	1.2	78	0
100 × 50-EG-M	100	50	1.5	1.5	62	15
100 × 50-ETF-M	100	50	1.5	1.5	62	15
100 × 50-IG-M	100	50	1.5	1.5	62	15
100 × 50-ITF-M	100	50	1.5	1.5	62	15
100 × 100-EG-M	100	100	1.2	1.2	78	15
100 × 100-ETF-M	100	100	1.2	1.2	78	7.5
100 × 100-IG-M	100	100	1.2	1.2	78	7.5
100 × 100-ITF-M	100	100	1.2	1.2	78	7.5