~ Synopsis report of the PhD thesis entitled ~

Structural Performance of YSt-310 Cold-formed Steel Tubular Columns

Submitted by

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1 Introduction

Tubular steel sections have several advantages over open sections, such as high compression, bending and torsional resistances in addition to their aesthetically appealing nature, and are thus widely used in many industrial, commercial and residential buildings (Gardner *et al.*, 2010; Wardenier *et al.*, 2010). Tubular steel sections can be broadly classified into two groups based on the manufacturing processes used: a) hot-rolled, and b) cold-formed. Hot-rolled tubular steel sections are produced or finished at temperatures above their recrystallization temperature; whereas, in the case of cold-formed steel tubular sections, they are manufactured at ambient temperature by gradually forming an uncoiled metal sheet into circular tube and then to the desired shapes such as square or rectangular hollow sections, using a series of automated rollers with the ends are welded continuously through various welding techniques (see e.g. Davison and Birkemoe, 1983; Rossi *et al.*, 2013). During this process, stress-strain behaviour of cold-formed steel material is known to change from their virgin sheet (parent) material behaviour (indicated by a clearly defined yield point and followed by plateau region), to a rounded material model followed by certain amount of strain hardening (see e.g. Ringle, 1969; Afshan *et al.*, 2013). However, most of the contemporary international design codes pertaining to cold-formed steels do not incorporate the strength enhancement due to cold-forming and rely principally on elastic-perfectly plastic stress-strain material model, developed mainly for hot-rolled steel section.

Perforations (or cut-outs or holes or openings) are provided on the structural members (e.g. beams and columns) to incorporate various modifications or needs such as hidden electrical and signal wirings, heating and cooling air-circulations, inspection and maintenance work (especially for bridges and towers), fresh and waste water plumbing, connection to other members; aesthetic appearance; and material optimisation (see e.g. Shanmugam, 1997; Shanmugam *et al.*, 1999; Shanmugam and Dhanalakshmi, 2001; Moen and Schafer, 2009; Pellegrino *et al.*, 2009; Moen and Schafer, 2011; Yao and Rasmussen, 2012; Ghazijahani *et al.*, 2014; Kulatunga *et al.*, 2014; Feng and Young, 2015; Feng *et al.*, 2016; Yao *et al.*, 2016 and Sonu and Singh, 2017). However, introduction of a perforation in a tubular structural member can influence the member's load transfer mechanism. Due to the presence of perforation, redistribution of stresses can occur, thereby causing stress concentration and localised failure at the vicinity of the perforation (see e.g. Feng and Young, 2015; Yao *et al.*, 2016).

Looking at the Indian scenario, construction industries are mostly dominated by reinforced concrete structures, mainly because of their relatively long experiences and cheaper unskilled workforce. However, in the recent years, appreciable development in steel constructions has been observed where structural steels (particularly cold-formed steel tubular structures) are utilised in public building (*viz.*, skywalks, airports, stadia, railway platforms, shopping malls etc.), residential and industrial buildings. Amongst the various tubular steels specified in the IS code, such as YSt-210, YSt-355 (IS 4923, 1997), YSt-310 cold-formed steel hollow sections are one of the most widely used structural steel in India. YSt-310 steel has minimum yield and ultimate tensile strengths of 310 N/mm^2 and 450 N/mm^2 respectively, with a percentage elongation at fracture of ~ 10%.

2 Literature review

A detailed literature review on the previous research works conducted on the material characterisation, performance analysis and design aspects of cold-formed steel tubular stub columns, including both unperforated and perforated, are presented in **Chapter 2.** Based on the literature review, it has been observed that detailed and reliable investigations on the material characteristics of YSt-310 cold-formed steel tubular sections are very limited (e.g. Arivalagan and Kandasamy, 2010) and not readily available for ambient temperature. In addition, the structural performance of YSt-310 cold-formed steel tubular sections, at ambient temperature has not been studied so far and no test data are available.

The change in the properties of structural steel when exposed to elevated temperature is well documented in the literature, e.g., Outinen and Mäkeläinen (2004); Gunalan and Mahendran (2014); McCann *et al.* (2015); Chen *et al.* (2016); Liu *et al.* (2017); Li and Young (2017); Li and Young (2018) etc. However, for cold-formed steel tubular sections having nominal yield stress less than 460 MPa as per EC3-1-12 (2007), limited literatures are available (Outinen *et al.*, 2001; Balarupan, 2015; McCann *et al.*, 2015; Imran *et al.*, 2018). Moreover, since the reduction factors proposed by past researchers are based on individual test results (and hence valid for specific campaign), the applicability of the previously proposed equations to YSt-310 cold-formed steel needs to be assessed; and thus the need for investigating the elevated temperature mechanical properties of this steel material is imperative.

In the recent years, limited, but increasing research interests have been witnessed on the investigation of the residual post-fire mechanical properties of steel through tensile coupon tests. These studies were mainly focussed on deterioration of mechanical properties of different types cold-formed steel (see e.g. Outinen and Mäkeläinen, 2004; Outinen, 2007; Gunalan and Mahendran, 2014; Wang *et al.*, 2014; Lu *et al.*, 2016; Huang and Young, 2017; Li and Young, 2018). From the literature review, it is found that limited post-fire studies were conducted on cold-formed steel tubular sections. It has also been observed that, post-fire properties are depended on steel types (or grades). Moreover, it is also seen that the predictive equations to determine the mechanical properties of steel structure after a fire event, proposed by previous researchers are based on limited test data and hence there is a need to enrich the test database, so as to assess their suitability.

Further, it has been noted that an extensive research works has been reported from the late1950's, on steel plates (e.g. Ritchie and Rhodes, 1975; Shakerley and Brown, 1996; Shanmugam *et al.*, 1999; Cheng *et al.*, 2013) and beams (e.g. Yu and Davis, 1973; Narayanan and Rockey, 1981; Sivakumaran and Zielonka, 1989; Shan *et al.*, 1994; Shan *et al.*, 1996; Moen, 2008; Chen and Cao, 2010; Feng *et al.*, 2017 and Sonu and Singh, 2017 etc.), and columns (e.g., Marshall and Nurick, 1970; Shanmugam *et al.*, 1999; Dhanalakshmi and Shanmugam, 2001; Moen, 2008; Moen and Schafer, 2011) demonstrating the reduction on member strength capacity due to presence of perforation. However, it has been evident that most of the published experimental and numerical studies focussed mainly on plates and open cold-formed steel sections, and an apparent lack of a systematic study on perforated rectangular tubular (closed) steel sections subjected to axial compression, can be seen.

3 Objectives

Based on the literature review presented above (Section 2), three key objectives have been identified for the current research work. The primary objective of this thesis is to investigate the fundamental material characteristics of YSt-310 cold-formed steel so that it can contribute to the pool of experimental data for cold-formed steel tubular sections, and thus making them readily available to researchers and design engineers. The second objective is to investigate the structural performances of unperforated and perforated short columns through experimental and numerical (finite element) studies. The third objective is to assess the applicability of existing design standards and proposed equations, based on the test and finite element results.

4 Chapters

In **Chapter 3**, the ambient temperature material characteristics of YSt-310 cold-formed steel rectangular and square hollow sections such as elemental composition, metallographic structure, and mechanical properties has been investigated through various standard test methods. Key stress-strain parameters *viz.*, Young's moduli, proof stress, ultimate strength, percentage elongation, strain hardening exponent etc. have been computed from the stress-strain curves generated from tensile coupon tests. Metallographic examination revealed the occurrence of relatively larger grains in the flat regions as compared to those of corner regions wherein smaller but elongated grains have been seen. Also, the ambient temperature tensile test results showed the strength enhancement in the corner material (due to cold-forming) in particular the average proof stress and ultimate stress of corner material have been found to by higher by ~ 26% and 34% respectively.

Elevated temperature mechanical properties of YSt-310 cold-formed steel have been studied through steady-state elevated temperature tensile coupon tests (**Chapter 3)**. A total of 31 tensile coupon have been performed at temperatures ranging from approximately ambient to 800 °C and the reduction factors of key material parameters have been estimated. Elevated temperature reduction factors of YSt-310 cold-formed steels are then compared with those presented in design guidelines and reported by earlier researchers. Based on the comparison, following concluding remarks have been made: a) except for elastic modulus, the design reduction factor for key material parameters presented in most of the international design standards are observed to be unsuitable for cold-formed steels tubular sections; b) design reduction factors in IS 800 (2007) for elastic modulus and yield stress are found to be unsuitable for YSt-310 material; and c) a new set of fire design reduction factors for key material parameter, based on lower bound values of the present and existing test results, has been proposed.

Additionally, in **Chapter 3**, post-fire mechanical property of YSt-310 cold-formed steel tubular section have been studied through standard tensile coupon and microhardness tests at ambient temperature. Stress-strain curves, key material parameters and microhardness values, generated from the tests, have been analysed and the following important findings are made: a) the reduction in elastic modulus due to fire exposure of YSt-310 cold-formed steel material is insignificant; b) for exposed temperature up to ~ 400 °C, the reductions in yield strength and tensile strength is approximately zero, however the strengths are found to reduce by ~ 59% and 77% respectively at the exposed temperature of ~ 800 °C; c) two best fit linear correlations between yield and tensile stress against microhardness values have been developed and d) two sets of empirical equations to predict the post-fire reduction factors of cold-formed steel have also been develop separately for i) YSt-310 steel material and ii) cold-formed steel of various grades presently available in the literature, using the present test and existing test results from literature.

In **Chapter 4**, the structural performance of YSt-310 cold-formed steel tubular stub columns has been investigated through experimental and numerical programme. The extent of strength enhancement in the corner region due to cold-forming has been investigated using microhardness tests. A total of 12 stub column tests have been performed to investigate the cross-sectional capacity of YSt-310 cold-formed SHS and RHS stub columns. Using validated FE models (considering 3D laser scanner measured local geometric imperfections and non-linear material properties), parametric study has been performed to study the performance of stub columns covering a wide range of cross-sectional slenderness. The column capacities generated from the test and FE models have been utilised to assess the accurateness of the current international guidelines for design of cold-formed steel columns, such as European Standard, EC3-1-1 (2005), AISI standard, AISI S100-16 (2016) and modified DSM design equations by Rossi and Rasmussen (2013) and Arrayago *et al.* (2017). Based on the test and FE analysis, following concluding remarks are presented: a) strength enhancement due to cold-forming was found to confine within the corner regions only; b) local geometric imperfection for cold-formed steel tubular sections have been found to be in the range ~ 0.012–0.047 mm; c) the design strength predicted by EC3-1-1 (2005), CSM Zhao *et al.* (2017), DSM (Direct Strength Method) in AISI S100-16 (2016), modified DSMs Rossi and Rasmussen (2013); Arrayago *et al.* (2017) are generally found to provide conservative prediction for non-slender cross-sections. However, for the case of slender cross-section, CSM (Continuous Strength Method) provides accurate design prediction and modified DSM proposed by Rossi and Rasmussen (2013) results in conservative design prediction; d) the Class 3 cross-sectional slenderness limit presented in EC3-1-1 (2005) of 42 was found to be unsuitable and thus a recommendation value of 38 has been proposed; and e) a modified design equation based on DSM was proposed based on current test and FE column capacities and found to provide conservative prediction with least scatter as compared to existing design equations of unperforated stub columns.

Chapter 5 presents an extension of the work highlighted in **Chapter 4**, by taking into account two opposite central circular perforation at mid-height of the column. Parametric study has been performed covering a wide range of cross-sectional slenderness and perforation diameters to width ratios, to study the effect of perforation sizes on the ultimate capacity of columns. Based on compression test and numerical analysis, as well as assessment of current design predictions for perforated columns, following points are highlighted: a) introduction of circular perforation increases the local geometric amplitude of perforated cold-formed steel tubular stub columns and using test results, a modified imperfection amplitude formula for both unperforated and perforated cold-formed steel stub columns has been developed; b) stub column test results showed that smaller perforations (say lesser than perforation ratio of 10%) are found to have little effect on the ultimate capacity, however, for perforation size ratios of 30%, 50%, 70% and 90%, the average percentage reduction on column capacities are observed to be ~ 9.57%, 18.24%, 31.15% and 40.00% respectively; b) most of the presently available design equations are seen to provide conservative and reliable but scattered predictions and c) a modified design equation based on DSM guidelines provided in AISI S100-16 (2016), for design of perforated tubular stub columns, considering perforation size ratios and cross-section slenderness, has been proposed.

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List of publications:

Journals:

1) **Singh, T. G.**, & Singh, K. D. (2017). Structural performance of YSt–310 cold-formed tubular steel stub columns. ***Thin–Walled Structures***, 121, 25–40.
2) **Singh, T. G.**, & Singh, K. D. (2018). Experimental investigation on performance of perforated cold-formed steel tubular stub columns. ***Thin–Walled Structures***, 131, 107–121.
3) **Singh, T. G.**, & Singh, K. D. (2019). Post-fire mechanical properties of YSt–310 cold-formed tubular steel sections. ***Journal of Constructional Steel Research***, 153, 654–666
4) **Singh, T. G.**, & Singh, K. D. (2019). Mechanical properties of YSt–310 cold-formed steel tubular sections at elevated temperatures, ***Journal Constructional Steel Research***, 158, 53–70.
5) **Singh, T. G.**, & Singh, K. D., Numerical modelling and design of perforated coldformed steel tubular stub columns: DSM approach (*Under preparation*)

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1) **Singh, T. G.**, & Singh, K. D. (2018).Capacity of cold-formed steel hollow stub columns with central circular perforations. ***Ninth International Conference on Advances in Steel Structures (ICASS18)***. Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hong Kong, China.
2) **Singh, T. G.**, & Singh, K. D. (2019). Design of Perforated Cold-formed Steel Tubular Stub Columns. ***17th International Symposium on Tubular Structures (ISTS17).*** Department of Civil and Environmental Engineering, National University of Singapore, Singapore (Full paper submitted).