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Structural performance of YSt–310 cold–formed tubular steel stub columns

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ABSTRACT

This paper describes experimental and numerical investigations conducted to characterize the basic material properties and design of YSt–310 cold–formed structural steel sections at Indian Institute of Technology, Guwahati. Square (SHS) and rectangular (RHS) hollow sections with minimum yield strength of 310 MPa manufactured by Tata Steel India, were considered in the study. Initially, results from elemental analysis via optical emission spectrometer (OES) investigation and metallographic examination using optical microscope are presented. Key stress–strain parameters viz., Young's modulus, proof stress, ultimate strength, percentage elongation, strain hardening exponent etc. were generated based on flat, corner and weld coupon tests data. Extent of corner strength enhancement due to cold – forming determined using Vickers's microhardness test are reported. Additionally, cross – section capacity of the stub columns were also investigated experimentally and numerically. The column capacities generated from test and finite element study are compared with the existing design code – EN 1993–1–1 (EN 1993-1-1, 2005) [1] and design rules – continuous strength method (CSM) (Zhao et al., 2017) [2] and direct strength method (DSM) (North American Specification for the Design of Cold-Formed Steel Structural Members, 2016; Arrayago et al., 2017) [3,4]. Based on the comparison, modifications on the existing design code and rules are suggested to provide a more accurate and reliable compressive design prediction.

1. Introduction

Cold–formed steel members have been increasingly used in many industrial, residential and commercial steel buildings due to their relatively good strength to weight ratio and speedy construction [5–8]. Further, unlike conventional hot–rolled sections, cold–rolled sections are usually thinner and are generally associated with high strength and stiffness to weight ratios, as a result of rolling process at ambient temperature [9]. With the advancement of cold–forming techniques, thicker steel plated up to 25 mm are now manufactured [9]. In the steel market, besides the traditional cold–formed square, rectangular and circular hollow sections, interesting newer sections such as flat oval [10,11], elliptical [12,13] and semi – elliptical [14] tubular sections are now introduced. Cold forming process is known to change the stress–-strain behaviour of carbon steel (with clearly defined yield point and followed by plateau region), to a rounded stress–strain model with strain hardening [15]. However the present design codes do not utilise the enhancement in strength due to cold forming and relies on elastic–perfectly plastic stress–strain model which is mainly applicable for hot–rolled section. To capture the strain hardening behaviour observed in stainless steel and cold–formed carbon steel, deformation based design method such as CSM (Continuous Strength Method) [2,16,17] were developed. In addition, modifications to DSM (Direct Strength Method), which was originally developed by Schafer and Peköz [18] to eliminate the limitations in finding cross–sectional area using effective width method has been reported, to account for strain hardening behaviour by researchers such as [4,19].

In India, construction industry is mainly dominated by reinforced concrete structures, with limited steel structures. However, of late, a visible increase in the adoption of steel structures (especially cold–-formed steel sections) has been observed, in the construction industry, for structures such as airport, shopping malls, stadia, railway platform sheds, skywalks, industrial buildings etc. Amongst the cold–formed structural steel members, one of the most widely used structural steel in India, is the YSt 310 variety, conforming to Indian standard IS 4923 [20] with nominal yield strength of 310 N/mm^2, tensile strength of 450 N/mm^2 and minimum percentage elongation at failure of 10%. However, to the best of authors' knowledge, detailed and reliable investigations on its material characteristics and structural performance for this particular steel are very limited (e.g. Arivalagan and Kandasamy [21]) and not readily available.

In this paper, a comprehensive experimental investigation on YSt–310 cold–formed SHS and RHS structural steel sections has been carried out, with the intention of providing basic material properties for

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researchers and design engineers. Laboratory experimental programme comprised of investigating elemental composition, metallographic examination, hardness test, tensile coupon test, measurement of geometric imperfection and stub columns test, was performed on four SHS and three RHS Tata Structura [22] specimens. Column capacity of a wide range of cross-sections, which was not covered in the experimental programme was investigated, using general purpose finite element (FE) software Abaqus. The column capacities from test and FE are compared with the design resistance calculated using the design predictions by EC3 [1], CSM [2], DSM detailed in AISI specification [3] and modified DSM [4]. The reliability of the design strength predicted by the above aforementioned design code and methods was assessed following the procedure detailed in section B of the commentary on AISI specification [22] for design of cold-formed steel structural member. A modified DSM design rule was then proposed in this study, which provides more accurate and reliable prediction for the design of YSt 310 cold-formed structural steel stub columns. A detailed description of the experimental procedures and equipments used, FE validation and parametric study and codal comparisons are discussed in the following sub–sections.

2. Experimental investigation

2.1. Chemical composition

The manufacturer's laboratory test results for chemical composition and tensile test on a RHS – 50 × 50 × 2.9 specimen, as given in the mill certificate are shown in Table 1. The notation followed for the specimens here is $B \times D \times t$ (see Fig. 1), and hence RHS – 50 × 50 × 2.9 denotes a rectangular hollow section with width, depth and thickness of 50 mm, 50 mm and 2.9 mm respectively. The metal chemical components of Yst 310 cold–formed hollow sections were determined on three specimens – 66 × 33 × 2.6, 60 × 40 × 2.9 and 40 × 40 × 3.2. Optical Emission Spectrometer (OES) was used to investigate elemental composition. The percentage of elemental compositions (e.g. C, Si, Mn, S, Fe etc,) found in the above three specimens are shown in Table 2.

It can be observed from Tables 1 and 2 that the quantity of Carbon and Phosphorus content resulted from the present test are slightly higher than those mentioned in the mill certificate; however Manganese and Sulfur content are quite matching. Element such as Silicon, Copper, Nickel, Titanium, Aluminum, Niobium and Nitrogen are also found to be present based on the present test results. It may be noted that mill certificate does not specify the method followed to measure chemical composition.

2.2. Microstructure

Metallographic examination for YSt 310 steel was conducted on three samples – 66 × 33 × 2.6, 60 × 40 × 2.9 and 40 × 40 × 3.2 to investigate the characteristics of microstructure for the flat, corner and weld portions using an optical microscope. Three transverse

Table 1
Chemical composition and mechanical strength of YSt 310 as per mill certificate.

Chemical composition (%)						Mechanical strength		
Section	C	Mn	S	P	Fe	Yield strength (N/mm^2)	Tensile strength (N/mm^2)	Elongation at failure (%)
50 × 50 × 2.9	0.049	0.768	0.007	0.011	Bal.	435.00	475.00	28.00

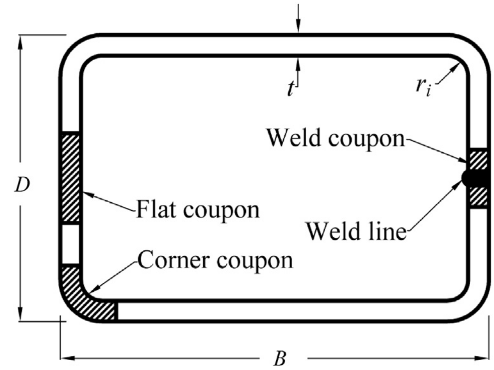

Fig. 1. Definition of symbols and position of coupon specimens.

cross–sections from 66 × 33 × 2.6, 60 × 40 × 2.9 and 40 × 40 × 3.2 were cut using a rotary hacksaw and milled flat using a lathe machine. The surfaces were ground on a series of silicon carbide paper under a continuous flushing of water and polished using 50 nm aluminum oxide abrasive to remove any scratch formed during cutting. Finally the sample was etched using a solution of 5% nitric acid and ethanol.

A typical microstructure seen under optical microscope of flat and curved portion is shown in Fig. 2(a) and (b) respectively, where the white areas are primary ferrite and the grey areas are pearlite (a mixture of ferrite and cementite). A difference in the morphology of flat and corner grains has been observed: the grains in the flat region are found to be relatively larger (see Fig. 2(a)) in comparison to those of corner regions wherein the grains are smaller and elongated (see Fig. 2(b). The elongated grains in the corner region may due to the mechanical pressure applied during cold-forming process. This could be the primary reason for enhanced material strength seen in curved coupon specimens as compared to flat coupon specimens (further discussion in Section 2.4). Size of weld coupon (see Section 2.4) was determined based on the microstructure of weld as shown in Fig. 3. Different zones of a typical weld region (welded using high frequency induction welder, HFIW) of 66 × 66 × 2.6 cross-section at higher resolution is shown in Fig. 4(a). The welded seam is composed of three zones namely weld zone (or fusion zone), heat affected zone (HAZ) and parent (or base) material [23]. The weld junction consists of white ferrite grains due to decarburization during welding. HAZ further consists of three layers: overheated, recrystallised and partially – recrystallised area. Widmanstätten pattern were observed in the overheated area (see Fig. 4(b)) and smaller (as compared to parent material) grains of ferrite and pearlite layer were observed in the recrystallised area (see Fig. 4(c)). The formation of coarser grain and Widmanstätten pattern in the overheated area as well as finer ferrite and pearlite grain in the recrystallised area would be the main reason for higher mechanical strength and hardness value observed in weld coupon (see Section 2.4) and microhardness test respectively [6,23] (see Section 2.3). However, it may be mentioned that post weld heat treatment process can reduce and homogenize higher hardness value in the HAZ (e.g. Sisi and Mirsalehi [23]).

2.3. Micro–hardness test

Extent of strength enhancement beyond the corner region due to cold–forming were reported by researchers previously (e.g. [5,24]) using Vickers microhardness test, since corner coupon tests provide only the average corner strength magnitudes. Microhardness test was conducted to capture variation of hardness profile with a finer resolution. The Vickers microhardness test was used in this present study and hardness was measured on three different cross sections – 66 × 33 × 2.6, 60 × 40 × 2.9 and 40 × 40 × 3.2, repeated for each section where the first section is represented by S1 and the second is represented by S2. Six samples having approximately 30 mm length were