Experimental investigation on performance of perforated cold-formed steel tubular stub columns

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ABSTRACT

This paper describes an experimental study to estimate the stub columns capacity of cold-formed square (SHS) and rectangular hollow sections (RHS) containing two opposite central circular perforations at column mid-height. The stub columns were extracted from commercially available Tata Structura-YST 310 tubular sections, with minimum yield strength of 310 MPa, conforming to Indian Standard 492. The influence of two opposite central circular perforations on the structural performance of tubular steel stub columns under concentric loading was investigated for perforation size to flat width ratios up to 0.9. The local geometric imperfections, load-end shortening curves, strain distributions at mid height of column and typical failure modes observed from the present test programme are documented in this paper. Further, the ultimate column capacities recorded from the test programme are compared with codified design predictions as well as design equations proposed by various researchers. Based on the comparison, it is observed that the predictions made by most of the currently available design equations are conservative and reliable but generally scattered for design of cold-formed tubular structural steel stub columns having central circular perforations.

1. Introduction

Tubular 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 [1,2]. Perforations (or cut-outs or holes or openings) are provided on the structural members (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 [3–15]. However, an introduction of perforation in a tubular structural member can influence the load transfer mechanism. Due to this, redistribution of stresses can occur, thereby causing stress concentration and localised failure at the vicinity of the perforation [10,14].

Extensive research work have been reported from the late1950's, on steel plates [9,16–26] and beams [5,27–41], and columns (e.g [4,8–11,13,14,42–48]) demonstrating the reduction in member strength capacity due to presence of perforations. Marshall and Nurick [46] studied the symmetric progressive buckling load of thin-walled mild steel square tubes with circular perforations and reported a linear decrease in the buckling load as the perforation diameter increases. Pu et al. [47] investigated the impact on size and position of rectangular perforations on the ultimate strength on lipped channel steel stub columns and observed that the strength of a thin channel column could be severely reduced if the perforation is located in the effective area, however for perforations located in ineffective area, the strength was found to be hardly affected. Based on the finite element (FE) analysis results of steel plates having circular or square perforations, Shanmugam et al. [9] concluded that plates with circular perforations have higher capacities as compared to those with square perforations. Further, based on best fit regression analysis on the numerical data, design formulae were developed to predict the ultimate load capacity of perforated plates. Ultimate load capacity of perforated equal–angle stub columns were determined experimentally by Dhanalakshmi and Shanmugam [48] and observed that the reduction in ultimate capacity were ~ 50% for 60% perforations whereas the effect was found to be negligible for 20% perforations; and further, using FE results, a design equation was proposed to compute the load capacity for perforated equal–angle stub columns. Shanmugam and Dhanalakshmi [8] developed a simplified design equation to predict the ultimate capacity of plain and lipped channel section having circular perforations, via an extensive parametric study using FE analysis. Shariati and Rokhi [42] studied the effect of elliptical perforations on the performance of thin cylindrical shells subjected to axial load through both experimental and

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numerical approaches; and proposed an empirical formula to determine the buckling capacity. Moen and Schafer [43] demonstrated the reduction in post-peak ductility, and observed that the influence on ultimate strength due to the introduction of slotted perforations in lipped channel stub columns was minimum. Using 78 test and 213 FE column strength data, Moen and Schafer [4] modified the Direct Strength Method (DSM) given in North American Specification (NAS 2007) [49], extending design expressions for cold–formed steel columns containing perforations into six different options. Among the six options, the Design Option 4 (wherein the local buckling capacity was limited to net area based yield capacity) was found to be adopted in North American Specification (NAS 2012) [50]. Yao and Rasmussen [13] studied inelastic stress distributions, load transfers and failure modes on perforated plates and C-section columns in compression by considering parameters such as perforation shapes, sizes and spacings using isoparametric spline finite strip method (ISFSM) and concluded that perforation shape has marginal influence on the ultimate capacity of columns. Based on FE analysis, Kunal et al. [44] observed the decrease in column buckling load was demonstrated to be maximum for a single circular perforation when located at mid–height of circular stub column. Feng and Young [10] conducted a series of tests on high strength aluminium alloy SHS stub columns with central circular perforations. Based on the comparison of column design predictions with test results, it was concluded that the present design equations (e.g. [9,48–51]) for perforated cold–formed carbon steel was found to be inappropriate for the design of aluminium alloy stub columns having central circular perforations. Feng et al. [11] investigated the effect of perforation size and number of perforations on the ultimate strength of aluminium alloy circular hollow section (CHS) columns. The appropriateness of presently available design equations for aluminium (e.g. [52–54]) and perforated steel structural members (e.g. [8,9,48–50]) was examined based on perforated aluminium circular column test data. It was observed that Chinese aluminium code [53] and effective area method (in which the effective area is calculated by deducting the perforated area from the gross area of CHS) of cold–formed steel design rules in [49,50] for perforated structural members are found to be more suitable for the design of perforated aluminium alloy CHS columns. Yao and Rasmussen [14] conducted a comprehensive parametric study to investigate the structural performance of SHS and RHS stub columns containing two opposite central circular perforation at mid–height on the flat faces perpendicular to the face containing a running seam weld was conducted. It may be noted that the perforation diameter to width ratio, in publicly available design standard such as [57] for cold–formed carbon steel is limited to 0.5, and hence in the present work, the perforation diameter to width ratio has been extended up to 0.9, to see the effects of larger perforations on load capacity. The local geometric imperfection of cold–formed carbon steel stub columns before and after the perforations have been made were measured and calibrated with Dowson and Walker [58] imperfection formula. The strain distributions along the direction of column length during compression test near the perforation were captured using unidirectional single element strain gauges to assess the strain variation. The load versus end–shortening curves recorded as well as typical failure modes observed from this present study are documented. Further the column capacities recorded from the test programme are compared with design predictions from various design rules and recently published literatures. Finally, reliability analysis was performed to check the applicability of the design codes and rules presently available.

2. Experimental investigation

2.1. General

An experimental programme into the member capacity of stub SHS and RHS columns containing two opposite central circular perforations was conducted in Department of Civil Engineering at Indian Institute of Technology Guwahati. Fig. 1 shows the dimension levelling system adopted in this paper, where $B$, $D$, $t$, $w$, $r$, and $L$ are the width, depth, thickness, diameter of perforation, flat width, outer corner radius and...