Engineering Structures 94 (2015) 43–53

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Innovative hollow corrugated columns: A fundamental study

Mohammad Nassirnia [a], Amin Heidarpour [a,*], Xiao-Ling Zhao [a], Jussi Minkkinen [b]

[a] Department of Civil Engineering, Monash University, Melbourne, VIC 3800, Australia
[b] SSAB, Harvialantie 420, 13300 Hämeenlinna, Finland

ARTICLE INFO

Article history:
Received 6 June 2014
Revised 10 March 2015
Accepted 11 March 2015
Available online 2 April 2015

Keywords:
Innovative column
Corrugated plate
Mild steel
Compression test
Energy absorption

ABSTRACT

This paper focuses on the development of much-needed numerical and experimental models for understanding the mechanical behaviour, section capacity and energy absorption of the innovative fabricated columns consisting of corrugated mild-steel plates. The corrugated square columns proposed in this paper are fabricated by welding four corrugated plates which are originally produced from 3 mm thick flat mild steel plates. The experiments consist of applying a compressive axial force to the columns to determine load–displacement curves of the fabricated sections. The effects of geometric parameters such as inclination angle and corrugation height are also investigated experimentally by considering three different types of corrugated columns. Moreover, a finite element model in which the effects of material and geometric nonlinearities as well as residual stresses are taken into account is developed using ABAQUS. The experimental results are also compared with those given by the finite element (FE) model whilst a good agreement is achieved. A cost analysis is also conducted in which the cost of the innovative columns proposed in this research is compared to those of conventional welded columns currently available in the civil engineering market.

1. Introduction

The extensive use of thin-walled steel structural systems in the building and construction industry is mostly indebted for their high strength to weight ratio attributes and remarkable fabrication versatility. Corrugated plates fallen in this category, also have a wide range of application in various engineering fields. They are lightweight, economical, and have much higher load carrying capacities than flat plates, which ensure their popularity and have attracted research interest since they were introduced. The corrugation shape provides continuous stiffening which permits the use of thinner plates. A corrugated plate can easily be bent in one direction, whereas it retains its rigidity in the other direction. Fabrication costs for elements with corrugated panels are normally lower than those with stiffened plates [1–3].

It has been demonstrated that high performance sections are required to be developed for extreme action [4,5]. Many researchers have studied capacity of various types of novel cross sections. Aoki et al. [6] studied the local buckling behaviour of short length regular polygonal steel columns fabricated from two half section pieces made of folded plates. The empirical design formula based on the test data were presented for five different section profiles. Heidarpour et al. [7,8] have recently studied the mechanical behaviour of a new-style innovative stub columns utilising mild-steel flat plates and stainless steel tubes or very high strength steel tubes at the corners. Narayanan and Mahendran [9] investigated the buckling behaviour of a series of innovative cold-formed steel columns all of which failed by distortional buckling with very little post-buckling strength. Sixteen innovative column sections made of G550 and G250 steel with variety of cross-sections and dimensions were investigated. Tao et al. [10] presented the improvement of ductile behaviour of stiffened composite stub columns with various methods. Their research showed that although all different stiffening methods have potentials to improve the ductility of the stiffened stub columns to some extent, adding fibres to concrete is the most effective and reliable measurement in increasing the ductility capacity. Furthermore, buckling analysis of individual corrugated plates has been carried out using spline finite strip method [11], Galerkin method [12], and energy method [13]. Whilst some researchers have examined corrugated plates individually [11–13], others have focused on using these folded plates as a web in I-girders [14,15].

It is also worth noting that limited research has been conducted on the *structures* consisting of corrugated *shells* [16,17]. From the other side, although corrugated *plates* have been studied either individually or implemented in girders web, hitherto they have

* Corresponding author at: Rm 125, Department of Civil Engineering, Monash University, VIC 3800, Australia. Tel.: +61 3 99024435; fax: +61 3 99054944.
E-mail address: amin.heidarpour@monash.edu (A. Heidarpour).

http://dx.doi.org/10.1016/j.engstruct.2015.03.028
0141-0296/

never been used in fabricating of hollow columns. Therefore, in order to better understanding of the performance of the proposed corrugated columns, numerical and experimental models are required to be developed. Moreover, due to the geometry of innovative corrugated columns, some particular kinds of beam-to- column connections, currently under investigation at Monash University, like collar corner (as recommended by AISC [18]) and diaphragm-included connections are required to be developed.

This paper aims to address the results of both numerical and experimental studies on the hollow stub columns consisting of corrugated plates under compressive loading whilst research on developing design formula for longer columns with various slenderness ratios is currently being conducted at Monash University.

2. Innovative fabricated columns

In the current study, innovative fabricated square columns are referred to those columns consisting of four corrugated steel plates which are welded at corners. Corrugated steel plates particularly those which are thicker (thickness of 3 mm) than skinny corrugated sheets (thickness of around 1 mm) are regularly produced by cold forming of initial flat steel plates. In Fig. 1, a variety of corrugation configuration such as sinusoidal, triangular, and trapezoidal, etc. is shown whilst the latter type is chosen for this research.

2.1. Trapezoidal corrugated plates

Since the geometry of the corrugated plate may have effect on the compressive behaviour of the fabricated columns, three particular types of the corrugated plates, in which the effects of the inclination angle (α) and corrugation height (h) can be well studied, are considered. Fig. 2 shows a typical trapezoidal corrugated plate considered in this study. It is assumed that all corrugated plates have three modules of corrugation ($b = 3 \times l$).

The geometric parameters corresponding to centre line (dashed line in Fig. 2) for each corrugated plate are listed in Table 1. These dimensions are chosen such that each corrugated plate has the same unfolded width.

2.2. Corrugation procedure

Structural steel members made by cold-forming have become more popular in steel constructions since they allow for reducing the weight and thus provide appreciable savings over conventional hot-rolled sections.

A folded plate from initial flat plates could be cold-formed by various methods. Two main categories of these methods are roll-forming and press-braking [19]. Due to cold-forming mechanical properties of virgin material are changed. In general, cold-forming decreases ductility and increases the yield and ultimate stresses in and around folded regions. The nature of these changes depends on the chemical composition of the steel, its initial metallurgical history, its cold-working history, and the type and magnitude of plastic strains caused by the cold work [20].

In terms of the material properties of the finished product compared to those of virgin plate, the important difference between the two basic forming methods is the fact that in press-braking method strength enhancements are restricted to the corner regions and the properties of the flat parts remain relatively unaltered, whilst in roll-forming there might be modest strength gains in the flat regions with yet further enhancements in strength in corner regions [19]. However, comparing to roll-forming which is a mass-production process, forming by press-brake is a straight bending, semi-manually operated process of more limited production capacity. In the current study, press-braking method is utilised to create corrugated plates from initial flat plates. A 220 tons press-brake machine is utilised and individual folds are created between 16 mm V-block die and 1 mm radius punch.

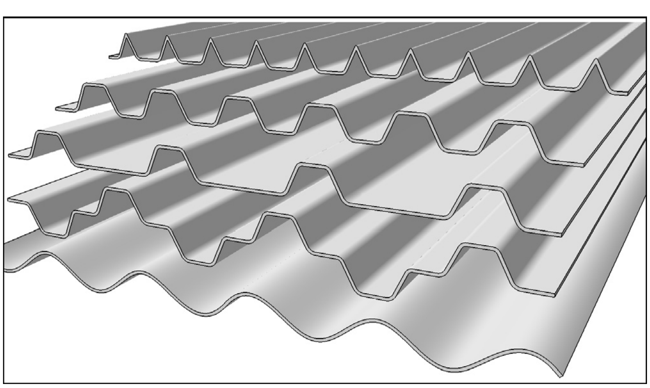

Fig. 1. Different common patterns for corrugated plates.

2.3. Fabricated corrugated columns

As a hollow section, each corrugated column is consisting of four similar corrugated plates. These plates are welded at the corner so that an integrated column shown in Fig. 3 is formed. The length of all corrugated columns is assumed to be constant ($L = 1$ m). The double-pass butt weld was used at the corners for fabricating columns and was based on Gas Tungsten Arc Welding (G.T.A.W) procedure, utilising ER2209 wire.

3. Experiments

The experimental tests performed to investigate the performance of innovative corrugated columns under compressive loading are discussed in this section. The tests include large scale static compression tests as well as material tests on the tensile coupons taken from different parts of corrugated plates. The trapezoidal corrugated plates have been produced from initially flat Grade 250 steel plates. In addition to the proposed innovative fabricated columns, a conventional hollow welded square column consisting of four 3 mm thick Grade 250 mild steel flat plates, named as control column, is fabricated such that the performance of the innovative corrugated columns can be compared with that of conventional column currently available in the civil engineering market. The cross-section perimeter of the control column is also the same as that of the corrugated columns such that the total weight for all aforementioned columns is the same. In other words, this process gives a chance to compare the performance of innovative columns with that of corresponding conventional sections at the same amount of material usage.

3.1. Imperfections

In reality, thin plates have out of plane geometric imperfections which oblige them to deflect under compressive plane load. In the specimens studied in this research, geometric imperfection might emerge due to corrugation, welding/fabricating process or even may exist initially in flat plates. As shown in Fig. 4, a precise reference table in conjunction with a digital touch-probe coordinate measuring gauge was used to accurately record the local imperfection of nominated points compared to a reference point. For each side of column, 15 spots (5 points in longitudinal direction and 3 points in transverse direction) were marked to measure their coordinates relative to reference point so as to generate imperfection