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Innovative hollow columns comprising corrugated plates and ultra high-strength steel tubes

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ABSTRACT

Latest development in material and manufacturing technologies make it possible to increase the yield strength of steel to more than 1200 MPa. These steel grades are suitable for structural and safety-related automotive components. The high-strength level gives potential for considerable weight reduction and a cost-effective way to produce energy efficient products. Following the recently introduced hollow corrugated columns, this paper presents an advanced innovative hollow corrugated column by incorporating ultra high-strength (UHS) steel tubes. The superior performance of the proposed column under compressive loading is investigated in the present work. UHS tubes used at the corners have yield stress of 1250 MPa. Three different corrugated plates are introduced and fabricated so that the effect of corrugation geometry parameters such as angle of inclination and height of corrugation get experimentally investigated. Along with experiments, an advanced finite element model is developed for predicting the behaviour of proposed columns and validated by experimental results. The geometric imperfection, material and geometric nonlinearities, and heat affected zone generated due to welding are included in the FE analysis. The results prove the high capacity and ductility of the proposed innovative columns under compression compared to the accumulated capacity of the individual components. Finally, the proposed high-strength columns are compared with the conventional columns in terms of weight and manufacturing costs.

1. Introduction

Nowadays, ultra high-strength (UHS) steel has potential to be used widely in civil construction due to its superior properties such as higher strength to weight ratio, formability, weldability, energy absorption, etc. Steel manufacturing with the use of continuous annealing makes it possible to produce UHS steel with up to 1400 MPa tensile strength. This kind of UHS steel is suitable for cold forming of structural and safety-related automotive components such as cold-formed high-strength tubes used in cranes and door impact guards in vehicles [1]. However, their lower ductility compared to structural mild steel is still a challenging issue for civil engineering construction.

In 1990s, Migita et al. [2] carried out 23 tests on closed polygonal section steel columns under axial compression loading. Some of the samples were stub columns with rectangular, pentagonal, hexagonal, heptagonal, and octagonal sections, whilst the others were medium-length columns with rectangular, hexagonal, and octagonal sections. Their research resulted in an empirical formula based on the compression tests to predict local buckling strength and interaction between local and overall buckling capacities of closed polygonal steel columns. An innovative X section with intermediate stiffeners was suggested by Chen and Jin [3] to enhance the local buckling stress of thin-walled specimens. The proposed stub column was tested as both hollow steel tubes and concrete-filled steel tubes.

From material point of view, many construction materials such as steel, aluminum, and the like fall into isotropic material category. However, certain materials display direction-dependent properties; consequently, these materials are referred to as anisotropic. In anisotropic materials stressed in one of the principal directions, the lateral deformations in other principal directions could be smaller or larger than the deformation in the direction of the applied stress depending on the material properties [4]. For a general anisotropic material, the matrix of material constants contains 21 independent constants. This means that all strains are coupled to all stresses. Some materials such as wood, plywood, and fiber-reinforced plastics, etc., fall into this category. These materials possess natural anisotropy. Besides plates made of

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anisotropic materials, a number of plates even made of isotropic materials also may fall into the category of anisotropic plates due to their geometry such as corrugated and stiffened plates. Such a type of anisotropy is referred to as structural anisotropy [4].

Aoki and Ji [5] developed an innovative way of increasing the capacity of steel columns without sacrificing other properties. The idea was to weld steel tubes to the apexes of square and triangular steel columns. It was concluded that the plates provide lateral restraint to the steel tubes which postpone the buckling whilst the total load supported by the fabricated sections was greater than the load obtained from summation of the capacities of individual components. Recently, Javidan et al. [6] conducted several experimental tests on long hollow columns utilizing mild-steel plates and tubes. This structural solution has further been developed by replacing the mild steel tubes with UHS steel [7–11] and stainless steel tubes [12]. The combination of steel plates and UHS circular tubes either as hollow [7,9,13] or concrete filled columns [11] have also been investigated.

This paper addresses an advanced form of sections established earlier by the authors [14]. The new sections consist of UHS tubes welded to the apexes of hollow corrugated columns. The performance of these sections is studied, both experimentally and numerically, under compression. Different trapezoidal corrugation profiles are used in order to investigate the effect of corrugation parameters on the proposed columns. Last, a cost analysis is conducted to demonstrate the superior performance of innovative columns by comparing the fabrication cost of proposed sections with conventional sections fabricated from flat plates.

2. proposed innovative columns

Due to low ductility of ultra high-strength steel tubes, they may not be used individually in civil construction; however this paper aims to introduce an innovative hybrid section shown in Fig. 1 utilizing mild-steel corrugated plates and UHS tubes to ensure the effective feasibility of utilization of UHS steel tubes in civil construction. In this configuration, not only the proposed column represents a ductile section, but also the ultimate load carrying capacities of these columns could be higher than that of conventional sections.

In the following sections, individual structural elements of the proposed section as well as fabrication process are discussed in detail.

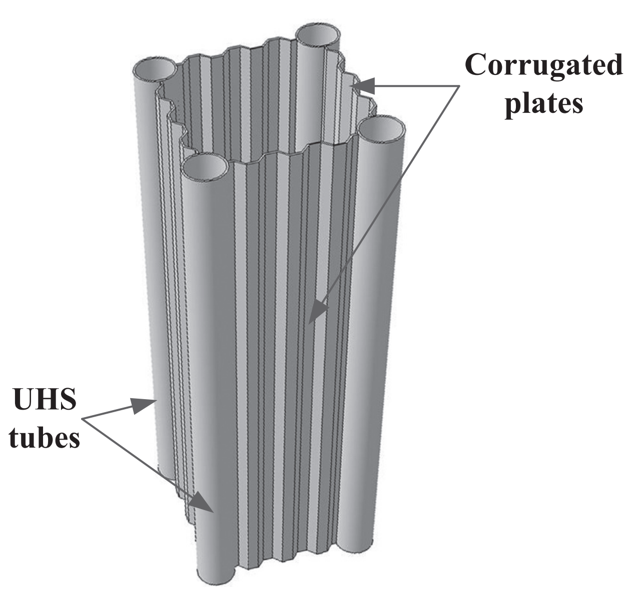

Fig. 1. A schematic drawing of proposed hollow corrugated column.

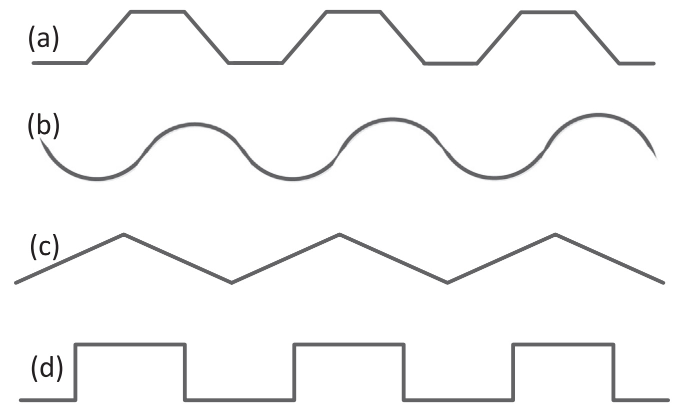

Fig. 2. Versatile corrugation profiles: (a) trapezoidal, (b) sinusoidal, (c) triangular, and (d) rectangular.

2.1. Corrugated plates

The corrugated plates, known as self-strengthened plates, are regularly produced from flat plates. The corrugations increase the bending strength of the plate in the direction perpendicular to the corrugations. The profile of a corrugated plate may have several shapes: sinusoidal, trapezoidal, triangular, or rectangular as shown in Fig. 2. The most common profiles used are trapezoidal and sinusoidal. In this research, trapezoidal profile is chosen to be studied as it exhibits more ductility and higher bearing capacity compared to sinusoidal profile [15].

The shape of profile has little influence on the performance characteristics of a self-strengthened plate; however as shown in Fig. 3, for a corrugated plate with thickness of (t), the depth of corrugation (h) and corrugation angle (α) are more influential parameters [16].

In the current study, three different types of profiles named as Type I, Type II, and Type III in Table 1 have been defined in order to examine the effect of geometry parameters on the performance of the innovative fabricated columns. Each corrugated plate is 3 mm thick (t =3 mm) and has 3 modules of corrugations.

2.2. Corrugation process

The corrugation process is usually carried out using roll forming method. This modern process is highly automated to achieve mass production with low costs. However, due to limited amount of corrugated plates needed in the current study, trapezoidal profiles were produced through press-brake method. In this method which is a common cold forming process, individual folds

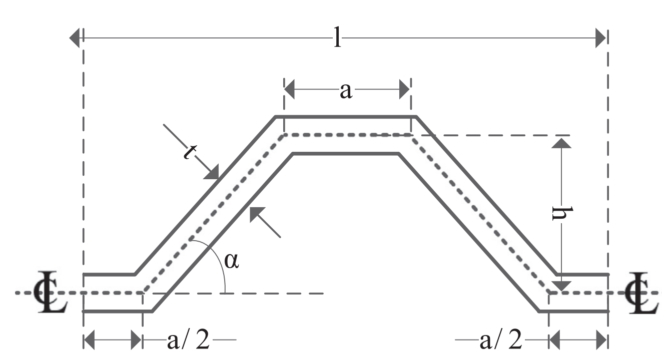

Fig. 3. The geometry dimension definition for a corrugation module.