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, a numerical 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.

Keywords: Innovative hollow column, corrugated plate, UHS tube, compressive loading, finite element analysis, heat affected zone.

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 vehi-

cles [1]. However, their lower ductility compared to structural mild steel is still a challenging issue for civil engineering construction.

On 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 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 Figure 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.

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 Figure 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 Figure 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 and corners are created from originally flat plate get punched in between a v-block and a die (see Figure 4). It is worth noting that the material properties of the corrugated plates are affected by the cold working process at and around the folded regions. Folding parameters (like machine capacity, punch radius, etc.) and measured radii of produced corners for corrugated plates are the same as those reported in earlier study [14].

2.3 UHS steel tubes

UHS steel tube is produced from durable high-strength structural steel material. The hollow UHS tube used in this study has a nominal wall thickness of 3.2 mm with nominal outer diameter of 76.1 mm. Utilizing individual UHS tube as structural elements is discouraged due to its low ductility and performance under compression; however, with regard to the high hardness and tensile strength properties of UHS tubes, an outstanding improvement in conventional sections once used in the proposed configuration is expected. Despite their high hardness and strength, the weldability of UHS tube is good. The UHS tubes used in this research are longitudinally welded tubes and manufactured by SSAB Corporation (branded as *Raex 400*). To briefly highlight main production stages of this particular tube, it should be noted that the decoiled strip is fed to forming section. Strip forming applies in small steps, ensuring smooth operation and uniform pipe geometry. Afterward, longitudinal welding takes place using an electric resistance welding technique called HFI (High Frequency Induction) welding process. In this process, the strip edges are heated to welding temperature and pressed together by rollers without any filler metals to give a homogeneous longitudinal weld. Finally, after cooling and sizing, a cut-off machine cuts the pipe to the specified lengths. Step by step manufacturing process of UHS steel tubes is shown in Figure 5.

2.4 Fabrication procedure

In the current study, trapezoidal corrugated plates and UHS tubes were welded together to form a hybrid square column. Once plates and tubes were precisely aligned with each other, they were clamped and get welded at some spots as shown in Figure 6a. Then other tubes and plates were assembled together by spot welds (Figure 6b). At the end, tubes and plates were completely bonded together along their outer interface by single-pass fillet welding. This type of welding was produced based on Gas Tungsten Arc Welding (G.T.A.W) method utilizing 99.99% argon welding gas and 2.4mm welding wire type AWS A5.9 ER2209 with speed range of 75 – 95 mm/min. The welding power supply provided current and voltage range of 80-120 amps and 9-11 volts, respectively. It is worth noting that all columns studied in this research were 1-meter long.

3 EXPERIMENTS

Along with the proposed corrugated column (Figure 7a), an equal weighted specimen with the same material properties called control column was also fabricated (see Figure 7b). The control column was consisting of four unfolded flat mild-steel plates welded with the same method to the UHS tubes at corners. The total nominal cross-section breadth for control column was 399.7 mm; whereas it was 362.2 mm, 330.5 mm, and 298.2 mm for Type I, II, and III sections, respectively. In addition, the experimental results are also compared with those of corrugated columns without corner tubes under compressive loading previously published by the authors [14].

3.1 Material properties

In order to find out the mechanical properties of the materials used in the proposed innovative hybrid columns, tensile tests were conducted on the coupons taken from corrugated plates and UHS tubes. For corrugated plates introduced in Table 1, the tensile coupons were taken from horizontal and inclined flat strips as well as corner regions. For each location, three tests were performed and the results were averaged. Further details such as coupon size, test setup configuration, etc. have been described in detail in the recent published work [14]. For UHS steel tubes, the material properties depend on the distance from the weld line. Therefore, the tensile coupons were taken from a location at 90° from the weld line (Figure 8a), as recommended by ASTM

standard [17]. These coupons were extracted from UHS tubes by waterjet cutting technique which is the preferred method when the materials being cut are sensitive to the high temperatures generated by other methods. The outward bend of the coupons taken from UHS steel tubes, as shown in Figure 8b, exhibits that developed longitudinal residual stress due to cold-forming process is in tension on the outer surface and compression on the inner surface. This residual stress pattern arises from the cold-forming process, which prevents the tube to spring back [18]. In order to prepare coupons to be well clamped between flat grips, both end sides of the coupons taken from UHS tubes were needed to get flattened. Each side was then separately sandwiched in between two rigid blocks and squashed under pressing machine; resulting in parallel faces at grip ends without touching the gauge length.

In Figure 9, a close-up view of the test setup for a coupon after flattening is shown. The displacement control test was conducted by the 100 kN Instron 4204 testing machine available in Civil Engineering Laboratory, Monash University. Samples were pulled with the rate of 0.5 mm/min, in accordance with ASTM standard [17]. Even though one strain gauge was attached at the centre of each coupon side, a non-contact MTS Laser extensometer was also utilized to capture strain values, particularly once strain gauges were failed over higher deformations.

Despite the superior properties of UHS steel, the welding of this steel may cause change in the mechanical properties of the material around the welding area. Under thermal exposure due to welding, evident changes in microstructure and property occur in the base metal adjacent to the weld metal shown in Figure 10. Sometimes, the change of the microstructure may lead to local brittleness in the area adjacent to the weld called Heat Affected Zone (HAZ). HAZ of welded joint is very narrow in width, and consists of many fine regions having different structures. In addition, stress concentration and higher residual stresses are plausible to coexist in the welded joint; thus fracture failure of weldment is still unavoidable [19].

In order to study the effect of HAZ on material properties, a stub column with length of $L=500\text{mm}$ was fabricated as shown in Figure 11a. In this column, two Type I plates and two Type II plates positioned on opposite sides were welded to four UHS tubes at the corner. In this way, the effect of the heat from the welding on corrugated plates and their corner regions, if any, could be revealed. The plates, tubes, and welding process were the same as those used in the compression tests. The tensile coupons were cut by waterjet technique right next to the weld line, either on corrugated plate or UHS tube (Figure 11b-c). The narrower gauge length leads to

better resolution of material properties within weld line vicinity; thus, sub-size coupons (Figure 11d) were chosen as recommended by standards [17, 20]. The closest coupons to the weld line were chosen on a way that their gauge lengths fall right next to the weld seam, which probably is the most affected area. The coupons just after waterjet, but still in the skeleton, are depicted in Figure 11c.

3.2 Large scale tests

Large scale specimens were also tested and examined under compressive loading. Figure 12 demonstrates the test set up for a typical innovative fabricated column under compression. The tests were conducted using a 5000 kN capacity Amsler testing machine. String pot and LVDTs were utilized during the tests to measure the vertical displacements. Strain gauges were also used to accurately capture deflections and local strains. Fourteen strain gauges including six strain gauges at mid-length and four strain gauges at a distance of 250 mm from either top or bottom end, were attached on the outer surface of each corrugated column. For control column, twelve gauges were attached to record local strains.

A single UHS tube with 6 strain gauges attached on was also tested under compression. For this purpose, 2 collar supports shown in Figure 13 were produced. These supports were used for restraining rotations at both ends and also upright sitting of the tube in between two supports of Amsler machine.

All strain gauges and deflection facilities were connected to a data acquisition system. The displacement rate for all quasi-static tests was set to 1 mm/min.

4 NUMERICAL MODELING

Further parametric investigation of the proposed column would be more convenient and economic by using a robust and validated numerical model. In this research, Abaqus 6.12-1 software package [21] is used to build numerical model of proposed columns. The thickness of plates and tubes is much smaller than other column dimensions, so the columns were modeled in shell. Four node shell element (i.e. S4R) was used to mesh the geometry. When material nonlinearity, geometric nonlinearity prior to buckling or unstable postbuckling response is needed to be considered, a load-deflection analysis must be performed. To achieve this target, the Riks method was used in this study [21]. Through this method, innovative columns are numerically analyzed so that a validated Finite Element (FE) model corresponding to each tested sample could be generated. With

the developed FE model, extensive case studies can be conducted without need for expensive experimental tests.

4.1 *Material modeling*

The average experimental tensile test results were converted, as discussed in former study of the authors [14], to the proper form of data expected by Abaqus. In addition to introducing elastic region, classical metal plasticity was also introduced for the elements. This plasticity uses isotropic hardening behaviour defines evolution of the yield surface size uniformly in all directions such that the yield stress increases (or decreases) in all stress directions as plastic straining occurs [21]. Furthermore, the experimental results show that corner material properties enhancement may affect the mechanical properties of the flat regions. Therefore, it is proposed to extend corner properties to adjacent flat regions, approximately at a distance of t away from each side [22].

4.2 *Imperfection*

The welding procedure inevitably induces some imperfections on comprising elements of the fabricated sections. The out-of-plane imperfections along the longitudinal centre lines of the plates were of particular concern. As shown in Figure 14, a digital touch-probe coordinate measuring gauge was used to precisely record the local imperfection of nominated points compared to a reference point. The nominated points on the corrugated plates were chosen the same as those reported in previous study [14]. Similarly, for corner tubes, local out-of-plane imperfection was measured compared to a reference point. The maximum measured imperfection to thickness ratio for type I, II, and III columns were 2.2, 1.4, and 3.5, respectively; where all of them were within the suggested range of Steel Structures Standard [23]. The recorded data was used for introducing imperfection to the FE model.

4.3 *Heat Affected Zone*

Based on the tensile experiments discussed in section 3.1, the tube is partitioned into 2 parts on each side of the weld line called zone 1 and 2 as shown in Figure 15. For each zone, averaged material properties of tested coupons were assigned in order to consider the HAZ and residual stress developed due to welding. It is worth noting that as the real material properties for the regions adjacent to weld beads (obtained from tensile experiments) were introduced to numerical model, there was no need to consider welding residual stress. In other words, the effect of welding residual stress is already considered in the introduced material properties.

5 RESULTS AND DISCUSSION

The experimental results obtained either from material scale tensile tests or large scale compression tests are illustrated and discussed separately in the following sections.

5.1 *Material properties comparison*

The extracted stress-strain curves for the coupons taken from UHS tubes, virgin material and also corner of corrugated plates are depicted in Figure 16. Test data shows that Young's modulus and yield stress for the virgin mild-steel (Grade 250) plate are 209 GPa and 262 MPa, respectively. On the other hand, for UHS steel tubes, the nominal 0.2% proof stress is 1250 MPa. It can be seen from Figure 16 that the UHS tubes lack ductility compared to virgin mild steel, but they have significantly higher ultimate tensile stress. The results show that the developed enhancement in corner region is dominantly related to the corner curvature and angle of inclination [22]; whilst the effect of corrugation height (h) on the mechanical properties of the corner material is negligible. It is worth noting that the stress-strain curves for flat regions of corrugated plates are similar to that of virgin material [24].

Tensile test results for HAZ investigation showed that the effect of HAZ on corrugated steel plates is negligible; however, it is considerable on UHS tubes. For the tubes, experimental data showed that the closest sample to the weld line is the most affected one. Quantitatively, the ultimate tensile stress drops by 7% right next to the weld line. The farther distance from weld line, the lower reduction in material properties occurs. The width of HAZ strips on either side of weld line on UHS tubes is approximately equal to 22 mm. So, these strips could be divided in two zones (see Figure 15) and averaged experimental HAZ material properties have been assigned to them as shown in Figure 17.

5.2 *Individual UHS tube*

The compression test result on a 1m long individual UHS tube show that they can carry up to 820 kN axial force. The load versus deflection curve of the tube is drawn in Figure 18.

In general, global buckling mode is the governing failure mode of slender single UHS tubes. However, by incorporating them at the corners of innovative columns, local buckling mode becomes the dominant failure mode such that the strength of the ultra high strength materials could fully be utilized. This is demonstrated as

ultimate load carrying capacity of an individual UHS tube is only 28% of the squash load; defined as the theoretical yield stress times the cross-section area.

5.3 Innovative fabricated column

Figure 19 illustrates the experimental curves of load versus deflection during compression tests on corrugated columns as well as control column with corner tubes. The axial end-shortening was measured from strain gauges, LVDTs and string pot. Since the strain gauges might not be able to give accurate strain values after buckling, the strain values from the strain gauges were only used up to the occurrence of column buckling. Afterward, the axial strain was calculated from the measured axial shortening to evaluate the post-buckling behaviour of the test specimens [25].

As illustrated in Figure 19, before peak point, innovative sections show stiffer behaviour compared to equivalent welded box sections. Apart from this, the ultimate load carrying capacity of proposed sections could be increased by 10% (about 360 kN which is equivalent to the capacity of one meter welded box section without corner tube) if replaced with proposed sections. Also, the post peak behaviour of control column illustrates that compressive load carrying suddenly drops once maximum load is reached. However, innovative columns show much more ductile post peak behaviour. Thus, the catastrophic failure of control columns could be significantly improved by replacing flat plates with corrugated plates as they absorb higher amount of energy, leading to more resilient structures and safer society. For instance, from structural designer point of view, proposed sections provide more evacuation timeframe in extreme actions.

Also, as shown in Figure 19, by comparing the area surrounded under each curve, it is clearly understood that corrugation has increased energy absorption and ductility, notably in Type III column. Quantitatively, the area underneath each curve from zero deflection to 10mm deflection for Type III, II, and I columns are 1.29, 1.16, and 1.14 times greater than that of control columns, respectively. The higher level of energy absorption, the higher performance of structures under extreme actions is expected [10, 12, 26-31]. Thus, depending on the nature of application where a hollow section is required, conventional columns could be replaced by suitable corrugated columns which have higher capacity for absorbing energy.

Comparing mechanical behaviour of proposed columns with corrugated columns without corner tubes [24] shows that innovative columns with tubes exhibit dramatically higher performance as shown in Figure 20. For instance, the compressive load which is carried by Type I column containing corner tubes is 5.5 times greater

than that of the same corrugated column without corner tubes. In addition, incorporating UHS tubes with flat side plates in a column (control column with corner tubes) can increase the compressive load capacity up to 11 times greater than that of similar flat column without corner tubes. It is crystal clear that innovative columns with corner tubes can significantly absorb higher amount of energy. Also, the displacement ductility ratio (μ), known as the ratio of ultimate load displacement (Δ_u) to the corresponding displacement at the onset of yielding (Δ_y) [32], is significantly higher in columns with corner tubes. For instance, the ductility factor is 3.1 and 5.6 for type III column without and with corner tubes, respectively.

Both experimental and numerical load bearing capacity of each specimen studied in this work is listed in Table 2. These data are also compared with already available results in literature [14]. On the other hand, the performance of innovative columns with corner tubes was compared with the superposition capacity of equivalent geometries; i.e. the same corrugated column and 4 individual UHS tubes. Additionally, the effectiveness of angle of inclination and height of corrugation as geometry parameters in section strengthening is depicted. Experiments result demonstrate that Type III column with corner tubes can approximately carry 10% more compressive load (which is equal to the compressive load capacity of one control column without corner tubes) compared to corresponding control column. However, the capacity of Type II column shows insignificant advantage compared to that of Type I, which could be justified due to higher values of geometric imperfections as mentioned in section 4.2. The last column of Table 2 shows the effect of utilizing UHS tubes at the corners of corrugated and control columns. It can be seen that innovative columns carry 5 times greater compressive load compared to the capacity of corresponding corrugated columns. This development is even more significant for control columns, as capacity of conventional box sections is originally quite low.

The slenderness ratio ($\lambda = L/r$ where L is column length and r is the radius of gyration) for each column in Table 2 is calculated based on the dimensions reported in Table 1. This ratio is increasing from control column to Type III which demonstrates the fact that by using innovative columns, even more slender columns can carry more compressive load.

Despite appealing high strength of an individual UHS tube, as mentioned earlier, they are not ductile and their low dominant global buckling mode discourages to be used solely as structural element. In the proposed innovative columns, owing to the ductile behavior of mild-steel plates, the global buckling mode of slender

tubes is replaced by local buckling mode shapes. In the proposed configuration, not only their strength benefit is obtained, but also their poor properties in terms of ductility and buckling are compensated. This is evidenced by comparing the capacity of the proposed innovative column with those obtained from the superposition of comprising element capacities which indicates a capacity ratio of greater than 1.05 as shown in the last column of Table 2.

It is worth noting that for Type I and II columns under compression, test data was recorded until post-peak load reached around 3 MN. However, for further investigation, Type III column as an innovative section representative was kept loaded until the stroke limit of Amsler machine reached. Full history of recorded axial load versus deflection is drawn in Figure 21.

At the deflection of 32 mm, a sudden increase in recorded load can be seen, probably due to unsymmetrical fabrication process and imperfection of geometry and boundary conditions. Also, Figure 21 shows several small drops in recorded load from 40 mm deflection onward. At any of them, a noise sound was heard within the test, which is expected to coincidence with small ruptures around the column as shown in Figure 22a; then by further deflection, small fractures next to weld line started to propagate, exactly align with weld seam (Figure 22b). Based on the post peak behaviour of Type III column in Figure 21, it could be seen that proposed column also show capability to fix small defects.

5.4 FE Model Validation

The developed FE model for innovative columns was validated by experimental results. The boundary conditions of end supports were assumed to be clamped. First of all, as shown in Table 2, ultimate load capacity of innovative columns can be estimated by 2% discrepancy at most by using the developed FE model. Also, experimental failure mechanism of individual UHS tube and innovative column (i.e. Type I as a sample) under compression was compared to that of FE model, as illustrated in Figure 23. It is clear that the plastic mechanism captured by numerical model is in good agreement with that of experimental test.

The material nonlinearity, imperfection and HAZ as mentioned in section 4 were needed to be considered in FE model in order to generate more accurate results. The effect of HAZ as a considerable phenomenon appeared in this study could affect the load carrying capacity as depicted in Figure 24.

The results show that considering HAZ could result in reducing strength of the column about 3% and changing post-bifurcation behaviour of load-deflection curve. It is worth mentioning that since extracted material

properties from adjacent region to weld are directly used in FE material model, it is not needed to implement residual stress distribution due to welding in this study.

The validated finite element model is currently being used to develop design formulations by performing an extensive parametric study at Monash University.

5.5 *Plastic mechanisms*

Thin-walled steel members often develop local buckling and local plastic mechanisms, both of which are essential features determining their behaviour. For these members subjected to in-plane compression, two common types of local plastic mechanisms could be developed, namely the roof-shaped and flip-disk mechanisms. In Figure 25, the failure mechanisms of proposed columns extracted from validated FE models are presented and compared with alternative sections and members.

The failure mechanism for an individual tube is similar to its first buckling mode shape i.e. global failure (Figure 25a). For a welded box section, only one flip-disk mechanism appears on each plate leading to the failure of column (Figure 25b). When tubes are added to the apexes of a box section, not only the global failure mechanism of tubes changes to local, but also failure shape of flat plates converts to roof-shaped and occurs in several locations along the length (Figure 25c). The change in shape and number of plastic hinges in the sections with corner tubes results in higher capacity and ductile behaviour. The developed mechanism for corrugated columns without tubes [14] is not similar to any abovementioned shapes (Figure 25d), and even once tubes are added to the corner of this section, no change in plate mechanism occurs whilst in the tubes, again local failure mechanism governs (Figure 25e).

5.6 *Benefit-cost analysis*

As discussed earlier, experimental results demonstrate superior behaviour of innovative columns with corner tubes. This enhancement is apparently for the sake of corrugated plates which inevitably increase fabrication fees for folding, but could reduce the weight; so, cost and weight of the proposed columns should be considered. Thus, seven different cases are considered as listed in Table 3. All cases in this table represent 1m long columns.

Cases 1 to 4 are the columns examined and tested in the current study. Cases 5, 6, and 7 are referred to corresponding conventional square hollow welded columns with the same load carrying capacity and cross-section breadth to those of cases 2, 3, and 4 (as stated in section 3), respectively. In order to find out desirable plate

thickness in cases 5 to 7 for which the aforementioned comparison criteria are satisfied, the regulations and formula in Australian standard is utilized [23]. The nominal member capacity (N_c) calculations show that equivalent columns (cases 5 to 7) should be within the thickness range of 10.5mm, approximately 3.5 times thicker than the plate thickness of proposed columns.

In Table 4, the detailed costs and weight for seven cases of columns are listed. The rates for cost calculation is based on current rates in Australia and also in accordance with Rawlinsons construction cost guide [33] whilst weight data is nominal calculations. It can be seen that innovative columns (cases 2-4) are not only cheaper than equivalent columns, but also they are much lighter. This huge reduction in a 1m column's weight could lead to major benefit in a full-scale infrastructure. The decreasing trend in total cost and weight of cases 5-7 is due to similar coverage area assumption; in other words, by considering all columns are 1m long, as case 4 is more slender than cases 3 and 2, then case 7 column is also more slender than cases 6 and 5.

6 CONCLUSIONS

This paper has discussed the post-buckling behaviour of the innovative corrugated columns with UHS corner tubes. The test experiments were conducted not only on the large scale samples, but also on the material scale as well.

Three different types of corrugated plates were introduced. The plates were welded to UHS tubes at the corners to form a square hollow section. For the comparison purposes, another hollow column similar to innovative column but with flat plates called control column was also considered.

From experiment results, it can be concluded that proposed innovative columns can boost bearable axial loading by 10% compared to control columns. The innovative corrugated columns with tubes can carry axial load up to 5 times higher than that of corrugated columns without UHS tubes carry. In addition, the loading capacity of innovative columns with corner tubes is higher than the accumulated capacity of individual elements consisting of a corrugated column and 4 individual UHS tubes, which shows superior performance of proposed sections in resolving buckling limitation of UHS tubes.

The developed finite element model in this research showed a very good agreement with the experimental results of the proposed sections; so it can be used as a tool for further numerical investigation of innovative sections. However, a general formulation for estimating load carrying capacity of these novel sections is still a

need which is currently under development by the authors. Thereafter, optimized geometric parameters for comprising corrugated plates can be provided.

Apart from mechanical performance of innovative columns, the proposed columns were competitive in terms of cost and weight compared to the sections already available in the civil market.

All studied columns in this research were short innovative columns; however, longer columns are also fabricated and currently under investigation in Monash University.

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Figure 1. A schematic drawing of proposed hollow corrugated column

Figure 2. Versatile corrugation profiles: a) Trapezoidal, b) Sinusoidal, c) Triangular, d) Rectangular.

Figure 3. The geometry dimension definition for a corrugation module

Figure 4. Schematic view of press-brake forming machine

Figure 5. Longitudinally welded tube manufacturing process (courtesy of SSAB)

(a)

(b)

Figure 6. a) Spot weld, b) In-progress assembling of an innovative column

(a)

(b)

Figure 7. A fabricated a) innovative corrugated and b) control column with UHS corner tubes

Figure 8. a) UHS tube tensile coupon location; b) UHS coupon before flattening

Figure 9. A close-up view of tensile coupon test setup

Figure 10. HAZ development within welding process

Figure 11. a) Fabricated stub column; b) marks representing coupon location; c) coupons on tubes; d) coupon dimensions

Figure 12. A schematic view of Amsler testing machine in compression mode

Figure 13. Collar support sketch for individual tube test

Figure 14. Imperfection measurement instruments

Figure 15. HAZ material properties assignment to the tube area next to weld

Figure 16. Stress-strain behaviour of ultra high strength steel compared to that of mild steel flat plate and corner regions

Figure 17. HAZ effect on UHS steel stress-strain behaviour

Figure 18. Load vs. deflection curve for single UHS tube

Figure 19. Experimental load vs. deflection curves for innovative columns with corner tubes

Figure 20. Innovative columns performance comparison with or without corner tubes

Figure 21. Full range experimental load vs deflection for Type III column

(a)

(b)

Figure 22. a) Rupture initiation; b) Rupture propagation along with the HAZ next to weld region

Figure 23. Comparison of experimental and numerical results for a) a single tube b) Type I innovative column

Figure 24. Influence of HAZ in a) Type II and b) Type III innovative columns

Figure 25. Failure mode shape comparison of a) individual tube, b) welded box section [14], c) control column, d) Type III column without tube [14], and e) Type III column with tube

Table 1. Different corrugated plate types (dimensions).

	$\alpha(^{\circ})$	$a(mm)$	$h(mm)$	$l(mm)$	<i>Drawing</i>
<i>Type I</i>	45	20	15	70
<i>Type II</i>	75	25.7	15	59.4
<i>Type III</i>	75	18.4	22	48.7

Table 2. Experimental and Numerical load carrying capacity [kN] of innovative columns

	Without corner tubes [14]			With corner tubes			Individual UHS Tube		$4 \times \text{circle} + \text{square}$ Superposition		With corner tubes to superpo- sition ratio	Column with tube to with- out tube ratio
	λ	FE	EXP	λ	FE	EXP	FE	EXP	FE	EXP	EXP	EXP
Control	9.9	362	371	6.7	4203	4103	830	822	3682	3657	1.12	11.06
Type I	11.1	808	795	7.5	4376	4315	830	822	4128	4081	1.06	5.46
Type II	12.9	848	839	8.3	4397	4337	830	822	4168	4125	1.05	5.14
Type III	15.0	955	953	9.3	4554	4464	830	822	4275	4239	1.05	4.68

Table 3. Column case number definition.

	<i>Description</i>
<i>Case 1</i>	Control column
<i>Case 2</i>	Type I innovative column
<i>Case 3</i>	Type II innovative column
<i>Case 4</i>	Type III innovative column
<i>Case 5</i>	Conventional welded column equivalent to case 2 (without corner tubes)
<i>Case 6</i>	Conventional welded column equivalent to case 3 (without corner tubes)
<i>Case 7</i>	Conventional welded column equivalent to case 4 (without corner tubes)

Table 4. Cost and weight comparisons of defined cases

	Cost (AUD)			Weight (kg)		
	Material	Fabrication	Total	Tubes	Plates	Total
<i>Case 1</i>	127	320	447	6.0	23.2	29.1
<i>Case 2</i>	127	387	514	6.0	23.2	29.1
<i>Case 3</i>	127	387	514	6.0	23.2	29.1
<i>Case 4</i>	127	387	514	6.0	23.2	29.1
<i>Case 5</i>	252	320	572	6.0	33.8	85.5
<i>Case 6</i>	226	320	546	6.0	32.1	85.3
<i>Case 7</i>	215	320	535	6.0	32.1	86.6