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3 **Compressive behaviour of concrete-filled double-skin sections**

4 **consisting of corrugated plates**

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7 **Mojtaba Farahi¹, Amin Heidarpour¹, Xiao-Ling Zhao¹, Riadh Al-Mahaidi²**

8 ¹Department of Civil Engineering, Monash University, Melbourne, VIC 3800, Australia

9 ²Department of Civil and Construction Engineering, Swinburne University of Technology,
10 VIC 3122, Australia

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19 Corresponding author: Dr Amin Heidarpour; Department of Civil Engineering; Monash University;
20 VIC 3800; Australia. Tel: (+61) 3 99024435; Fax: (+61) 3 99054944; Email:
21 amin.heidarpour@monash.edu

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Abstract

This paper deals with the static compression behaviour of concrete-filled double-skin tubular (CFDST) columns with corrugated plates. These sections take advantage of the high strength of their infill concrete as well as the ductility of their steel skins. Static compression tests were performed on CFDST column specimens with inner or outer skins built up from corrugated plates. The steel hollow sections fabricated from corrugated plates exhibited a more stable response under axial compression loading. Hence, implementing them in CFDST columns is expected to enhance the overall behaviour of these columns. These tests reveal how the overall behaviour of CFDST columns is affected by replacing their inner/outer skin with one fabricated from corrugated plates. The corrugated plates have an insignificant effect on the strength of column specimens. However, the ductility and energy absorption capacity of CFDST columns are improved dramatically. A finite element modelling framework was also developed to simulate the response of CFDST columns with corrugated plates and validated against the results of the experiments.

Keywords: Concrete-filled double-skin columns; Compressive behaviour; Corrugated plates; Uniaxial large-scale tests; Numerical modelling

1. Introduction

The structural performance of concrete-filled double-skin tubular (CFDST) sections has been the subject of a notable number of studies in recent years. Conventional CFDST sections consist of two hollow flat steel skins, and the gap between these two skins is filled with concrete. Since CFDST sections use the merits of the high compression strength of the concrete core as well as the ductility of the steel material in the surrounding skins, these sections are an astute choice in structural design.

The interaction between the steel and concrete parts of composite sections has been clarified since Sewel performed pioneering experiments on concrete-filled tubes in 1902 [1]. He reported a greater capacity for the entire section than the sum of the individual capacities of the steel and concrete components. Similar to other steel-concrete composite sections, in the CFDST sections, the steel skins provide the confinement for the concrete core, while the concrete core prevents them from inward buckling. Consequently, this interaction enhances the overall strength of the section as well as its ductility. However, the efficiency of the confining action has been shown to be dependent on the shape of the steel skins, and circular steel skins are expected to provide most confinement for the concrete core [2].

The effects of the shape and the geometry of the components of CFDST columns on their overall compressive behaviour have been investigated in previous studies. Tao *et al.* [3] reported more severe post-peak strength deterioration for circular CFDST columns with hollow cross-sections. Based on the results of tests on square and circular CFDST short columns with different geometries, Han *et al.* [4] concluded that the ultimate strength and the ductility of CFDST columns are affected by the slenderness of their steel skins. This effect was also probed by Zhao *et al.* [5], who performed several tests on circular CFDST columns under large axial displacements to establish the allowable slenderness limit for the steel skins

1 of these columns. Other researchers have tried to develop representative numerical models
2 and to take advantage of numerical simulations to determine different aspects of the
3 behaviour of concrete-filled columns [6-9]. For instance, Thai et al. [10] performed a number
4 of analyses utilizing different ranges of width-to-thickness ratios, the yield stress of the steel
5 tubes and the compressive strength of the concrete core to develop an equation to predict the
6 confining pressure on the concrete core of CFST columns.

7 Retrofitting and improving the overall behaviour of steel-concrete composite sections have
8 also been studied by some researchers. Welding stiffeners along the steel tubes, employing
9 continuous spirals or utilizing FRP wraps around the steel skins are some strategies proposed
10 to improve the strength and the ductility of CFST columns [11-13]. All of these strategies
11 were implemented to enhance the buckling behaviour of the steel skins of CFT and
12 consequently CFDST columns Aslani et al. [14] also tried to improve the behaviour of
13 CFDST columns by incorporating high-strength steel plates.

14 Meanwhile, Nassirnia et al. [15] performed compression tests on square hollow columns built
15 up from corrugated plates. The results of their experiments showed that corrugated plates
16 enhance the local and global stability of the fabricated columns. Since the compressive
17 behaviour of CFDST columns is directly influenced by the stability of the steel skins, the
18 global behaviour of these sections might be enhanced by improving the performance of the
19 steel skins under compressive loading. Consequently, substituting steel skins built up from
20 flat plates with those fabricated from corrugated plates can be considered as a strategy to
21 improve the compressive behaviour of CFDST columns. This paper, therefore, deals with
22 both experimental and numerical investigations carried out to test this hypothesis. In order to
23 do so, various CFDST column specimens with outer or inner corrugated skins and an
24 ordinary reference CFDST column sample were constructed and then loaded monotonically.
25 Numerical models were also developed and validated based on the experimental results.

Numerical simulations enabled the provision of reasonable explanations for the experimental observations.

2. Static Compression Experiments

In the first stage, an experimental plan was designed in order to investigate the effect of corrugation geometry on the performance of corrugated CFDST columns under compressive loading. The test plan was also expected to reveal the difference between the response of a CFDST section with a corrugated inner skin compared with the same CFDST section with a corrugated outer skin. The results of the experiments could also provide a reliable benchmark to validate the finite element (FE) modelling procedure which is presented in the following sections of the paper. The experimental plan included five square CFDST columns with corrugated plates as well as a reference sample which was a square ordinary CFDST column with flat plates. It is worth noting that in order to study the effect of the geometry of corrugated plates on the performance of the proposed CFDST columns, the weight of all columns was kept the same.

Three different types of corrugated plates, named Type 1, Type 2 and Type 3, were utilized to form the steel skins in this study. The height of the corrugations and the inclination angle differ among these three corrugation types. The geometric properties of these corrugated plates are illustrated in Fig.1 and Table 1. Fig.2 shows the sections of the CFDST column specimens in the experimental plan. As shown in Fig. 2, **I/O** as the first letter of the name of an experimental specimen indicates whether corrugated plates were used to form the inner skin or the outer skin of each specimen, the letter **C** indicates corrugation, and the number after the letter C represents the corrugation type. In other words, corrugated plates Types 1, 2 and 3 were used in fabricating the inner skins of column samples IC1, IC2 and IC3,

respectively, whilst the outer skins of column samples OC1 and OC2 were constructed with corrugated plate Types 1 and 2, respectively.

2-1. Fabrication of CFDST Archetypes:

All corrugated plates used in this research project had originally three corrugation modules, and they were cold-formed from Grade 250 mild-steel flat plates 247.5 mm wide, 1000 mm long, and 3 mm thick. The press-braking method was implemented to fold the original flat plates into corrugated plates. This method of cold-forming affects the mechanical properties of the folded plates at the corner of the corrugated plates. Reduction in ductility as well as increased yield strength and ultimate strength can be expected in these areas [16]. The outer and inner skins of the reference sample were fabricated by welding four of the original flat plates along their edges. The type of welding implemented to assemble all steel skins was butt (groove) welding. ER2209 wires were utilized to conduct the gas tungsten arc welding (G.T.A.W) welding procedure with 0.2% proof stress and tensile strength of 560–620 MPa and 800–835 MPa, respectively.

In order to keep the weight of all column samples the same, one of the corrugation modules in IC1, IC2 and IC3 specimens was omitted. Hence, the dimension of the outer flat skins in IC1, IC2 and IC3 specimens and also the dimensions of the inner flat skins in OC1 and OC2 specimens could be determined to keep their weight the same as that of the reference sample.

Since the hollow steel skins were fabricated utilizing longitudinal welding, slight imperfections along and across the different faces of the steel skins could be expected. These imperfections and dislocations were measured in order to be implemented in the FE modelling. In order to measure the imperfections, the fabricated hollow boxes were first placed on a table with a flat surface, and the imperfections were then measured on each face with respect to a reference point. The measurements were conducted at 9 nodes along and

1 across each face using a digital indicator fixed to a vertical stand. The maximum distortions
2 measured for the fabricated hollow steel skins are reported in Table 2.

3 Four small mild-steel rods were used in the next stage to fix the fabricated inner and outer
4 skins together. Square base plates were welded to the end of the assembled hollow steel skins
5 to make concrete pouring possible between the skins.

6 The gap between the hollow steel skins was filled with self-consolidating concrete (SCC) as
7 the final step in fabricating the experimental archetypes. This type of concrete was chosen for
8 the sake of convenience during concrete pouring in the small gap between the steel skins. It is
9 noted that the required vibration along the height of the archetype columns can be eliminated
10 by using this type of concrete. The SCC mixture was designed such that the average ultimate
11 compressive strength of 40 MPa could be achieved after 28 days for standard cylindrical
12 samples. The SCC mixture proportion is listed in Table 3. All CFDST columns were filled
13 with concrete mixtures with the same proportions in order to have uniform ultimate
14 compression strength for the concrete cores of all the archetype columns. The compression
15 strength of the concrete mixtures was measured utilizing cylindrical samples 100 mm in
16 diameter and 200 mm high according to Australian Standard AS1012.1 [17]. Some of the
17 concrete cylindrical samples made from each mixture were cured in a water tank, while the
18 others were wrapped with a plastic cover and left in room conditions to represent the curing
19 condition of the infill concrete used in the archetype columns. All the CFDST specimens and
20 the concrete cylindrical samples cast from their infill concrete were tested on the same day
21 and at least 28 days after the concrete pouring. The average ultimate compression strength of
22 the infill concrete of the archetype columns and their other characteristics are reported in
23 Table 4. The top surface of the CFDST archetype columns was ground when the curing
24 period of the infill concrete elapsed. The grinding was performed in order to remove the
25 uneven surfaces caused by longitudinal shrinkage effects in the concrete. Hence, the final

measured length of the CFDST archetype columns was between 1 to 2mm less than the original length of the hollow steel skins (1000mm).

2.2. Test Set-up

A testing machine able to exert a uniaxial load up to 5000 kN was used to conduct the experiments. The archetype columns were mounted in the upright position between two rigid plates. These plates prevented any possible rotation with the aid of two solid blocks at the top of the upper plate and two others underneath the bottom plate. Fig.3 depicts the experimental set-up for a typical CFDST column. When the bottom rigid plate is pushed up by hydraulic jacks, the specimen between the loading plate and the fixed upper plate undergoes an excessive compression force. The overall axial displacement of the archetype specimens was captured by two linear variable differential transformers (LVDTs) recording the upward movement of the loading plate at its two opposite corners. Six strain gauges were also utilized to obtain a better idea of the local deformations and plastic strains developed locally at different faces along the height of each archetype specimen. Four of these strain gauges were placed at the centre of the external faces of each CFDST archetype specimen, while two others were attached on the first and the last quarter lengths of one of the external faces.

2.3. Experimental Results and Observations

In the next stage, static compression tests were performed on the reference CFDST specimen and the CFDST archetypes with corrugated plates when the infill concrete reached its ultimate strength after 28 days. The loading rate was chosen to be equal to 1mm/min, which is small enough to neglect inertial effects. Recording the force developed in the archetype specimens during the experiments made it possible to draw the axial force-deformation curve for each specimen under static compression loading. This curve is shown in Fig.4 for the reference sample and in Fig.5 for sample OC1. Fig.6 and 7 show these columns during the

1 experiments. Each stage is titled with a letter which was also used to clarify the relevant point
2 on the axial force-deformation curves. In these curves and the other similar curves in this
3 study, the axial deformation is represented by the nominal axial strain, calculated as the ratio
4 of the overall axial deformation of the column to its initial length.

5 The steel skins of CFDST columns buckled severely and the plastic deformations increased
6 rapidly at the top of the specimens once the ultimate strength of the specimen was achieved.
7 This phenomenon was simultaneous with crushing of the infill concrete leading to an abrupt
8 drop in the force-deformation curve. Since the progress of the experiments became too slow
9 after peak load, the loading procedure was terminated when the capacity of the specimen
10 dropped roughly to 40% of its ultimate compression capacity. The intensive plastic
11 deformation at the top part of the outer skins of almost all specimens caused ruptures at the
12 corner welds (Fig.8).

13 After severe buckling of the steel skins of the archetype columns and the sudden intensive
14 drop in the axial strength, the strength deterioration rate alleviated in all specimens, and the
15 strength started to decrease smoothly as the axial deformation was increased. This can be
16 explained considering the fact that the crushed concrete particles filled the gaps caused by the
17 buckling of the steel skins at the top of the columns. Therefore, the confinement was
18 retrieved for the crushed concrete leading to the entire column preserving its residual strength.
19 The plastic deformation due to the local buckling was more concentrated and severe in the
20 steel skins made up of flat plates compared to that observed in the corrugated steel skins.
21 However, the buckling shapes captured during the experiments were different from the
22 buckling modes of the individual hollow steel skins. Hence, the effect of the infill concrete on
23 preventing the steel skins from buckling inward cannot be debated.

Fig.9 shows the compression force-nominal axial strain curves of all CFDST specimens with corrugated inner skins compared to that of the reference sample. The same curves for the specimens with corrugated outer skins are shown in Fig.10. It can be inferred from these figures that replacing the flat plates of the reference sample with corrugated plates during the construction of the CFDST columns remarkably enhances their ductility. It is also evident from the results that utilizing deeper corrugations or corrugations with larger inclination angles results in more ductility and increased post-peak compression strength.

In order to investigate the difference between using the corrugated plates as the inner skin and the outer skin of the proposed CFDST sections, the compression force-nominal axial strain curves for specimens IC1 and OC1 are depicted in Fig.11, while Fig.12 illustrates the corresponding curves for specimens IC2 and OC2. The outer skin of specimen OC1 and the inner skin of specimen IC1 were constructed from Type 1 corrugated plates, whilst both specimens had the same weight. However, more ductile behaviour and less post-peak strength were captured for specimen OC1. The same trend is seen when the ductility and post-peak strength of specimens IC2 and OC2 are compared. Hence, it can be concluded that in terms of ductility, employing corrugated plates as the outer skins of CFDST columns is more efficient than employing them as the inner skins of these columns. Furthermore, comparing the overall behaviour of the proposed column samples elucidates the fact that the abrupt strength drop in the compression behaviour of CFDST specimens with corrugated outer skins was more alleviated than that of the other specimens. Therefore, the brittle and abrupt failure mechanism as a notorious characteristic of CFDST columns can be eliminated to some extent by using corrugated plates as their outer skins.

The lack of bonding between steel and concrete at the early stages of a compression loading might affect the initial stiffness of CFDST sections. The values of initial stiffness of Reference specimen and specimens IC1 and OC1 were also compared in this study based on

the data recorded by the strain gauges at the early stages of the experiments. Although the recorded data at the onset of the tests were not enough stable to make a precise quantitative comparison, it seems that the initial stiffness of specimen IC1 was quite the same as the initial stiffness of Reference sample. However, the initial stiffness of specimen OC1 was quite more than the initial stiffness obtained for the mentioned both other specimens. Hence, the corrugated geometry of the outer steel skins can be also beneficial to reduce the outlined adverse effect.

Although the deterioration rate of post-peak compression strength was less in the specimens with corrugated outer skins, the post-peak residual strength in these members was less than the corresponding values for the specimens with corrugated inner skins. Therefore, another index is required to evaluate the general performance of column samples such that the area underneath the axial force-axial deformation curve for each specimen is calculated as an index that shows the energy dissipation during the loading procedure. The area was calculated from the starting point of the curve until the points relevant to the ultimate compression strength and the fracture initiation, respectively (see Fig.13 (a) and (b)). The values of the energy dissipated by all specimens from the beginning of the experiments to their ultimate compression capacity were not perceivably different. However, these values are scattered when they are calculated from the beginning of the experiments until the first signs of fracture in the specimens. Fig.14 shows these values calculated for all specimens besides the average value calculated for CFDST columns with corrugated plates (grey dashed line). The energy dissipated by the specimens consisting of corrugated plates is much greater than the energy dissipated by the reference sample. This foregrounds the effect of implementing corrugated skins in CFDST sections on their post-peak behaviour. The enhanced energy dissipation capacity of CFDST sections consisting of corrugated plates distinguishes their performance from ordinary CFDSTs in extreme events such as earthquakes, blast and fire

[18-26]. It is also evident from this figure that the calculated values for the specimens with corrugated outer skins exceed the average value.

3. Numerical Simulation

In conjunction with the experiments, a numerical modelling framework was also developed in this study, and the experimental results were utilized to validate the numerical models. Hence, a finite element (FE) model was developed for each of the CFDST column specimens tested previously with the aid of ABAQUS software. These models, which are discussed in more detail in this section, were expected to capture the results obtained from the experiments, including the loading-displacement curves as well as the local and global deformations. The interaction between the steel skins and the infill concrete of CFDST columns affects the overall behaviour of these columns, as was shown in the experimental phase. Therefore, the development of a model to accurately simulate this interaction was one of the most challenging parts of the modelling procedure. In addition, it was necessary to select appropriate material models in order to represent the nonlinear behaviour of the steel and concrete parts separately.

Numerical stability of the FE simulations during each solution step along the equilibrium path was another concern. Because of the abrupt strength drop observed after the inception of local buckling in the steel skins, it was probable that the local instabilities would jeopardize the whole solution's stability. In such cases, global load control methods such as the Riks method might not be an appropriate method of analysis. However, ABAQUS/Standard is claimed to be able to evade the problem by implementing damping throughout the model. The introduced viscous forces are sufficiently large to prevent instantaneous buckling or collapse, but small enough not to affect the overall behaviour while the solution is stable [27]. In this research, the adaptive damping factor was utilized during each analysis changing from

each increment to another, and it was calculated in such a way that the dissipated energy in each increment approaches a small fraction of the strain energy in the previous increment [27]. This fraction, called the “dissipated energy fraction”, was chosen as equal to 0.05. The minimum limit for the increment size was also chosen to be small enough to improve the stability of the analyses.

3.1. Material Modelling

CFDST columns with corrugated plates consist of steel and concrete materials which both can undergo severe plastic deformation under high axial compression loading [28, 29]. Crushing and cracking of the infill concrete as well as large plastic strains in the steel skins, especially in buckled areas, seem inevitable in these members. Hence, the implementation of appropriate nonlinear material models is a complex part of the modelling procedure.

The steel material utilized to build up the hollow skins is the same as that used in previous studies. [30]. The required modelling parameters as well as the constitutive relation for the steel material were determined based on the experimental data published by Javidan et al. [30].

The results of the compression tests performed on the concrete samples cured under room conditions were utilized to model the infill concrete. Since the concrete in CFDST columns is confined by the steel skins, its compression behaviour is affected by this confinement. An equivalent concrete model suggested by Han et al. [4] for confined concrete material was then introduced to ABAQUS. This model was used to amend the concrete compression behaviour due to the confinement without affecting the ultimate compression strength. For square-shaped sections, the stress (σ) versus strain (ϵ) relation for confined concrete is given as follows in this model:

$$1 \quad \begin{cases} y = 2x - x^2, (x \leq 1) \\ y = \frac{x}{\beta(x-1)^\eta + x}, (x > 1) \end{cases} \quad (1)$$

2 where,

$$3 \quad x = \frac{\varepsilon}{\varepsilon_0} \quad (2)$$

$$4 \quad x = \frac{\sigma}{\sigma_0} \quad (3)$$

$$5 \quad \sigma_0 = \left(1 + \left(-0.0135\xi^2 + 0.1\xi \right) \left(\frac{24}{f'_c} \right)^{0.45} \right) \times f'_c \quad (4)$$

$$6 \quad \varepsilon_0 = \varepsilon_{cc} + \left(1330 + 760 \left(\frac{f'_c}{24} - 1 \right) \right) \xi^{0.2} \cdot \varepsilon \quad (5)$$

$$7 \quad \varepsilon_{cc} = 1300 + 12.5 f'_c \varepsilon$$

8 (6)

$$9 \quad \eta = 1.6 + 1.5/x \quad (7)$$

$$10 \quad \begin{cases} \frac{f_c'^{0.1}}{1.34\sqrt{1+\xi}}, (\xi \leq 3) \\ \frac{f_c'^{0.1}}{1.34\sqrt{1+\xi}(\xi-2)^2}, (\xi > 3) \end{cases} \quad (8)$$

11 The units for stress and strain are N/mm² and $\mu\varepsilon$ respectively, and ξ is the confinement factor

12 which can be calculated by the following equation:

$$13 \quad \xi = \frac{A_s f_{ys}}{A_c f'_c} \quad (9)$$

14 in which A_s is the cross-section area of steel skin, A_c is the cross-section area of concrete, f_{sy}
15 is the yield stress of steel skin, and f'_c is the compression strength of infill concrete.

16 Since a multi-axial plasticity model was employed in the modelling procedure, the effect of
17 the confinement on the ultimate strength of the infill concrete was directly taken into account

in the FE simulation [27]. Among the modelling features of ABAQUS, the “Concrete Damage Plasticity” model was used to implement the non-linear behaviour of the concrete in the modelling procedure. This model is a continuum plasticity-based damage model for concrete, which considers two main failure mechanisms for this material: tensile cracking and compression crushing [27]. The elastic compression stiffness degradation was assumed to be only a function of plastic strain, and the effect of temperature and other field variables were neglected. Other required parameters for the concrete damage plasticity model, including the ratio of the compressive strength under biaxial loading to uniaxial compressive strength (f_{bo}/f_0), dilation angle (ψ), and the ratio of the second stress invariant on the tensile meridian to that on the compressive meridian (K_c), were evaluated according to the suggestions of Tao et al. [31]. The following equations were suggested by these researchers:

$$\Psi = 40^\circ \quad (10)$$

$$\frac{f_{bo}}{f_c} = \frac{1.5}{f_c'^{0.075}} \quad (11)$$

$$K_c = \frac{5.5}{5 + f_c'^{0.075}} \quad (12)$$

f_c' in the above equations was substituted with the compression strength of the infill concrete.

3.3. Modelling Features

Because of the small thickness of the steel skins, these parts of the CFDST columns were modelled utilizing shell elements. Four-node reduced integration shell elements (S4R) with 6 degrees of freedom per node were used to model the steel skins. On the other hand, the infill concrete was simulated using eight-node reduced integration linear brick elements with three degrees of freedom at each node (C3D8R). The upper half of the column specimens seems to be more prone to local effects, based on the experimental observations. Hence, the maximum mesh size at the bottom half was chosen to be two times of the maximum mesh size at the top

half. After performing a mesh-sensitivity analysis, the maximum mesh size was chosen to be equal to 10 mm for the top part of the simulated columns.

3.4. Steel-Concrete Interaction and Boundary Conditions

Once a CFDST column is loaded, the side surfaces of the infill concrete interact with the steel skins in both normal and tangential directions. The “surface-to-surface” type of the “contact pair” option in ABAQUS was used to model this interaction. The normal contact between these surfaces was modelled with “hard” contact formulation. In this case, when the surfaces are in contact, the contact pressure can be developed and transferred between them, and the contact pressure can also reduce to zero after separation of surfaces [27]. The “Coulomb friction model” was implemented in the simulation procedure to take the tangential interaction between the surfaces into account. The friction coefficient was chosen as equal to 0.25 and the shear stress developed between the surfaces was limited to 0.86 MPa [10, 32].

The concrete surface as well as the edges of the inner/outer skins were fully constrained at one end. At the other end, a rigid plate was attached to the simulated column specimen, and the axial displacement was exerted on this plate. The “tie” constraint option in ABAQUS was utilized to constrain the degrees of freedom of the steel skins at their top edges to the adjacent nodes at the bottom of the rigid plate. The interaction between the rigid plate and the concrete face in their contact area was also simulated with the “hard” contact option.

3.5. Imperfections

The pattern of initial local imperfections in the steel skins was assumed to be similar to the combination of the first and second buckling mode shapes of these hollow sections. The buckling mode shapes of steel skins can be obtained from an eigenvalue buckling analysis, while the infill concrete and its interaction with the steel skins were omitted from this linear

analysis. Therefore, the nodal displacement results of these analyses were scaled and imported to the main load-deflection analyses as the initial imperfections. The scale factors were chosen to anchor the magnitude of these initial imperfections to the maximum measured imperfections on the different faces of the hollow steel skins. As discussed previously, the imperfections were measured along and across each face of the fabricated hollow skins. Thus, the maximum distortions reported in Table 2 were utilized to scale the initial nodal displacements.

3.6. Numerical Modelling Results

When the numerical modelling procedure was finalized, the experimental results were then employed to validate the numerical models developed for the CFDST column specimens. With no exception, all numerical models were able to accurately predict the elastic behaviour of the column specimens. The ultimate strength values obtained from numerical simulations were also in excellent consistency with the values captured from the experiments. However, modelling of the post-peak behaviour of the specimens was challenging, because of the simultaneous crushing of the infill concrete and buckling of the steel skins, which the integrity of the specimens. Although the abrupt drop in the strength of the specimens was well simulated by the numerical models, the strength retrieval which occurred after that was barely captured using the current modelling procedure. If the accumulation of the crushed concrete particles is a reasonable explanation for the post-peak strength retrieval of the CFDST specimens as described before, the current continuum FE modelling procedure cannot be expected to predict this effect accurately.

The compression force with respect to nominal axial strain curves obtained from both the experimental results and the numerical simulations are depicted in Fig.15 for all CFDST

column specimens studied in this research. More severe local deflections were captured for the outer skins of the archetype specimens compared with their inner skins, due to the fact that the slenderness of the outer skins is more than that of the inner skins.

In the specimens with flat outer skins, this demand was even more severe and more concentrated. However, the improved stability of the corrugated plates in comparison to flat plates helps the specimens with corrugated outer skins to preserve better integrity in their overall behaviour during the compression loading. Therefore, the proposed numerical modelling framework predicted their behaviour after the abrupt strength drop more accurately.

Due to the fact that the column specimens were trapped between two rigid steel plates during the tests, the buckling behaviour and the evolution of the plastic strains in the inner skins could not be captured in the experiments. However, the numerical simulations for all specimens disclosed that the inner skin buckled after the peak strength of the specimen and also after the buckling of the outer skin. The severe plastic deformations due to the buckling in the inner skins formed from corrugated plates were less than those in the flat inner skins. Hence, the higher post-peak strength for specimens IC1, IC2 and IC3 in comparison to the post-peak strength of other archetype columns can be attributed to the superior performance of their corrugated inner skins. On the other hand, regardless of almost the same ultimate compression strength of these three samples, the post-peak strength decreased from specimen IC3 to specimen IC1. In other words, employing corrugated plates with higher corrugation heights or greater inclination angles in fabricating the inner skin mitigated the buckling deformation and the strength deterioration of the inner skin. Although the geometry of the inner skin did not affect the ultimate strength of the CFDST columns, it dominated the post-peak behaviour of these columns.

4. Conclusion

Static compression tests on CFDST column specimens with corrugated plates as well as the results of numerical simulations provided evidence to outline the following conclusions:

- First visible signs of local buckling in the outer steel skins were observed in all of the experiments after the column samples reached their ultimate strength. The compressive strength of the intended sections reduced abruptly once they reached their ultimate capacity. The post-peak softening then continued at an alleviated rate.
- The ultimate compression capacity of the CFDST column specimens with corrugated plates was close to each other and almost the same as the capacity of the reference CFDST sample. While different corrugated and flat steel skins with different geometries were utilized to fabricate the column specimens, the compression capacities of their concrete cores were approximately the same and dominated their overall compression capacity.
- In general, the employment of corrugated plates to fabricate the steel skins of CFDST columns enhances their post peak behaviour notably in terms of ductility and post-peak strength. Utilizing corrugated plates to construct the inner skins of CFDST columns may increase the post-peak strength more than that of specimens with corrugated outer skin. However, implementing corrugated outer skins may result in greater energy dissipation capacity.

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Table 1. Geometric properties of the corrugated plates utilized in this study

	α ($^{\circ}$)	a	h	t	l	d	c	b
Type 1	45	20.00	15.00	3.00	70.00	15.00	21.21	210.00
Type 2	75	25.70	15.00	3.00	59.42	4.01	15.53	178.26
Type 3	75	18.44	22.00	3.00	48.67	5.89	22.78	145.98

Table 2. Maximum absolute values of imperfections for the hollow steel skins

Specimen	Maximum Imperfection (mm)			
	Inner Skin		Outer Skin	
	Transverse	longitudinal	Transverse	longitudinal
Reference	1.09	1.39	1.26	1.60
IC1	1.63	2.24	1.90	1.71
IC2	1.84	1.58	0.89	1.24
IC3	0.78	3.52	1.10	1.16
OC1	0.79	1.51	2.10	3.55
OC2	0.67	1.26	1.87	2.86

Table 3. The utilized self-consolidating concrete mixture proportions

Content	Proportion
Water (Kg/m ³)	177
Fly Ash (Kg/m ³)	131
Slag (Kg/m ³)	131
Cement (Kg/m ³)	104
Fine Aggregates (Kg/m ³)	865
Coarse Aggregates (Kg/m ³)	817
Super Plasticizer (ml/m ³)	1725

Table 4. The mechanical and geometrical properties of the fabricated archetype CFDST columns with corrugated plates

Specimen Name	Outer Skin Area (mm ²)	Inner Skin Area (mm ²)	Concrete Area (mm ²)	Total Section Area (mm ²)	Estimated Weight (kg)	Weight of Fabricated Specimens (kg)	f _c ' (Cured in water) (MPa)	f _c ' (Cured in ambient condition) (MPa)
Reference	2934	1944	31097.3	61256.3	112.9	119.0	47.5	34.5
IC1	2904	1978	33321	60025	118.3	125.0	47.6	35.0
IC2	2724	1979	32488	52900	114.9	124.0	43.3	35.1
IC3	2604	1375	32043	48400	108.1	120.0	47.3	34.1
OC1	2966	1500	34016	50400	116.7	119.0	58.1	42.0
OC2	2969	635	33643	37124	109.0	107.5	52.7	41.6

Figure 1. Typical geometry of the cross-section of corrugated plate [14]

Figure 2. The cross-sections of column specimens

Figure 3. Experiment set-up for a typical CFDST column

Figure 4. Axial force versus nominal axial strain for the reference specimen

Figure 5. Axial force versus nominal axial strain for specimen OC1

Figure 6. The deformed shape of the reference specimen at different stages of the compression loading: (a) 100kN (b) 1000kN (c) 2000kN (d) 1700kN (e) 1250kN (f) 900kN

Figure 7. The deformed shape of specimen OC1 at different stages of the compression loading: (a) 200kN (b) 1750kN (c) 2280kN (d) 1600kN (e) 1000kN (f) 857kN

Figure 8. Fracture at the corner welds of specimen IC1 at the end of the experiment

Figure 9. Axial force-nominal axial strain for Reference specimen and the specimens with inner corrugated skins

Figure 10. Axial force-nominal axial strain for Reference specimen and the specimens with outer corrugated skins

Figure 10. Axial force-nominal axial strain for the reference specimen and specimens IC1 and OC1

Figure 11. Axial force-nominal axial strain for the reference specimen and specimens IC2 and OC2

Figure 13. Calculation of dissipated energy for specimen OC1 from the experiment initiation until (a) the ultimate compression capacity (b) the fracture initiation

Figure 14. The area under the axial force-deformation curves for all specimens calculated from the starting point of the experiments to (a) the ultimate compression strength (b) the relevant fracture initiation point

Figure 12. Axial force (in kN) versus nominal axial strain curves obtained from the experiments and numerical simulations for all specimens