Structural Behavior of Short Thin-Walled Steel Columns Filled with High Strength Concrete Made of Recycled Aggregate

Haitham A. Samir[1, a*] and Ali H. N. Almamoori[1, b]

[1]Civil Engineering Department, University of Karbala, Karbala, Iraq

[a]haithemeng2005@gmail.com
*Corresponding author

Abstract. This paper introduces an experimental work to study the behavior of 12 recycled aggregate concrete-filled steel tubular (RACFST) short columns with high-strength concrete grade subjected to axial compression loading. These columns formed from six different cross-sections involving triangle, elliptical, and hexagon, whereas the other three sections included traditional forms for control purposes, involving square, rectangular, and circular. All RACFST columns used are made of mild steel plates. These columns were divided into two groups. The steel tube thickness was the only parameter modified to study its effect properly. In addition, the study included the search for the best effective section concerning the properties of stability and confinement, so these columns were designed so that the cross-sectional areas of steel tubes were approximately equal. Also, composite action and level of ductility for these columns were studied. The ultimate failure axial load, the reduction in the axial column length, the failure pattern of cross-section shape, and lateral displacement were recorded during the test. Regarding the two groups of columns with (1 and 2) mm thick steel plates, testing data obtained from RACFST columns with elliptical and circular cross-sections respectively showed better stability and confinement of concrete and the ability to withstand a higher ultimate failure stress. Moreover, columns with polygonal sections showed when the number of ribs for the steel plates of the model or increased the angle between the two sides is (90°) or more, column cross-sections can achieve more stability and confinement, respectively. In general, increasing the thickness of the steel tubes increases. Finally, for all columns, the higher values of the concrete contribution ratio (C.C.R) led to an increase in the strength index (S.I.) values. An increase in values of final failure stresses accompanied this increase.

Keywords: Short length column; thin-walled steel tubes; (RACFST); (RCA); axial compression; section shape.

1. INTRODUCTION

Columns are one of the most important structural elements on which the various structures and buildings depend. One of these types is recycled aggregate concrete-filled steel tubes (RACFST). It is a composite column consisting of two basic materials: recycled aggregate concrete as a filler and hollow steel tubes. These tubes are manufactured in many ways, either by welding steel plates, rolling on Hot, or by cold forming. Commonly used sections for these columns are circular, squared, and rectangular, where they are often called circular hollow sections (CHS), square hollow sections (SHS), and rectangular hollow sections (RHS). Concrete-filled steel tubes (CFST) have many features and unique properties, including high resistance to strength and fire, preferred ductility, ability to absorb energy, speed, and ease of installation with other structural members, no need to use molds in concrete works, thus reducing the cost and time of work, resistance high for earthquakes. The many advantages of these composite columns led to the expanded use of this technology in construction work for various civil engineering sectors [1].

Concrete has high compressive strength and low tensile strength. In addition, concrete under double- or triple-axial confining pressure leads to better compressive strength. As for the steel structural members, they have high tensile strength, but under compression, the possibility of local buckling to the shape increases. To harness the properties of steel tubes and concrete and benefit from their unique properties, this was done in (CFST). Here, the steel tubes provide confined pressure to the concrete, and in return, the concrete core reduces the occurrence of local buckling for steel tubes. The ideal and commonly used cross-sections of concrete-filled steel columns are circular, square, and rectangular; each type of cross-section has unique properties. The circular column cross-section (CHS) generates strong confinement of concrete. While the cross sections of both square (SHS) and rectangular (RHS) columns have the probability of occurring local buckling. However, CFST columns with these sections are still widely used for their ease of design and connection to structural members of buildings and their high rigidity against sectional bending.

The concrete-filled steel tubes CFST columns with special cross-sections such as elliptical, hexagonal, and square have been used for many reasons, including aesthetics, ease of manufacture, availability of raw materials, and low cost [2]. Therefore, these columns with special sectional shapes were the focus of the researcher's study by comparing their structural behavior with the commonly used columns of circular, square, and rectangular sections. Before discussing the literature on RACFST columns, the structural behavior of CFST short columns from previous studies have been discussed when filled with `high-strength' ordinary concrete due to their proximity to the current investigation, as below. The mechanism of failure of circular CFST specimens was crushing the concrete, and then local buckling occurred for steel tubes [3]. It was observed that the values of SI increased when the ratio of diameter to thickness (D/ t) of steel tubes decreased. This indicated the composite act was more important for columns with slender cross sections [4]. The ultimate strength of circular CFST columns increased as the concrete strength increased. In addition, when the diameter-to-thickness ratio (D/t) of steel tubes decreased, the confinement increased, but the ductility decreased [5]. Crushing the concrete and local buckling was a typical failure for examined specimens. Besides, circular CFST columns exhibited higher final capacities than rectangular columns with equal steel area [6]. The CFST columns with high-strength concrete exhibited the highest loads. Also, the values of CCR proved high performance when filled with HSC, mainly for thin-walled circular columns steel tubes [7]. The concrete mixes with low strength showed better confinement and ductility than concrete mixes with high strength [8]. The values of final load capacity increased with increasing steel tube thickness [9]. The ductility of columns decreased when concrete strength increased [10].

It is worth noting that one of the most important properties of recycled coarse aggregate is its high ability to absorb water when it is not previously wet compared to natural coarse aggregate, so it works to reduce the ratio of water cement ratio (w / c) of concrete. It thus increases the strength of concrete [11]. This feature was confirmed by Chen et al. (12). At the same time, they have shown in their study that the use of recycled aggregate concrete (RAC) in concrete-filled steel tubes as a structural material is possible and safe. Some authors, though different experimental programs, Safiuddin [13], Yuyin Wanga [14], and Wan-Qing Lyu [15], Have shown that recycled Coarse Aggregate Concrete (RAC) can be used completely instead of natural coarse aggregate to obtain concrete with strength ranging from (80-90) % of the strength of natural coarse aggregate concrete. The researcher Azevedo [16] explained in their study that the resistance of a composite column not only depends on the compressive strength of concrete but also on the ratio between the compressive strength of both steel and concrete, i.e. (fy/fc), besides to that, they stated the confinement effect be a significant factor in the strength of the RACFST column.

The researchers You-Fu Yang [17], You-Fu Yang and Lin-Hai Han [18], Zong-ping Chen [19], Wengui Li [20], Niu and Cao [21], Dongdong Yang [22] Presented experimental studies on the behavior of RACFST columns filled with recycled aggregate concrete, they mentioned the failure of all specimens is failure buckling. Also, they illustrated that the failure patterns for those columns were similar to counterparts in CFST columns, and all tested specimens behaved ductile. In addition to that, there is also an accepted consensus that the structural behavior of (RACFST) columns is slightly less than that of (CFST) columns filled with natural aggregate concrete. Here it should be noted that the importance of this research lies in benefiting from each of the mechanical properties of recycled concrete and thin-walled hollow steel tubes. The combined action of both materials improves these properties. Through composite columns, the structural properties of the recycled concrete were improved and thus increased the effectiveness of these structural elements. Especially if we take into account the use of high-strength concrete, as this type of concrete can increase the maximum load-bearing capacity of the RACFST columns. This reduces the size of the columns by using cross-sections with smaller areas, thus reducing the weight of dead loads for buildings while providing larger service spaces. In addition, short, thin-walled steel columns were studied here due to their frequent use in various buildings and their low cost compared to other columns. Also, this study looked at some forms of special sections for thin-walled steel columns and tried to find the optimal section in terms of stability and confinement while comparing them with sections commonly used. Moreover, it achieves the architectural requirements from an aesthetic point of view by providing the sections with special forms while providing the required information about the possibility of using them in various civil engineering sectors.

Finally, recycled coarse aggregates were used as fillers for these columns due to their great importance in promoting environmental conservation and reducing natural resource depletion, preserving the environmental diversity of living organisms, and reducing noise and environmental pollution of land and air. Also, recycled aggregate is undoubtedly of great importance in several aspects, including reducing costs compared to the continued use of natural aggregate and helping to get rid of the rubble of destroyed or old buildings due to natural disasters or wars. Based on the aforementioned, using recycled concrete, which includes coarse aggregate, in various civil engineering facilities can contribute effectively to promoting and developing sustainability. This is regarded as one of the basic requirements of modern construction. Thus, achieving the overall quality of use for the welfare of the people without continuing to deplete the natural resources that can be provided for future generations.

Despite the availability of previous studies, it was concluded that there is a lack of experimental investigations on RACFST columns when filled with HSC in terms of the effect of thin-walled steel cross-sections of different shapes and thicknesses on the final bearing capacities of those columns. To understand the structural behavior of this type of composite member. The effect of the cross-section shape was studied in terms of the number of ribs that formed the shape of the model and the angles between these ribs on the final bearing capacity of these columns. Also, the effect of changing the thickness of the steel tube on the final failure stress was studied for all the samples examined. This study's main goals for recycled aggregate concrete-filled steel tubular (RACFST) thin-walled short columns are adopted when filled with high-strength concrete and subjected to axial compression loading.

1) Present practical experiments on the structural behavior of RACFST columns because experimental and numerical studies related to the compressive behavior of these columns are still insufficient. Moreover, no design methods are available for the local stability of these columns.
2) Investigation for the more effective cross-sectional shape for all RACFST short columns. Regarding confinement properties, stability, and the maximum capacity of failure stress, with unusual cross-section

shapes such as elliptical, triangular, and hexagonal. After that is compared these sections with traditional cross-sectional shapes such as circular, square, and rectangular.

3) Investigating the effect of steel tube thickness on the final failure stress of all RACFST columns.

2. MATERIALS and Methodology

After a detailed study of the previous literature, the materials required for both mild steel plates and recycled concrete needed in the experimental work were identified and provided. Then, a total of 12 samples were prepared. The shape of the cross-sections of these samples and their details are shown in Figure 1 and Table 1, respectively.

2.1 Description of Hollow Steel Tubes Specimens.

The columns specimens that were used in this study are twelve RACFST columns with six different cross-sections, three of which are commonly used for comparison purposes, which are circular, square, and rectangle. The remaining are special cross-sectional shapes, including the elliptical, hexagon, and triangle, as shown in Figure 1. The symbols have been used ("CC", "CH", "CE", "CS", "CR", and "CT") to identify all RACFST specimens. The first letter represents the composite column specimen. The second letter denotes circular, hexagonal, elliptical, square, rectangular, and triangular.

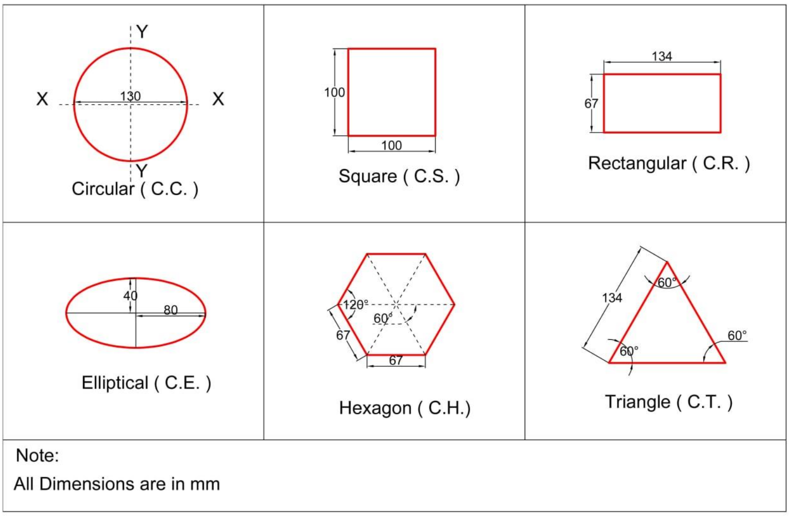


Figure 1: Various Cross Sections of RACFST Columns.

All specimens were divided into two groups and manufactured with two thick (1 and 2) mm. The first group with a thickness of (t = 1) mm, whereas the second group with a thickness of (t = 2) mm. Sections of all RACFST columns were designed with approximately an equal external perimeter (P); therefore; as a result, the area of the cross-section of the steel tube (As) was approximately equal for each group. On the other hand, this led to a difference in the cross-sectional area of the concrete (Ac). The length (L) of each specimen was 300 mm, while the external perimeter of the cross-section of each column was 400 mm, with a difference ranging from (+2 to -3%) of this length. The information for these specimens was recorded in Table 1.

Table 1: Data obtained from the proposed design of the RACFST columns models.

Group no.	**Section's Shape**	**Symbols**	**P, mm**	**L, mm**	**t, mm**	**As, mm²**	**Ac, mm²**
G1	Ellipse	C.E.	388	300	1	388	10053
	Hexagonal	C.H.	402	300	1	402	11663
	Square	C.S.	400	300	1	400	10000
	Circle	C.C.	408	300	1	408	13273
	Triangle	C.T.	402	300	1	402	7772
	Rectangle	C.R.	402	300	1	402	8978
Group no.	**Section's Shape**	**Symbols**	**P, mm**	**L, mm**	**t, mm**	**As, mm²**	**Ac, mm²**
G2	Circle	C.C.	408	300	2	816	13273
	Square	C.S.	400	300	2	800	10000
	Hexagonal	C.H.	402	300	2	804	11663
	Ellipse	C.E.	388	300	2	776	10053
	Triangle	C.T.	402	300	2	804	7772
	Rectangle	C.R.	402	300	2	804	8978

2.2 Experimental Method and Mechanical Properties of the Materials.

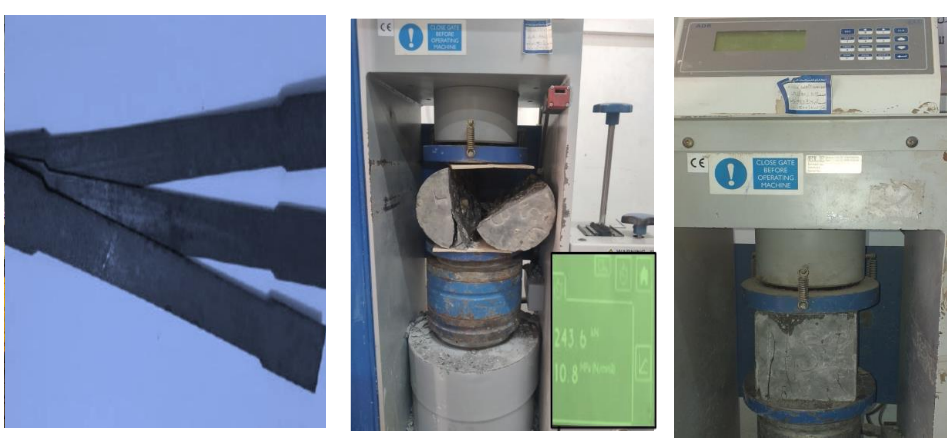
Sulfate-Resistant Portland Cement (SRC) called locally (Kar) in this experimental work was used. The test results showed that the cement conformed to Iraqi Standard No. 5/1984 (23). Fine aggregate with brand-named Al-Ukhaidir sand, with an optimum grain size of (4.75 mm) was used for the concrete mixtures in this investigation. This sand's chemical and physical properties comply with what is required according to the Iraqi standard specification (IQS) No. 5/1984 (23). The waste concrete resulting from the demolished concrete buildings was the resource of the recycled coarse aggregate (R.C.A.) with a gradation of (5-19) mm. The aggregate was separated by sieve analysis.

The results of the gradient test comply with Iraqi Standard No. 45/1984 (24). These aggregates were soaked in water for 24 hours to get the saturated surface condition before mixing. Recycled coarse aggregate concrete (RCAC) with high-strength concrete (H.S.C.) was used as a filling material in all hollow steel tubes after completing all these tests. Three mix trials have been carried out to find the best proportion, and the chosen mix with the proportion of (cement: sand: recycled aggregate) for (1) m³ were (400, 500, 750 kg/m³ is 1:1.25:1.875) respectively with water cement ratio (W/C=0.3) and superplasticizers in a ratio 2% by weight of cement. From this proportion, the cylinder compressive strength and splitting tensile strength of the green concrete mixture were (40 and 3.94 MPa) respectively.

To find the steel plate's mechanical properties, this was used to manufacture the hollow steel tubes. Standard coupon tensile tests have been carried out, which comply with the specification of American Steel Testing Materials (ASTM A370-17) (25). The results of failure strength, yield strength, and modulus of elasticity of steel plates with two thicknesses of (1 and 2) mm were (455 MPa,258 MPa, and 217 G Pa) respectively. Figure 2, Illustrates steel samples for tensile stress and testing some mechanical properties of hardened concrete after 28 days.

2.3 Manufacturing of Specimens

Using the AutoCAD program, the sections of the columns were drawn according to the required measurements. After that, these cross sections were cut from thin steel plates, and based on these sections, the columns were manufactured according to the required shapes. Each sample has been formed from two symmetrical parts, so its longitudinal welding is also symmetrical. A steel plate with a thickness of 2 mm and dimensions (20*20) mm was welded as a base for these specimens. This base provides three-side confining conditions, prevents the leakage of fine materials from the specimens for the concrete mixture, and increases its stability, as shown in Figure 3(a). Green concrete mix (G.C.) was used, with recycled coarse aggregates (RCA) for mixing instead of using normal coarse aggregates (NCA). The green concrete mixture was designed with a cylinder compressive strength of 40 MPa and then cast all the specimens of RACFST columns as illustrated in Figure 3(b,c). Finally, these samples were placed in water basins to complete the curing process for 28 days.



a: Steel Coupons of Tensile Strength Test. **b: Splitting Tensile strength.** **c: Compressive Strength.**

Figure 2: Steel coupons of tensile strength test and testing some mechanical properties of hardened concrete.

a: Prepare Column Molds. **b: Pouring Stage.** **c: After Curing Stage.**

Figure 3: Preparation of the pouring specimens process of RACFST columns.

2.4 Test Setup

Before starting the tests required for the samples, it was validated that the device of the test and its connected devices were working properly. Next, it was verified that the applied load could be applied to the samples without happened eccentricity. This was achieved by checking the horizontality of the base of the device and making sure that the center of the load cell of the device matched the center of the sample to be examined. The test included a study of the failure's patterns, the ultimate load for each sample, the vertical deformation load, the transverse deformation load, the amount of tensile strain in steel for all samples, the effect of steel tube thickness on the maximum load, and the effect of cross-section shape on the amount of the ultimate failure load.

Three variable linear differential transformers (LVDT) devices have been used to measure the deflection in the sample due to the applied vertical load. One is to measure vertical deflection, the second is to measure the horizontal movement on the long side of the model, and the third is to measure the horizontal movement on the other side. All of them are installed in the middle of the column. Also, 6 cm long strain gauge stickers were installed to measure the longitudinal tensile strain in steel in the middle of columns, as shown in Figure 4(a). The axial load was applied to all samples in the same way, using a hydraulic compressor pressing the sample vertically from the top using the load cell as shown in Figure 4(b) below, where the load was regularly increased by 10 kN until failure or when a sudden collapse occurred to the specimen. The axial load was applied by a load cell with a maximum capacity of 2000 kN linked to the computer.

a: Location of Strain Gauge sticker & LVDT. **b: Installing the Sample for the Axial Loading test.**

Figure 4: Location of strain gauge stickers and (Lvdt) on RACFST columns.

3. RESULT AND DISCUSSION

3.1 Experimental Results

Data on ultimate failure axial load (Nu) have been recorded in the experimental tests. In contrast, other information, including the ultimate failure stress (δu), strength index (SI), ductility index (DI), and concrete

 https://doi.org/10.1051/e3sconf/202342702024

contribution ratio (CCR), which are discussed later in detail, were obtained by some mathematical approaches. The information for these specimens is recorded in Table 2 below.

Table 2: Data obtained from the specimens test of RACFST columns.

Group no.	Sec. Shape	Symbols	P mm	L mm	t mm	As mm²	Ac mm²	Nu kN	δu MPa	SI	DI	C.C.R.
G1	Elli.	C.E.	388	300	1	388	10053	502.084	298.742	1.103	1.32	5.01
	Hexa.	C.H.	402	300	1	402	11663	548.550	288.455	1.065	1.58	5.28
	Squa.	C.S.	400	300	1	400	10000	481.130	285.394	1.054	1.64	4.66
	Circ.	C.C.	408	300	1	408	13273	572.322	270.639	1	1.44	5.43
	Tria.	C.T.	402	300	1	402	7772	281.171	200.641	0.741	1.25	2.71
	Rect.	C.R.	402	300	1	402	8978	310.725	199.639	0.737	1.55	2.99
Group no.	**Sec. Shape**	**Symbols**	**P mm**	**L mm**	**t mm**	**As mm²**	**Ac mm²**	**Nu KN**	**δu MPa**	**SI**	**DI**	**C.C.R.**
G2	Circ.	C.C.	408	300	2	816	13273	794.693	315.016	1	1.35	3.77
	Squa.	C.S.	400	300	2	800	10000	600.729	288.002	0.914	1.13	2.91
	Hexa.	C.H.	402	300	2	804	11663	582.167	252.711	0.802	2.61	2.80
	Elli.	C.E.	388	300	2	776	10053	507.753	245.450	0.779	1.57	2.53
	Tria.	C.T.	402	300	2	804	7772	390.754	216.681	0.687	1.69	1.88
	Rect.	C.R.	402	300	2	804	8978	410.006	209.354	0.664	1.38	1.97

3.2 Observation of Tested Specimens and Failure Patterns

For all tested columns, ductile failure was noticed. All RACFST columns failed due to capillary cracks and then cracking and expansion of the recycled concrete core. Continuing with the loading, an external local buckling occurred near the middle of the RACFST column. During the final steps of the applied loading, more external local buckling occurred near the top and bottom edges of the tested columns. Figures 5 and 6 show the failure patterns of all tested column samples for (1 and 2) mm steel plates, respectively. In general, the section shape had a distinct effect on the failure patterns in the tested samples, as the failure patterns of polygonal cross-sections such as hexagons, squares, and rectangles were slightly different from those of circular and elliptical sections. The RACFST triangular cross-section column had a different behavior than the remaining shapes, as its failure represented a local buckling along the circumference of the bottom base of the column. In contrast, the failure of the square cross-section column was a multiple circumferential local buckling starting from the top middle of the column to its end. However, the limit of plastic deformation for the samples was almost equal for the first and second groups, except for the hexagonal cross-section column, which gave a higher result in the group with thickness (2) mm, and this is related to the type of failure that occurred in this section.

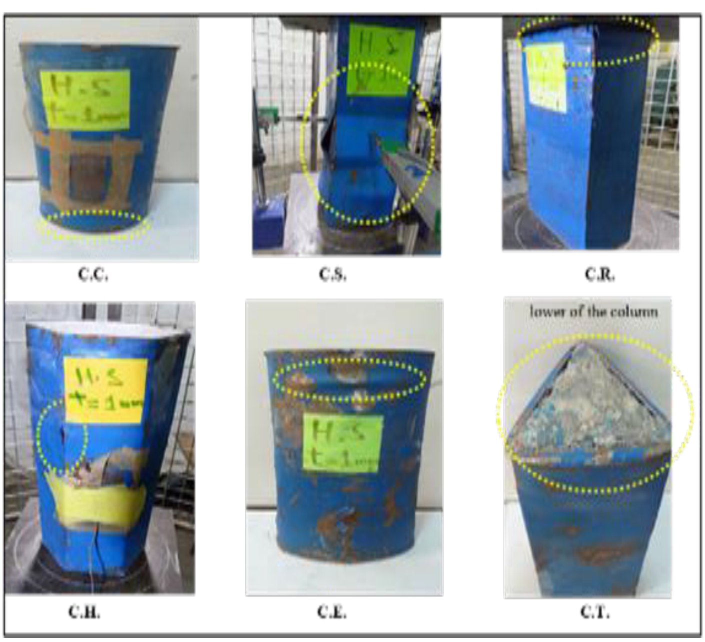


Figure 5: Failure patterns for all tested RACFST columns of steel tube thickness (t) =1 mm.

Figure 6: Failure patterns for all tested RACFST columns of steel tube thickness (t) =2 mm.

3.3 Load-Deformation Curves

Figures 7 and 8 show the plots of experimental axial load (N) versus axial displacement (D) in the axial (load-displacement) curve for each of the RACFST columns tested, which included both an elastic phase and an elastic-plastic phase until the failure load. It showed after obtaining the outward local buckling of RACFST until reaching the ultimate strength of the column and beyond. The maximum axial load capacity of the cross-section related by the tested RACFST circular column and its slope in relation to axial (load-displacement) curves was higher than all other RACFST columns. Anyway, the final failure load here cannot be applied as a method of evaluation between the samples. This fact is because all the tested columns differ from each other in the concrete cross-section area of each column due to maintaining an equal cross-section area for all hollow steel tubes during the design despite the different shapes of these sections. Therefore, failure stresses were used to compare all RACFST columns, which are discussed later in detail.

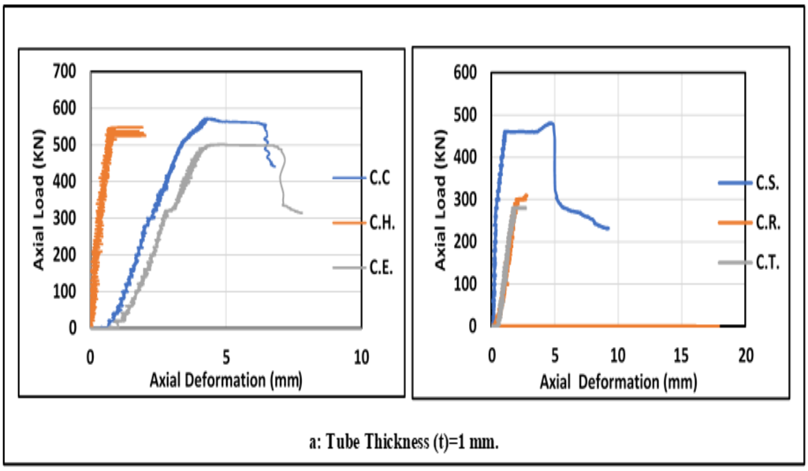


Figure 7: Axial load (N) versus axial deformation (D) of RACFST columns.

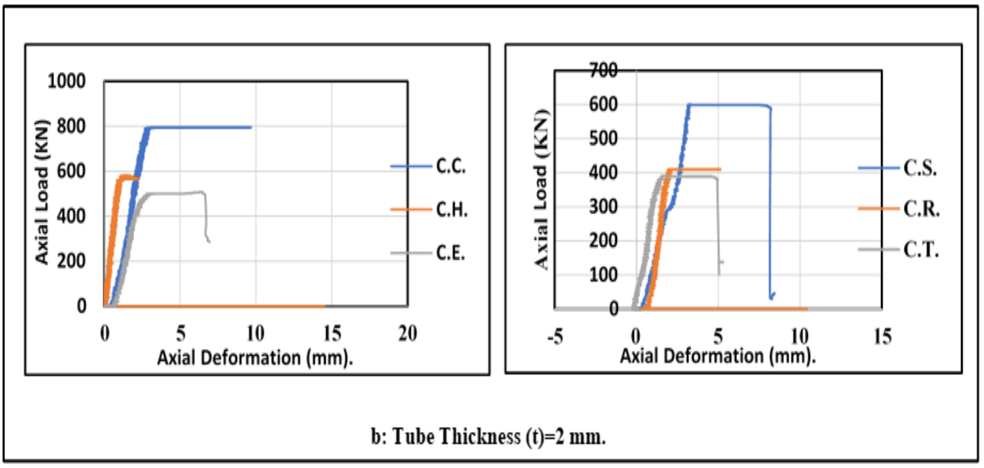


Figure 8: Axial load (N) versus axial deformation (D) of RACFST columns.

The relationship connecting the axially applied load (Nu) with the lateral displacement (D) was plotted in the mid-height of the axes of the tested RACFST columns, as shown in Figure 9, due to the application of the load axially without eccentricity and the fact that the columns were short. Hence, the deflection values were mostly small in the areas close to the middle of the column. Shortly after the applied load reached its maximum value, the external local bucking increased almost equally around the columns of similar cross-sections. After that, the lateral displacement developed significantly after exceeding the post-peak stage.

The results of the group (G1) showed that the lateral deformation values of the polygon cross-section RACFST columns for the (C.H) and (C.R) samples were smaller than the deformation values for the rest of the columns. At the same time, for the group (G2), the lateral deformation values of the (C.H) and (C.E) samples were smaller than the other deformation values of the rest of the columns. The reason for this was that the location of the local external buckling was far from where the linear variable transverse differential transformer (LVDT) was installed. The results showed that the transverse deformation values for the samples with a thickness of (1 mm) were higher than their counterparts with a thickness of (2 mm). From the above, it can be seen that the cross-sectional shape of the RACFST columns did not affect the relationship between the load and the lateral displacement of the column.

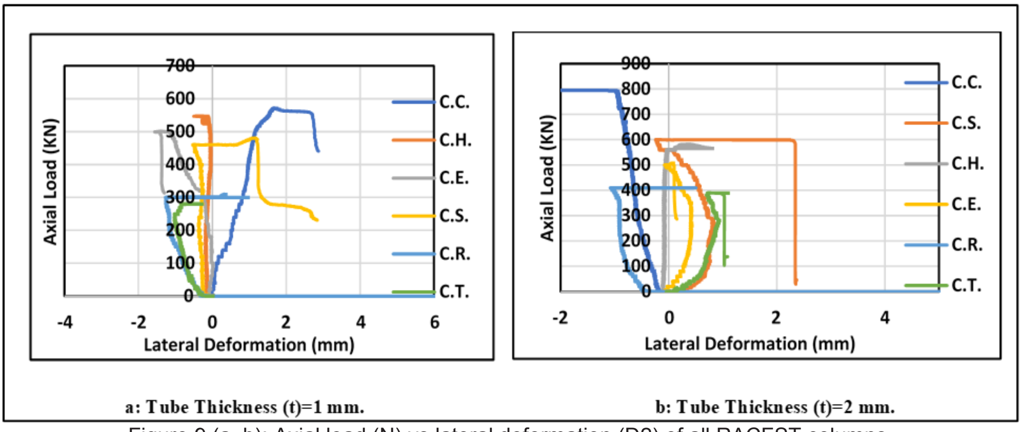


Figure 9 (a, b): Axial load (N) vs lateral deformation (D2) of all RACFST columns.

3.4 Ultimate Axial Load of RACFST Columns

Laboratory test results for all RACFST columns showed that the highest load was for the circular cross-section column. In addition, the lowest load was for the column of the triangle cross-section. All maximum axial loads were represented graphically in Figure 10 (a,b).

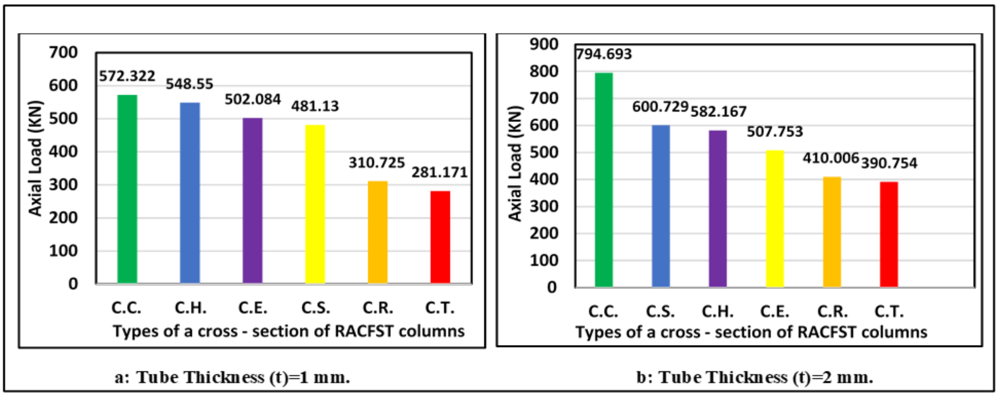


Figure 10 (a,b): Ultimate axial load of RACFST columns, tube thickness (t) =1 and 2 mm.

3.5 Effect of Section Shape on Final Failure Stress

As said previously, Sections of all RACFST were designed with approximately an equal external perimeter (P), as a result; the cross-section area of the steel tube was approximately equal for all columns. This led to a difference in the cross-section area of the concrete. Thus, it is suitable to calculate the strength for all RACFST columns by using the final failure stress that happened in each column by converting the composite section into an equivalent section of steel rather than the final failure strength. The final failure stress was calculated through the below equation [26].

$$\delta u = \frac{N}{At} \quad (1)$$

Where: $A_t = (A_s + A_c/n)$, $n = (E_s/E_c)$, N equal to the final failure axial load of RACFST columns or the highest value obtained through the experiment, (A_t) represented the area of steel equivalent to the cross-section area of each composite column, while (n) represents the modular ratio, ($n = E_s/E_c$), which equals (7.777) and depend on the properties of the materials used in this investigation. The final failure stress (δ_u) for each RACFST column was illustrated below in Figure 11 (a,b).

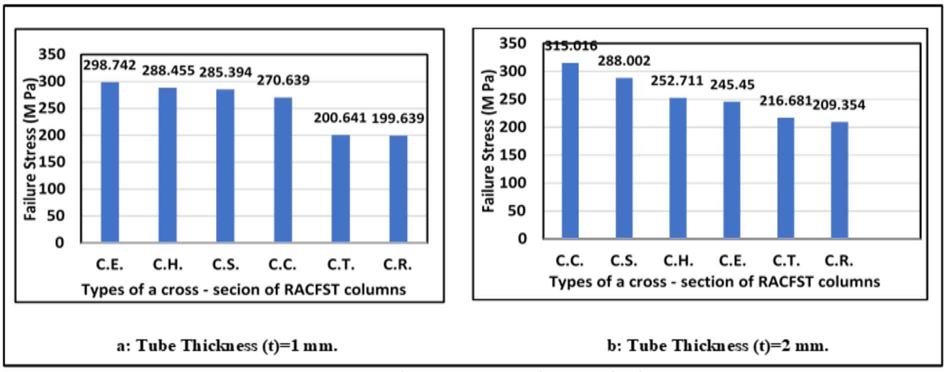


Figure 11 (a,b): Final failure stress of all RACFST columns.

In the first group(G1), with a thickness of 1 mm for steel tubes, the elliptical RACFST column showed better concrete confinement and better bond stress between steel and concrete. This behavior increased the effective compound effect in the member and thus its ability to bear greater ultimate failure stress from the other sections for columns. Conversely, the column with a rectangle section showed less ability to bear the stress compared with all columns with other sections. For the second group with a thickness of 2 mm, the results showed that the column with a circular cross-section showed the ability to bear ultimate failure stress more than all the columns with other sections. The column with a rectangle cross-section was less able to bear the stress than all columns with other sections, as shown in Figure 11(a, b).

The ultimate failure stress of the RACFST circular column showed better concrete confinement and better bond stress between the steel and concrete. This behavior increased the effective compound effect in the member and thus increased its ability to bear the maximum pressure from the concrete core. The main reason for this is that this column was made of two pieces of steel plates; the dimensions of each piece are (204 x 300) mm. The dimension (204) mm has been rotated in a half-circle shape and (300) mm in height to form half of a circular column. The same way was done for the second piece so that the circular column was manufactured after welding symmetrically from both sides along the column. This rolling process was like a pre-stress for the steel and thus gave the circular shape a greater ability to bear the stress. In addition, the circular shape could generate better confinement of the concrete section compared to column other cross-sections. The same understanding above applies to the column with an elliptical cross-section.

In the first group(G1) with a thickness of (1) mm for steel tube, Figure 11 (a, b) shows a hierarchical arrangement of the ultimate stress of RACFST columns with polygonal sections, i.e., hexagon (C.H.) has the highest ultimate stress bearing followed by a square (C.S.), a triangle (C.T.), and then rectangle (C.R). Here, the column with a triangle cross-section advanced on the column with a rectangle cross-section because of the early welding failure of the last. In the second group (G2) with a thickness of (2) mm for steel tube, the same result stayed about the hierarchical arrangement of the ultimate stress of RACFST columns with polygonal sections. Except for the column with a square cross-section, where the column was advanced with a hexagon cross-section because the first exhibited good confinement using high-strength concrete.

Thus, a distinctive pattern was observed here, with an increasing number of corners of steel plates for the model, that is mean, the greater the number of formed sides and the greater the angles between the sides are (90°) degrees or more, there was more stable and confinement for the section, respectively. For example, in the hexagonal RACFST column that showed the highest ultimate stress, the section was made with a circumference of 402 mm equally distributed on six sides with two same sections so that they were symmetrically welded along the shape. This ribbing process was like pre-stress work for the steel forming the model, allowing it to bear more significant stress. Also, the angles between both sides were 120°, which gave the shape greater ability to bear compression. This design allowed the concrete components to overlap well with the steel mold and reduced the possibility of decay or gaps between the concrete components and the steel model during pouring columns. The size of the recycled aggregate used in the concrete mix was with a gradient between 5-19 mm, and therefore, the measurement of these angles gave the column greater ability to withstand the applied compression. As for the square-section column, it had a circumference of 400 mm distributed on four sides. The width of each side was 100 mm, where the model was made of two halves in the form of (L) shape, and they were welded longitudinally and symmetrically. The same interpretation applies to all RACFST columns with polygonal sections.

3.6 Strength Index

The ratio resulting from dividing the value of the final stress of any examined column by the final stress of the circular column is called the strength index (SI) and is used to investigate compression applied. It can be computed from Equation 2 as follows [27]:

$$SI = \frac{\sigma u}{\sigma r} \quad (2)$$

where (σ_u) represented the final failure stress for a given column of RACFST columns, whereas σr represented the final stress of the circular RACFST column. The SI values of all tested RACFST columns are illustrated in Figure 12 (a, b) and are listed in Table 2. The columns with a thickness of (1) mm and the following cross-section shapes, elliptical, hexagonal, and square, have been shown higher confinement values for concrete core, respectively, from all other columns of both groups. The results showed that when the (SI) values were increased, the ultimate failure stress values for all (RACFST) columns also increased.

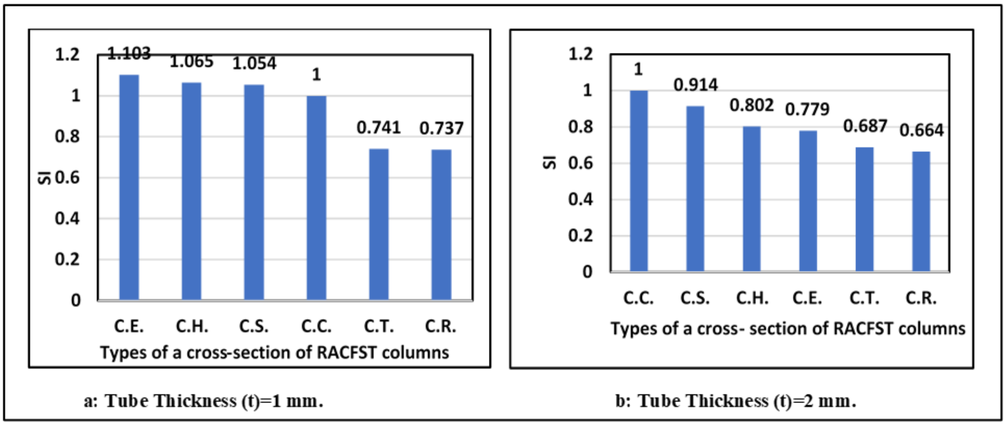


Figure 12: Strength index (SI) of all RACFST columns.

3.7 Ductility Index

Ductility is a mechanical property of a material that indicates the degree of plastic deformation, as it is considered an effective property of the material. The ductility index was defined as the ratio of the total axial shortening of a RACFST column as a result of the ultimate failure load during plastic phase loading to axial shorting up to 80% of the failure load per column, and it was defined as follows [28]. The ductility index values for all tested columns were listed in Table 2, while Figure 13 (a, b) showed a graph for these values.

$$\mathrm{DI} = \frac{\Delta u}{\Delta 80\%} \quad (3)$$

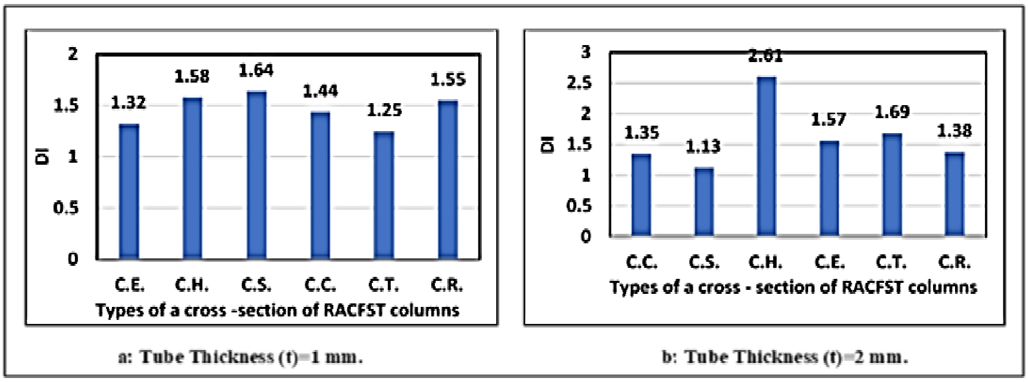


Figure 13 (a,b): Ductility index (DI) of all RACFST columns.

Regarding the first group with a thickness of 1 mm, the above figure shows that the ductility index (DI) values for all columns were close except for the column with a square cross-section, which showed a much higher value than the ductility of all other shapes. This was most likely related to the good confinement provided by the steel tube to the concrete core. During the advanced loading stages, this behavior of this sample led to multiple local buckling of the steel tube and thus increased the vertical axial deformation value. However, the RACFST column with a triangular sectional shape showed the smallest value of DI. This was related to the failure pattern of the model, which resulted from a reduced ability to withstand the failure stress. The small cross-sectional area of the concrete led to the early failure of the concrete, and thus, there was a non-development of axial vertical deformation of the model.

Regarding the second group with a thickness of 2 mm, the ductility index values for all columns were also close. Except for the column with a hexagonal cross-sectional shape, this showed a much higher value than the other columns. This was a result of increasing the thickness of steel from 1-2 mm, which led to a decrease in the percentage of the contribution of the concrete (CR) to withstand the failure pressure. After that, the continuation of loading led to the failure of the concrete by crushing. At the same time, this generated a large pressure towards the circumference of the steel tube; thus, the failure of the weld near the bottom base of the model caused an increase in the axial deformation. At the same time, the RACFST column with a square cross-sectional shape exhibited the smallest value of DI due to the symmetry of its internal ribs and angles. This symmetrical increased its ability to withstand ultimate failure stress and thus was reflected in the failure pattern. During the last stages of loading, this column exhibited local buckling deformation around the base of this sample less than the rest of the other columns. Thus, this has decreased the vertical axial deformation value.

3.8 Effect of the Thickness of the Steel Tube on:

3.8.1 Ultimate Axial Failure Load

For each column, the value of the experimental failure load was obtained. The final values are summarized in Table 2. Also, a comparison was drawn for these ultimate axial loads for steel tubes filled with recycled concrete (RACFST) using recycled coarse aggregate and for the two groups with thicknesses (1 and 2) mm, illustrated in Figure 14. As expected, the column capacity increased by increasing the thickness of the steel tube for all columns.

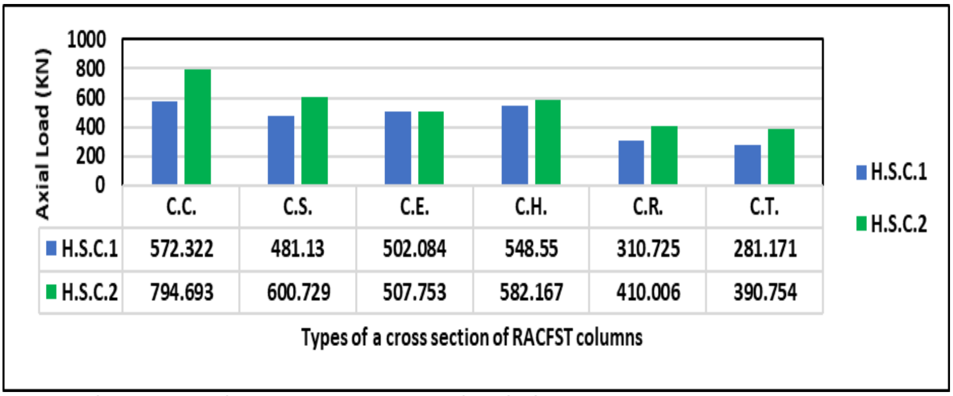


Figure 14: Comparison of the ultimate axial load of RACFST columns, tube thickness (t) = 1 and 2 mm.

3.8.2 Ultimate axial failure stress.

The experimental failure stress values obtained for all columns are listed in Table 2. These values were also compared for the two groups with 1 and 2 mm thicknesses and drawn in Figure 15. In general, the results showed a higher ability to withstand the final stresses applied to all RACFST columns with an increase in the thickness of the steel tubes from 1-2 mm, except for columns with elliptical and hexagonal sectional shapes, which showed lower capacity due to crack welding failure during the late stages of loading. This failure was due to the weak ductility of the weld. In addition, the column with a circular cross-section showed a clear superiority in withstanding the stresses applied to it compared to the rest of the columns. This behavior was due to the good confinement of concrete in this section.

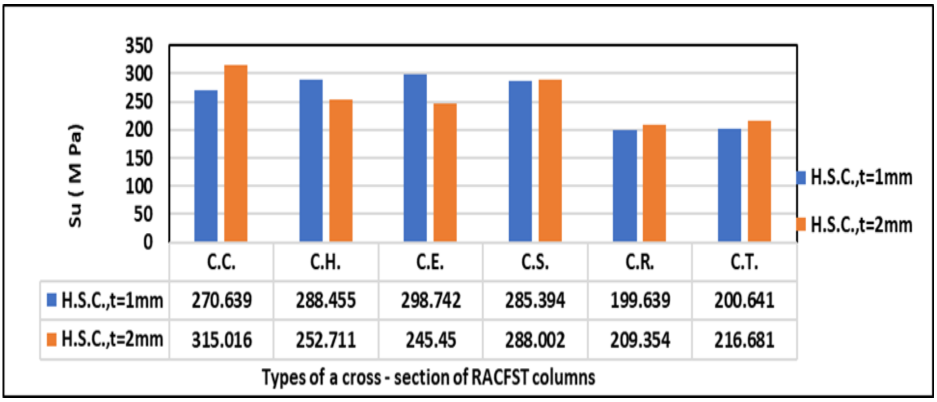


Figure 15: Comparison of the ultimate failure stress of RACFST columns, tube thickness (t)=1 and 2 mm.

3.9 Contribution Ratio of Concrete

The contribution of concrete fill for all samples was analyzed using the concrete contribution ratio (C.C.R.), which can be calculated from Equation (4).

$$\mathrm{C.C.R.} = \frac{\mathrm{Nexp.}}{\mathrm{As,eff\ .fy}} \quad (4)$$

Where Nexp. represented the practical ultimate failure load; (As eff) expresses the effective cross-sectional area of the steel tube as stated by the Eurocode 3 model, and fy represents the steel tube yield strength [28]. The values of this indicator (C.C.R) were calculated for each column, and their values are recorded in Table 2 for both groups. The results that have been obtained support what was noted for the failure load. As expected, the (C.C.R.) of 2mm steel tubes decreases as a result of the practical increase in the cross-sectional area of the steel. Data in Table 2 shows that in the triangular columns of RACFST thin-walled steel tubes with a thickness of 1 mm, the (C.C.R) values were lowest. In general, for the two groups with a thickness of 1 and 2 mm, the results showed that the higher values of (C.C.R) led to an increase in the values of (S.I.). This increase is accompanied by an increase in the values of ultimate failure stresses for all specimens. However, by comparing the columns for the same sections, it was found that when the thickness of the steel tube increased, this led to a decrease in the values of (C.C.R) due to the increase in the cross-section area for the steel tube.

4. CONCLUSIONS

This manuscript showed an experimental study of the behavior of twelve recycled aggregate concrete-filled steel tubular (RACFST) short columns under concentric axial loads. Two groups of thin-walled steel tubes (1 and 2) mm thick for different shapes of cross-sections were studied. High-strength concrete (H.S.C.) was used as a filling material in all hollow steel tubes. Depending on the analysis of the data obtained from the investigational work of this study, the observing conclusions below were obtained.

- The failure behavior for the tested RACFST short columns was relatively ductile. Capillary cracks and then crushing and lateral expansion of the recycled concrete core. Continuing the loading, outward local buckling occurred near the middle of the RACFST column. At the last steps of applied loading, more outward local buckling happened nearby from the top and bottom edges of the tested columns.
- The cross-sectional shape of the RACFST column clearly influences the failure patterns in the tested samples. The failure patterns of some columns with polygonal cross-sections, such as hexagonal and rectangular, differed slightly from those of columns with circular or elliptical sections. Besides, the behavior of failure patterns for RACFST columns with square and triangular cross-sections was not similar to the remaining shapes.
- The cross-sectional shape of the RACFST columns did not distinctly affect the relationship of the (load-lateral displacement) of the column. On the other hand, the results showed that the transverse deformation values for the samples with a thickness of 1 mm were higher than their counterparts with a thickness of 2 mm.
- Regarding both groups (G1 and G2) with steel plate thickness (1 and 2) mm, RACFST elliptical and circular columns, respectively, showed better stability and confinement of concrete and the ability to withstand greater final failure stress. Thus, these shapes can create better confinement of the concrete section compared to other column sections.
- Regardless of some results related to some columns. It can be said that all tested RACFST columns with polygonal sections showed when the number of ribs for the steel plates of the model or the angle between the two sides is 90° or more, column cross-section can achieve more stability and confinement, respectively.
- In general, the results showed a higher ability to withstand the final stresses applied to all RACFST columns with an increase in the thickness of the steel tubes from 1 to 2 mm, except for columns with elliptical and hexagonal sectional shapes, which showed lower capacity due to crack welding failure during the late stages of loading. This failure was due to the weak ductility of the weld.
- When the thickness of the steel tube increased, this led to a decrease in the values of (C.C.R) due to the increase in the cross-section area for the steel tube.
- In general, for all RACFST columns with a thickness of 1 and 2 mm, the results showed that the higher values of (C.C.R) led to an increase in the values of (S.I.). This increase is accompanied by an increase in the values of ultimate failure stresses for all specimens.
- The SI values of 1 mm thick RACFST columns with elliptical, hexagonal, and square-shaped cross-sections showed a high confinement effect, respectively. This led to a higher ability to withstand the final failure stresses applied to these sections, which exceeded the values of the circular column.

REFERENCES

[1] Han LH, Li W, Bjorhovde R. Developments and advanced applications of concrete-filled steel tubular (CFST) structures: Members. J Constr Steel Res. 2014; 100(1):211–228.
[2] Han LH, An YF. Performance of concrete-encased CFST stub columns under axial compression. J Constr Steel Res [Internet]. 2014; 93(1):62–76.
[3] Ekmekyapar T, Al-eliwi BJM. Thin-Walled Structures Experimental behaviour of circular concrete fi lled steel tube columns and design speci fi cations. Thin Walled Struct [Internet]. 2016; 105:220–230.
[4] Hassanein MF, Patel VI, Bock M. Behaviour and design of hexagonal concrete-filled steel tubular short columns under axial compression. Engineering Structures. 2017 Dec 15;153:732-48.
[5] Lai MH, Ho JCM. An analysis-based model for axially loaded circular CFST columns. Thin-Walled Struct. 2017;119(1):770–781.
[6] Ibañez C, Hernández-figueirido D, Piquer A. Shape effect on axially loaded high strength CFST stub columns. J Constr Steel Res [Internet]. 2018; 147(1):247–256.
[7] IBÁÑEZ USACH, Carmen; HERNÁNDEZ-FIGUEIRIDO, David; PIQUER VICENT, Ana. Influence of steel tube thickness and concrete strength on the axial capacity of stub CFST columns. In: Proceedings of the 12th International Conference on Advances in Steel-Concrete Composite Structures. ASCCS. Editorial Universitat Politècnica de València. 2018.
[8] He L, Lin S, Jiang H. Confinement Effect of Concrete-Filled Steel Tube Columns with Infill Concrete of Different Strength Grades. Frontiers in materials. 2019; 6(April):1–9.
[9] Ilanthalir A, Jerlin Regin J, Maheswaran J. Concrete-filled steel tube columns of different cross-sectional shapes under axial compression: A review. IOP Conf Ser Mater Sci Eng. 2020;983(1).

[10] Ahmed M, Liang QQ. Numerical modeling of octagonal concrete-filled steel tubular short columns accounting for confinement effects. Eng Struct [Internet]. 2021; 226(1):111405.
[11] Chen Z, Xu J, Xue J, Su Y. Performance and calculations of recycled aggregate concrete-filled steel tubular (RACFST) short columns under axial compression. Int J Steel Struct. 2014;14(1):31–42.
[12] Chen Z, Xu J, Chen Y, Lui EM. Recycling and reuse of construction and demolition waste in concrete-filled steel tubes: A review. Constr Build Mater [Internet]. 2016; 126(1):641–660.
[13] Safiuddin M, Alengaram UJ, Rahman MM, Salam MA, Jumaat MZ. Use of recycled concrete aggregate in concrete: A review. J Civ Eng Manag [Internet]. 2013;19(6):796–810.
[14] Wang Y, Chen J, Geng Y. Testing and analysis of axially loaded normal-strength recycled aggregate concrete filled steel tubular stub columns. Engineering structures. 2015; 86:192–212.
[15] Lyu WQ, Han LH, Hou C. Axial compressive behaviour and design calculations on recycled aggregate concrete-filled steel tubular (RAC-FST) stub columns. Eng Struct [Internet]. 2021; 241(1):112452.
[16] Azevedo S De, Lima LRO De, Pedro CG, Vellasco S, Maria E, Tavares N, et al. Experimental investigation on recycled aggregate concrete filled steel tubular stub columns under axial compression. J Constr Steel Res [Internet]. 2021; 187(1):106930.
[17] Yang YF, Han LH. Experimental behaviour of recycled aggregate concrete filled steel tubular columns. J Constr Steel Res. 2006; 62(12):1310–1324.
[18] Yang YF, Man LH. Compressive and flexural behaviour of recycled aggregate concrete filled steel tubes (RACFST) under short-term loadings. Steel Compos Struct. 2006; 6(3):257–284.
[19] Chen ZP, Chen XH, Ke XJ, Xue JY. Experimental study on the mechanical behavior of recycled aggregate coarse concrete-filled square steel tube column. Int. Conf. Mech. Autom. Control Eng MACE. 2010.
[20] Li W, Xiao J, Shi C, Poon CS. Structural behaviour of composite members with recycled aggregate concrete - An overview. Adv Struct Eng [Internet]. 2015; 18(6):919–938. Available from: https://doi.org/10.1260/1369-4332.18.6.919
[21] Niu HC, Cao WL. Full-scale testing of high-strength RACFST columns subjected to axial compression. Mag Concr Res. 2015; 67(5):257–270.
[22] Yang D, Liu F, Wang Y. Axial compression behaviour of rectangular recycled aggregate concrete-filled steel tubular stub columns. J Constr Steel Res. 2023; 201(1).
[23] ALNEBHAN, Kareem Mohammed; SHALLAL, Muhaned A. Effect of filling steel tube chords by concrete on the structural behavior of composite truss girders. Al-Qadisiyah J. Eng. Sci. 2020; 13(1): 167-174.
[24] Abbas AW. Reactive Powder Concrete- Filled Double Skin Tubular Column Subjected to Repeated Loading. 2021.
[25] Scalas A, Yoshida N, Roeder CW, Lehman DE, Bishop E, Ilanthalir A, et al. Concrete-Filled Steel Tube Arch Bridges in China. Thin-Walled Struct [Internet]. 2018; 129(1):143–155.
[26] Ren Q, Han L, Lam D, Hou C. Experiments on special-shaped CFST stub columns under axial compression. JCSR [Internet]. 2014; 98(1): 123–133. Available from: http://dx.doi.org/10.1016/j.jcsr.
[27] Han LH, Ren QX, Li W. Tests on inclined, tapered and STS concrete-filled steel tubular (CFST) stub columns. J Constr Steel Res [Internet]. 2010; 66(10): 1186–1195. Available from: http://dx.doi.org/10.1016/j.jcsr.
[28] Jain S, Chellapandian M, Prakash SS. Emergency repair of severely damaged reinforced concrete column elements under axial compression: An experimental study. Constr Build Mater [Internet]. 2017; 155(1): 751–761. Available from: https://doi.org/10.1016/j.