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† Research Paper

Structural behavior of square double skin self-compacting concrete columns incorporating recycled aggregate

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ABSTRACT

Construction and demolition waste is recognized as a major waste stream made by humans around the world. The use of crushed old concrete in a type of recycled aggregate concrete (RAC) has been a promising technique to promote construction sustainability. However, the mechanical behaviors and the durability of RAC are inferior to those of concrete incorporating natural aggregate. Therefore, the creation of effective methods to lessen these harmful consequences is crucial. It stands to reason that the dilatation of concrete can be restricted by placing it in a confinement state. Due to the confinement provided by the steel casing, a steel tube filled with concrete can be considered suitable for improving the working mechanism of the RAC. In this paper, a series of comparison tests were conducted to investigate the behavior of square double skin steel tubes filled with self-compacting concrete (SCFDST) columns under different loading conditions. Ten specimens consisting of five normal SCFDST and five recycled aggregate self-compacting concrete filled double skin steel tube (RSCFDST) columns were tested under (axial, uniaxial, and biaxial) compression loads. Loading eccentricity and full replacement of coarse aggregate were adopted as the main parameters in the experiments. Overall, the failure mode, ultimate capacities, and general deformational behavior have been presented in this paper. According to the results, comparable structural behavior and failure shapes were observed between the RSCFDST columns and their normal SCFDST counterparts with an acceptable reduction in ultimate bearing capacity. The ultimate bearing capacity of both RSCFDST and conventional SCFDST are significantly harmed by eccentricity, while the ductility of the columns was improved by the RAC replacement. The failure mode of normal SCFDST and RSCFDST columns was overall buckling under a uniaxial and biaxial compression load, whereas compression failure was the failure mode of the axially loaded columns. As expected, due to the confinement effect of the steel tubes, the strength of the sandwich concrete was enhanced, and all tested columns exhibited ductile failure.

1. Introduction

Steel-concrete composite is used in structures to maintain the benefits of both steel and concrete. Recent decades have seen great development in composite construction, steel-concrete composite columns have been used in structures to maintain the benefits of both steel and concrete to provide better performance in terms of high capacity, favorable ductility, fire resistance, and large energy absorption capacity which outperforms the traditional reinforced concrete structures Many buildings and bridges use composite systems in their construction, in addition to the superior structural performance that makes them very popular with many architects and civilians, they not only provide simple and efficient technical solutions but are also highly desirable for aesthetic reasons and their ease of implementation and resistance to external environmental factors, also they provide economic solutions at a limited cost [1]. Concrete filled steel tube (CFST) column system is one of the most effective composite column systems available. In recent years, the design of concrete columns has increasingly made use of various types of composite material systems to improve high strength, stiffness, ductility, and seismic resistance performance. Some of these composite columns include steel tubes filled with concrete, partially encased steel sections, and fully encased steel sections. One of the most efficient composite column systems available is the CFST column system, which is an example of a successful system that combines the benefits of many materials [2]. Concrete-filled double skin steel tube (CFDST) members are an advanced type of CFST obtained by substituting an inner steel tube with a significantly lower cross-sectional area for the middle concrete. The strength of columns is improved significantly, and as a result of the inner tube's lateral expansion during compression, greater confining pressure is applied to the concrete [3]. CFDST columns are composed of sandwich-shaped concrete that is poured between inner and exterior steel tubes. Due to the interplay between the inner and outer steel tubes, the sandwich concrete is subject to stress from three directions. Due to the existence of concrete, Steel tubes local buckling can be delayed or prevented, so their circumferential tensile behavior can be adequately displayed. More quickly than in standard CFST columns, the axial compression bearing capacity, ductility, and seismic performance all increased [4]. The CFDST column is a high-performance column that is used in bridge piers and high-rise composite constructions to carry a significant axial load. An existing CFST column can be strengthened by adding an outside steel tube, which, to make a CFDST column, is filled with either high-strength or conventional concrete [5]. Due to the city's rapid growth and renovation, concrete waste is created in enormous amounts.

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Nomenclature			
ASTM	Interfacial Shear Strength	*SCC*	Kurtosis
EFNARC	Styrene-Butadiene-Styrene	*SCFDST*	Root Mean Square Slope
CFDST	Polylactic Acid	*SP*	Developed Interfacial Area Ratio
CFST	Mean Texture Depth	*Abbreviations*	
kN	Three-Dimensional	*Dr*	Horizontal Projected Area
MPa	Hot Mix Asphalt	*fcu*	Degree Of Curvature
NSCC	Nominal Maximum Aggregate Size	*fsu*	Spatial Surface Area
RA	Asphalt Content	*fsy*	State Corporation For Roads And Bridges
RAC	Volume Of Sand	*ex*	Cationic rapid setting emulsion
RSCFDST	Total Material-Covered Surface Area	*ey*	Cationic slow setting -hard asphalt
RSCC	Arithmetic Mean Height	*w/c*	Rapid curing cut back at viscosity 70

When the old concrete is crushed and recycled, coarse aggregate is utilized to make new concrete, then fewer natural resources are needed, hence even lessening the requirement to dispose of excess concrete in landfills [6,7]. Recently, recycled aggregate concrete, also known as Sustainable concrete, has drawn more attention from academics and researchers. It may be utilized in place of natural aggregate concrete that consumes a significant number of natural resources; it has grown to be a major problem worldwide. Despite the apparent environmental benefits, there are few applications for recycled aggregate (RA) in construction. Owing to its inferior properties, such as plasticity, strength, modulus of elasticity, salient drying shrinkage and creep, and other distinct properties from those of natural aggregates especially in shape, texture absorption capacity specific gravity, and abrasion resistance in addition to its poor strength and considerable short and long-term deformations, which are mostly caused by the residual mortar that is linked to the RA, the use of RAC in constructions is restricted, also when RA is obtained from several sources, notably, the addition of RCA enhances the scatter of the compressive strength of RAC [8]. However, due to the confinement effects, encasing recycled aggregate concrete in a steel tube can boost its compressive strength, and meanwhile, shrinkage and creep are reduced because of the sealed environment produced by the outer steel tube [9,10]. Thus, the many issues with using RAC structurally are intended to be resolved by using steel tubes filled with concrete [11]. In practical applications, flaws like voids and holes may emerge when the CFST columns are being poured. Self-compacting concrete (SCC) is a type of concrete that may flow thickly and be filled with formwork without flocculation, seepage, segregation, or vibration tools when only its weight is applied. In CFST structures and other contemporary engineering constructions, SCC is primarily utilized due to the compactness, fluidity, and simplicity of manufacture and pouring [12]. Recycled self- compacting concrete (RSCC) is a type of SCC that incorporates RA that not only reaps the rewards of SCC but also properly discards any leftover concrete [13, 14]. Owing to the widespread usage of CFDST columns in the construction of high-rise structures, factories, and bridges in the modern era, many studies have been conducted to comprehend the strength and behavior of CFDST columns, and numerous experiments on CFDST columns have been undertaken. Yang and Zhu [15] studied 13 round steel tubes filled with recycled aggregate concrete (RACFST) that underwent the hysteretic behavior test. The research showed that the hysteretic behavior of the RACFST column was comparable to that of the CFST column; additionally, it possessed excellent deformation, energy dissipation, and bearing capacities. To calculate the multi-skin steel tube's slenderness ratio when filled with concrete, Salim, N. M., and Al-Khekany [16] tested fifty-five axially loaded columns of various heights. The results revealed that the slender limit decreases with a reduction in the number of steel layers and a reduction in column dimensions. E. K. Mohanraj [17] conducted a test to measure the axial response of round and square-section RACFST columns. The effects of concrete confinement, steel tube diameters, and forms were investigated, and it was figured out if the current design specifications for CFST columns applied to RACFST columns. Tests on RACFST columns loaded eccentrically were conducted by Chen et al. [18], and results detect that overall buckling was the failure shape for RACFST and normal CFST columns. The bearing capacity of RACFST and CFST columns reduced as the eccentricity or length-diameter ratio increased. Tang et al. [19] and Xu et al. [20] investigated the seismic behavior of the RACFST columns. According to test results, the seismic behaviors of the RACFST columns were similar to those of the equivalent conventional CFST columns, allowing for the use of RACFST columns in seismic areas. WU, Zhanjiang, et al. [21] presented the experimental research on 37 square steel tubes filled with recycled aggregate concrete stub columns that encountered a variety of temperatures. The influence of the RAC ratio, heating temperature, and cooling technique of recovered aggregate can be taken into account via a simple formula for estimating residual bearing capacity. D.S. Castanheira et al. [22] Eight circular, double-skin, concrete-filled tubular columns with stainless steel outer tubes were fabricated with two types of concrete (normal and RAC) and evaluated under axial compression loads. The results revealed that the RACFDST columns can achieve similar capacities to those of normal CFDST. Because it offers less confinement and a steel tube filled with concrete is mostly constrained at the corner, a square steel tube might not perform as well as a circular one. It is simple for local buckling to occur in the square steel tube. However, numerous theoretical and experimental studies on circular RACFST members have been conducted, while a few studies investigated the structural behaviors of square RACFST members. However, the behavior of RACFDST columns under concentric and eccentric loading has not yet been examined, as this point has been focused on in this study, an experimental comparison program was performed on ten SCFDST columns, which were tested under different loading conditions. Loading eccentricity and full replacement of natural coarse aggregate with recycled coarse aggregate were adopted as the main parameters in this study.

2. Experiment

2.1 Properties of materials

One type of steel tube was used to fabricate all specimens. Three coupons were cut from the flat portion of the square steel tube to perform the Standard tensile Coupon tests to measure the material qualities of the steel tubes. Yielding strength (fsy) and tensile strength (fsu) are depicted in Table 1. According to European guidelines of mix proportions selection (EFNARC) [23], two types of SCC concrete mixes were prepared and used, the first one with normal aggregate (NSCC) whereas the second had full replacement of natural coarse aggregate with recycled aggregate (RSCC). To keep the quantities of fine materials (cement and limestone powder), water, and fine aggregates constant in each SCC mix, the replacement process was volumetrically performed with consideration of the specific gravity of the used aggregates. To make the concrete more workable and ensure that freshly laid concrete can consolidate under its weight, a superplasticizer (SP) was added to both mixes, a quantity representing 0.12% of the cement weight was selected as specified in the design guide. The concrete was designed to achieve a compressive cube strength (fcu) of approximately 35 MPa at 28 days of curing. NSCC and RSCC reached average compressive cubic strengths (fcu) of 36.8 and 31.6 MPa, respectively. As shown in Fig. 1, to determine whether concrete is SCC, some tests like the slump flow, time of flow, and V-funnel test were carried out to evaluate the concrete's flow. The properties of the fresh concrete and the proportion of mixes are summarized in Table 2 and Table 3.

2.2 Preparations of Specimens

A total of ten SCFDST square cross-section columns, consisting of five utilizing conventional SCC and five with recycled aggregate self-compacting concrete, were designed and fabricated with a height of 1000 mm and a length of 101.8 mm for the outer side of the outer square steel tube and 50.8mm for the inner one. As shown in Fig. 2, each column consists of double layers of steel with a thickness of 2.2 mm for each steel layer. The space between the double layers is filled with two types of SCC. In the preparation of the test specimens, inner tubes were placed in the centre of the outer tube and confirmed by strips with a thickness of 2.2 mm welded to the ends of the tubes. The tubes are left partially open to allow the concrete to pour. In order to assure proper comparison among the analysed parameters, all other geometrical parameters, such as section dimensions, the height of specimens, and the ratio of length to the external dimension of specimens, were kept constant. The details of the test columns are listed in Table 4, (The specimen is labelled as follows: First letter S for square section and next 2 digits, 00 for normal aggregate and 10 for % RCA, second letter (E) for eccentricity, and the next 2 digits for x, y directions, respectively. e_x, e_y is the eccentricity of load in x, y directions. For example, $E20$ indicates that the eccentricity distance is equal ($2B$) in the x direction and no eccentricity in y direction, where B is the outer dimension of the specimen.

Table 1. Slump flow-T500 and V-funnel tests.

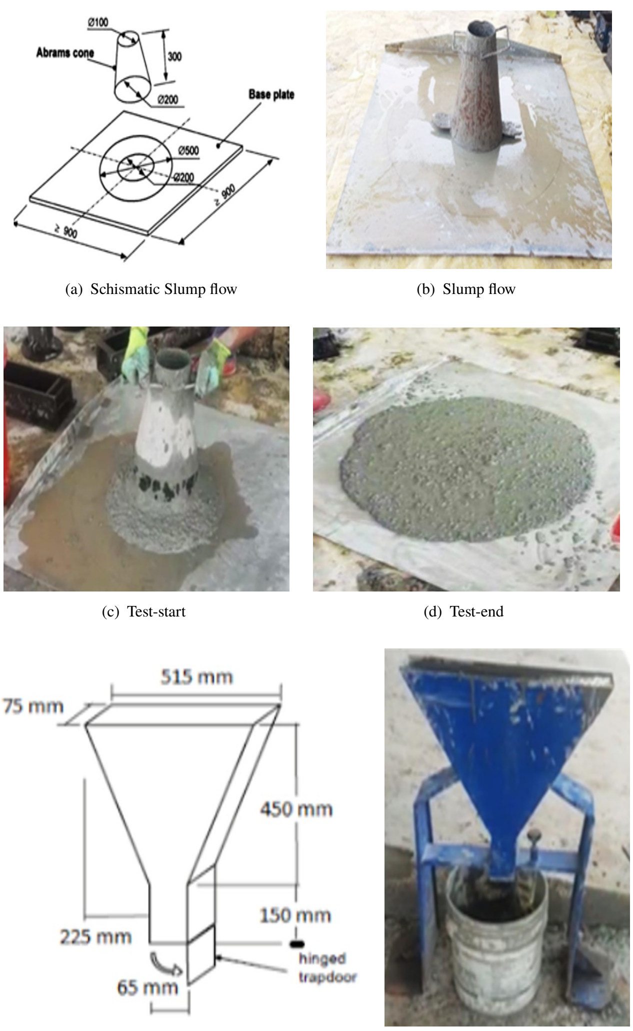
Plate thickness (*mm*)	Yield strength fsy (MPa)	Ultimate strength fsu (MPa)	Limit according to ASTM-A370	
			Yield Stress (Grade b) fsy (MPa)	Yield Stress (Grade b) fsu (MPa)
2.2	390.2	440	315	400

Table 2. Properties of the fresh concrete.

Mix Notation	Slump flow		V-funnel
	Spread, mm	T500, sec	*sec*
NSCC	725	3	5.1
RSCC	670	3.5	5.8

Table 3. Slump flow-T500 and V-funnel tests.

Mix Notation	Cement kg/m3	Coarse aggregate kg/m3	Fine aggregate kg/m3	Lime stone kg/m3	w/c ratio	SP	Water kg/m3
NSCC	400	840	640	160	0.47	0.12	175
RSCC	400	807	640	160	0.47	0.12	175



(a) Schismatic Slump flow (b) Slump flow

(c) Test-start (d) Test-end

(e) Schismatic funnel test (f) Funnel test

Figure 1. Slump flow-T500 and V-funnel tests.

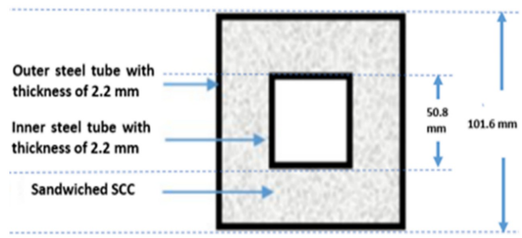


Figure 2. Framework for this study.

Table 4. Details of specimens and materials summary.

Groups	Specimens	fcu (MPa)	RA% replacement	Applied load type
Group-1	S00E00	36.8	0	Axial
	S10E00	31.6	100	Axial
Group-2	S00E10	36.8	0	Uniaxial
	S10E10	31.6	100	Uniaxial
	S00E20	36.8	0	Uniaxial
	S10E20	31.6	100	Uniaxial
Group-3	S00E11	36.8	0	Biaxial
	S10E11	31.6	100	Biaxial
	S00E22	36.8	0	Biaxial
	S10E22	31.6	100	Biaxial

2.3 Test Setup and Loading Scheme

The hydraulic test machine with a capacity of 2500 kN was used to test all specimens used in this study. This machine includes a hydraulic actuator, a load cell, and a plate to apply the load. The load cell readings were connected to the data logger. The schematic drawing of the test is shown in Fig. 3. Five digital dial gauges were attached to measure the axial shortening and the out-of-plane deflections. Two perpendicular dial gauges were placed at the mid–height and two perpendicular dial gauges at the top quarter, also one was fixed to the base plate. A total of ten SCFDST columns, including five RSCFDST were tested under axial, uniaxial, and biaxial loading conditions. Specimens were divided into three main groups, namely Group-1, Group-2, and Group-3. Group-1 consists of two specimens, one RSCFDST one SCFDST column, and the other two groups, each one consisting of two normal SCFDST columns and two RSCFDST columns, making four total. An axial compression was applied in the center of the columns of Group-1, a uniaxial eccentric force was applied at distances of 100 and 200 *mm* on the Group-2 specimens, and the biaxial eccentric projection force at distances of 142 and 284 *mm* on the columns of Group-3.

Figure 3. Framework for this study.

3. Results and Discussion

In this discussion, the performance of the tested columns was assessed in terms of failure mode, load- displacement response, and ultimate capacity.

3.1 Failure modes

According to the test program, ten test specimens in all were divided (according to the load type) into three groups and loaded under three different loading conditions. According to the results, comparable structural behaviour and failure shapes were observed between the RSCFDST columns and their normal SCFDST counterparts. Generally, the failure mode of normal SCFDST and RSCFDST columns was overall buckling under uniaxial and biaxial loading conditions, whereas compression failure was the failure mode of the axially loaded specimens. As presented in Fig. 4a, the failure mode of the axially loaded specimens is a typical compression failure without any overall buckling or influence by the second-order effect. The deformation increased gradually with the increase in load at the initial stage. As reaching its bearing capacity, outward bulges and other local deformations started appearing along the outer steel tube, with the crashing of the concrete at the end faces of columns without noticing any lateral deflection. It was amply demonstrated that the concrete was crushed at the steel tubes' outward buckling locations, showing that the steel tubular bulges were primarily brought on by the lateral extrusion forces between the steel and concrete. According to the results, the failure modes of the normal SCFDST columns were virtually the same as those of the RSCFDST columns. Fig. 4b and Fig. 4c show the failure modes of uniaxially and bi-axially loaded columns. All specimens exhibited an overall buckling failure mode at the mid-height section after reaching the ultimate strength. No signs of local buckling appeared on the surface of the steel tube even after reaching the ultimate strength. By continuing to apply load after failure, outward buckling deformations were observed near the top end of uniaxially loaded columns, while no signs of local buckling appeared on the columns under biaxial load. This indicates that the specimens under biaxial compression show more ductility and a good deformation performance. With an increase in load eccentricity, the lateral displacement that corresponds to the ultimate load rises. As a result, it is evident that the specimens with higher load eccentricity exhibit more ductility. This may be explained by the composite action between the steel tube and core concrete, which can sustain the concrete in an active way even after crushing and improves the performance of such types of composite columns. The ultimate bearing capacity for each specimen and the drop percentage (Dr%) in the ultimate bearing capacity of each RSCFDST column compared to the normal SCFDST counterpart are presented in Table 5.

(a) Group 1

(b) Group 2

(c) Group 3

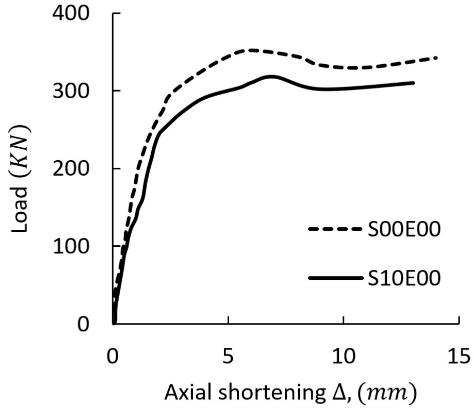
Figure 4. Failure modes.

Table 5. Details of specimens and materials summary.

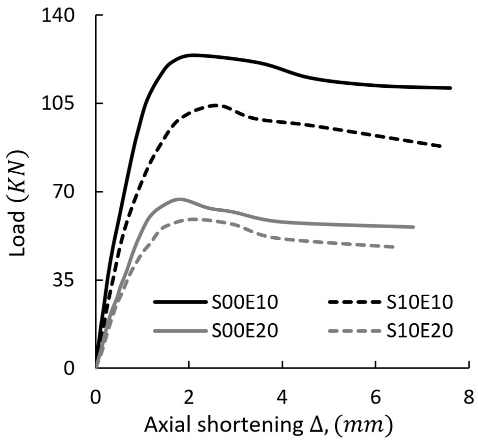
Specimen ID	Replacement ratio of RA%	e_x (*mm*)	e_y (*mm*)	e_u (*mm*)	Max load (*kN*)	Dr %
S00E00	00	00	00	000	352	00.00
S10E00	100	00	000	0	318	09.65
S00E10	00	100	00	100	124	00.00
S10E10	100	100	00	100	104	16.10
S00E20	00	200	00	200	067	00.00
S10E20	100	200	00	200	059	11.90
S00E11	00	100	100	142	083	00.00
S10E11	100	100	100	142	072	13.25
S00E22	00	200	200	284	050	00.00
S10E22	100	200	200	284	045	10.00

3.2 Load-end shortening responses

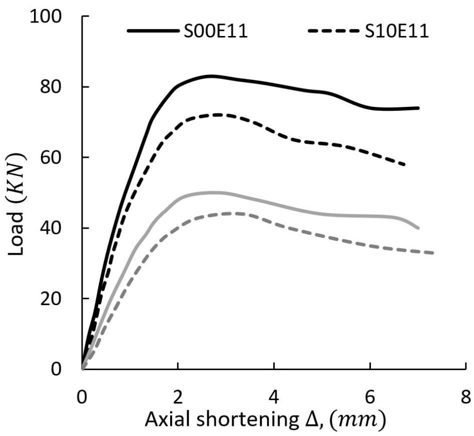
Load vs axial shortening δ) responses of the tested specimens are illustrated in Fig. 5, it shows that the ultimate bearing capacity of the RSCFDST is lower than that of the corresponding SCFDST columns, and generally, RSCFDST columns undergo higher deformation. For axially loaded columns, as shown in Fig. 5a, the shape of the load versus axial displacement curves is almost entirely unaffected by the type of coarse aggregate, and the ultimate strengths of the RSCFDST columns are marginally lower than those of the corresponding SCFDST column. From the comparisons of the load-axial displacement curves presented Fig. 5b and Fig. 5c, compared to their counterparts, the eccentrically loaded RSCFDST columns underwent a comparable increase in the axial distortion and an acceptable difference in terms of ultimate bearing capacity. It can be shown that the axial ductility and ultimate strength of the normal SCFDST column are marginally higher than those of the RSCFDST columns.



(a) Under axial compression



(b) Under uniaxial compression

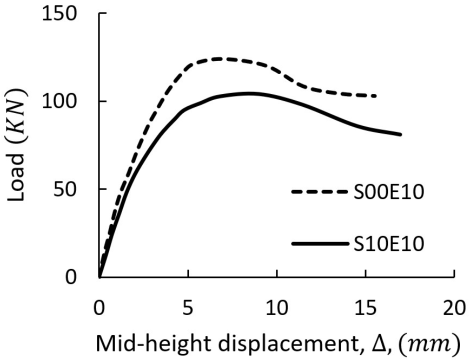


(c) Under biaxial compression

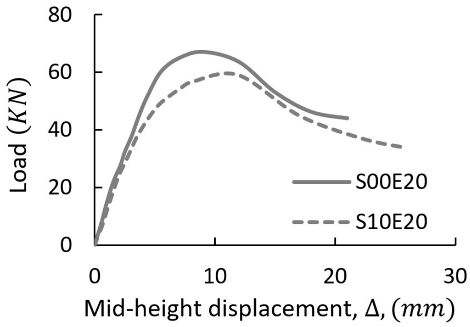
Figure 5. The applied load-end shortening (δ) responses.

3.3 load-lateral deflection responses

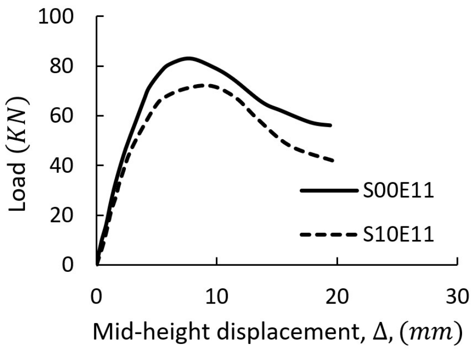
Two perpendicular dial gauges at the mid-height of columns were used to register the lateral deflection in two directions. The mid-height lateral deflection was calculated as a resultant (Δ) between the two perpendicular deflections:Δx (deflection along the x-axis) and Δy (deflection along the y-axis), where $\Delta = \sqrt{\Delta x^2 + \Delta y^2}$. Load-lateral deflection relationship curves at the mid-height are shown in Fig. 6. In general, the relation between the load and the lateral deflection for all RSCFDST and normal SCFDST columns under eccentric load consists of three phases: the first part is a linear phase and, in this phase, the steel tube and concrete core behave flexibly, the second phase represents the non-linear transition phase between the linear phase and the third phase which is the softening phase. In the linear elastic phase, the applied load increases linearly with increasing lateral deflection until the load reaches approximately 70% of the final load. Then, after entering the plastic phase, the curve deviates from the linearity stage and decreases to the peak load. After the peak load, the load gradually decreases as the lateral deflection continues to increase.



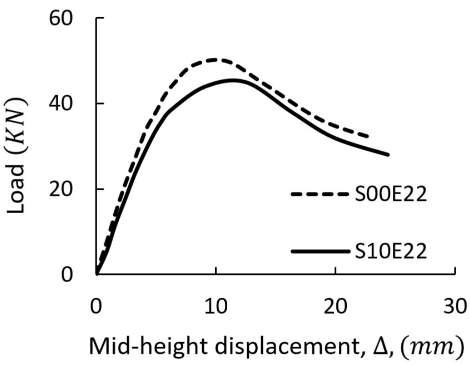
(a) Test-01



(b) Test-02



(c) Test-03



(d) Test-04

Figure 6. The applied load-end shortening (δ) responses.

According to the shape of the curves, it is evident that as the load eccentricity grows, so does the lateral displacement that corresponds to the ultimate load. This indicates that specimens with greater load eccentricity exhibit more ductility, while the effect of the presence of RA and the rate of reduction in the ultimate bearing capacity becomes less as the loading eccentricity increases.

4. Conclusion

A series of comparison tests was conducted to investigate the behavior of square double skin steel tube filled with self-compacting concrete columns under different loading conditions. Loading eccentricity and full replacement of coarse aggregate were adopted as the main parameters in the experiments. The main conclusions are as follows:

- The overall buckling failure shape was present in all eccentrically loaded columns, while the compression failure mode was seen in specimens under axial compression.
- the ultimate load of the RSCFDST column under axial loading decreased by only 9.65% lower than their corresponding NSCFDST column, which can be attributed to the lower strength of recycled aggregate concrete as compared to normal concrete.
- When compared to SCFDST columns, RSCFDST columns have somewhat lower but equivalent ultimate capacity. The range of these declines was between (9.65% - 16.1%).
- The lateral displacement that corresponds to the ultimate load rises as load eccentricity increases. Therefore, it is possible to conclude that specimens with larger load eccentricity exhibit better bending ductility. This proves the composite action between the steel tube and core concrete, which can sustain the concrete in an active way even after crushing, and improves the performance of such types of composite columns.
- The axial shortening responses showed a slight decrease in the axial load at the post-peak region, which points to acceptable axial ductility performance for the SCFDST and RSCFDST columns and indicates that SCC with RA can provide stiffness to the steel tubes comparable to SCC without RA.
- The ultimate bearing capacity and deformation capacities of both RSCFDST and conventional SCFDST are significantly harmed by eccentricity. Without regard to the type of eccentric loading, the bearing capacity drops in direct proportion to the rise in eccentricity.
- Load vs lateral deflection for all RSCFDST and normal SCFDST columns under eccentric load consists of three phases: elastic, elastoplastic, and descending phase.
- Under eccentric compression loads, all columns exhibit good ductility behavior, and the rate of reduction in the ultimate bearing capacity becomes less as the loading eccentricity increases.

Authors' contribution

All authors contributed equally to the preparation of this article.

Declaration of competing interest

The authors declare no conflicts of interest.

Funding source

This study didn't receive any specific funds.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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