A Comparative Study on Strength Behaviour of Circular and Square Hybrid FRP Concrete Steel Double Skin Tubular Columns under Axial Cyclic Loading

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Abstract - *Composite columns have been widely used in the construction industry mainly due to its high strength, durability, ease of construction and cost saving. Hybrid FRP Concrete Steel Double Skin Columns (Hybrid DSTC's) are newly developed composite column which combines the structural properties and advantages of FRP, steel and concrete. Hybrid DSTC's composed of inner steel tube, outer FRP tube and concrete is filled between the tubes. Two tubes in hybrid DSTC's are concentrically placed to produce a section form more suitable for columns. The Hybrid DSTC's possess excellent ductility hence they are well suited for seismic regions. Thus behaviour of Hybrid DSTC's under axial cyclic loading is of great importance. This paper focuses on numerically comparing the strength behaviour of circular and square Hybrid DSTC's under axial cyclic loading using ANSYS 16.2 WORKBENCH software. The effect of parameters such as void ratio, steel tube thickness, different FRP's and H/t_c ratio on both circular and square Hybrid DSTC's were also investigated.*

***Key Words*: ANSYS 16.2 WORKBENCH, Hybrid DSTC's, FRP, Ductility, Void ratio, H/tc ratio.**

1. INTRODUCTION

In construction industry now a days various technologies are used for construction methods, materials etc. In case of column construction, reinforced concrete (RC) columns are commonly used for any building due to its easily availability of materials, initial cost of construction etc. These RC columns can only withstand load up to certain extent hence they are not suited for all building constructions. And also reinforced concrete is not suited for every column construction.

In case of construction in coastal areas, bridge piers etc., the concrete gets abraded due to continuous contact of sea water and also lead to corrosion in reinforcement. In such cases, new types of columns such as Concrete Filled Steel Tubular Columns (CFST), Concrete Filled FRP Tubular Columns (CFFT), Concrete Filled Double Skin Tubular Columns (CFDST), Hybrid FRP Concrete Steel Double Skin Tubular Columns (Hybrid DSTC's) etc. are serve as a solution.

It is well recognized that FRP confined concrete can highly improve the strength and deformation of concrete and also it is self-evident that to reduce the self-weight of concrete is the most effective way to reduce the dead load on buildings and thus save construction cost and therefore lightweight and high performance structures have attracted extensive attentions nowadays [13]. Hence developed a new form of hybrid columns known as Hybrid FRP Concrete Steel Double Skin Tubular Columns (Hybrid DSTC's). Among the various new types of columns, Hybrid FRP Concrete Steel Double Skin Tubular Columns (Hybrid DSTC's) are effective because it possess various advantages over others types of columns. The new Hybrid column is an attempt to combine the advantages of all three constituent materials such as FRP, concrete and steel, so as to achieve a high performance structural member [1].

1.1 Hybrid FRP Concrete Steel Double Skin Tubular Columns (HYBRID DSTC's)

Hybrid FRP Concrete Steel Double Skin Tubular Columns (Hybrid DSTC's) is the new form of Hybrid columns. It consists of outer tube made of FRP and inner tube made of steel, with the space between the filled with concrete. The Figure 1 shows the cross section of Hybrid DSTC's. The inner void may be filled with concrete if desired. The FRP tube is provided with fibers which are predominately oriented in the circumferential direction to provide confinement to concrete and additional shear resistance to columns. The steel tube acts as the main reinforcement and prevents the concrete from inward spalling. The two tubes (FRP tube and steel tube) may be concentrically placed to produce a section more suitable for columns. Hybrid DSTC's may be constructed in situ or precast, with the two tubes acting as the stay-in-place form. It is lightweight due to hollow cross-section. Hybrid DSTC's possess significant advantages which includes lightweight, high strength, high ductility, excellent corrosion resistance and seismic resistance [1]. Shear connectors are provided between the steel tube and concrete, particularly in situations where bending dominates and such shear connectors are generally not needed between concrete and FRP tube if FRP tube has only a small longitudinal stiffness [2].
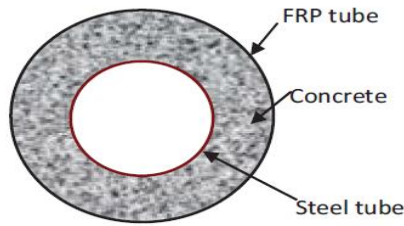

Fig -1: Cross section of Hybrid FRP Concrete Steel Double Skin Tubular Columns (Hybrid DSTC's) [1]

Hybrid DSTC's also uses FRP tube confinement mechanism as that of concrete filled FRP tubular columns (CFFT's) and they offer several advantages, including improved structural performance, improved durability that prolongs the design life, thereby reducing the cost of structural maintenance and urban renewal, significant improvements to the ease of construction that results in reduced construction costs, significant reduction to carbon footprint through more efficient use of materials that reduces required amount of raw materials. And also the inner void in the Hybrid DSTC's reduces the column weight without significantly affecting the flexural rigidity of the section and allows the easy passage of service ducts. The Hybrid columns are lighter due to elimination of redundant concrete. This new form of hybrid columns represents an innovation which combines the advantages of all three constituent materials such as FRP, concrete and steel and those of the structural form of DSTC's to deliver excellent structural and durability performance [6].

1.2 Cross Section of Hybrid DSTC's

The Hybrid DSTC's has several cross sections. And the most common sectional form of Hybrid DSTC's is both tubes are circular, referred as circular Hybrid DSTC's. These circular hybrid DSTC's are attractive for use as bridge piers. And another form of Hybrid DSTC's is square Hybrid DSTC's in which there is square FRP tube and circular steel tube. A circular inner tube is preferred over a square inner tube is that because circular inner tube provides better confinement to the concrete and less prone to local buckling. These square Hybrid DSTC's are used as columns of buildings because of aesthetic and other reasons. The confinement effect applied to concrete is best when hybrid columns are circular [3, 5]. Fig -2 shows common cross sections of Hybrid DSTC's.
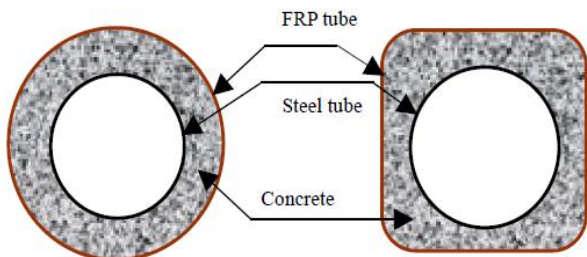
Circular Hybrid DSTC's   Square Hybrid DSTC

Fig -2: Common cross sections of Hybrid DSTC's [5]

The present study explores numerically the comparison of strength behaviour of circular and square Hybrid DSTC's under axial cyclic loading. The effect of parameters such as void ratio, steel tube thickness, different FRP's and H/t_c ratio on circular and square Hybrid DSTC's are also investigated.

2. NUMERICAL MODELLING AND ANALYSIS 0F CIRCULAR HYBRID DSTC BASE MODEL

Numerical modelling of circular Hybrid DSTC base model was done using ANSYS 16.2 WORKBENCH, a finite element software for mathematical modelling and analysis. A circular Hybrid DSTC consists of an inner steel tube and outer GFRP tube with space between the tubes filled with concrete. The steel tube and GFRP tube is of circular cross section.

2.1 Specifications of Circular Hybrid DSTC Base Model

The circular Hybrid DSTC base model was modelled in ANSYS 16.2 WORKBENCH with outer diameter of GFRP tube of 156.8 mm, inner diameter of steel tube of 88.9 mm, thickness of GFRP tube of 0.17 mm, thickness of steel tube of 5 mm and height of 400 mm. The space between the two tubes is filled with concrete and the circular Hybrid DSTC base model was modelled with loading plates at top and bottom of size 250 x 250 mm and 20 mm thick. Fig -3 shows modelled view of circular Hybrid DSTC base model.
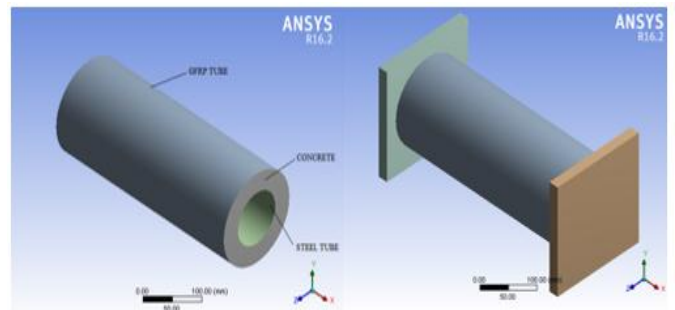

Fig -3: Modelled view of circular Hybrid DSTC base model

2.2 Cyclic Loading Program for Circular Hybrid DSTC Base Model

The cyclic loading program for circular Hybrid DSTC's was adopted as per the specifications of ATC 24. The cyclic loading program adopted has 27 cycles. With the help of Ansys software, the cyclic loading was given to analyze the behaviour of circular Hybrid DSTC base model. Fig 4 shows the cyclic loading program adopted for circular Hybrid DSTC base model.
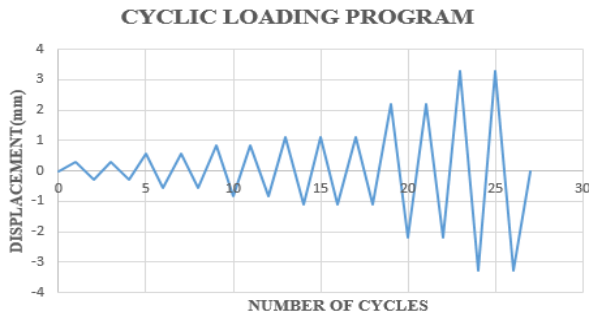
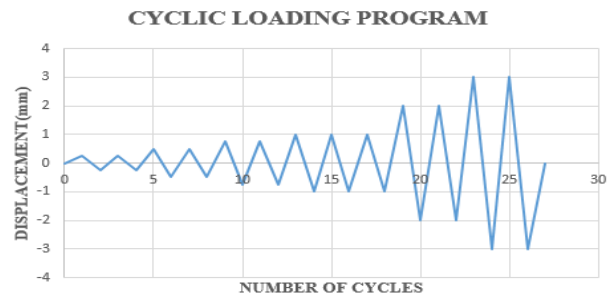**Fig -4**: Cyclic loading program for circular Hybrid DSTC base model[16]

3. NUMERICAL MODELLING AND ANALYSIS 0F SQUARE HYBRID DSTC BASE MODEL

Numerical modelling of square Hybrid DSTC base model was done using ANSYS 16.2 WORKBENCH, a finite element software for mathematical modelling and analysis. A square Hybrid DSTC consists of an inner circular steel tube and outer square GFRP tube with space between the tubes filled with concrete.

3.1 Specifications of Square Hybrid DSTC Base Model

The square Hybrid DSTC base model was modelled in ANSYS 16.2 WORKBENCH with an inner diameter of steel tube of 88.9 mm, side length of GFRP tube of 140.6 mm with corner radius of 25 mm, thickness of GFRP tube of 0.17 mm, thickness of steel tube of 5 mm and height of 400 mm. The space between the two tubes is filled with concrete and the square Hybrid DSTC base model was also modelled with loading plates at top and bottom of size 250 x 250 mm and 20 mm thick. Fig -5 shows modelled view of square Hybrid DSTC base model.
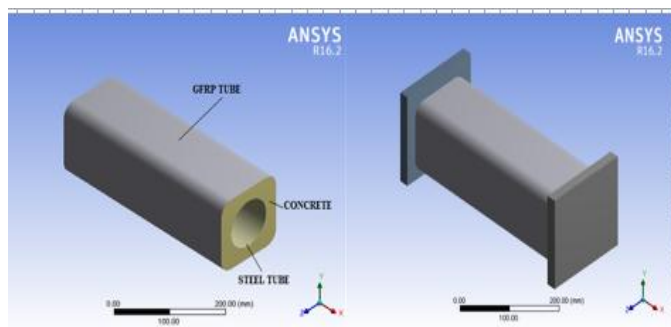

Fig -5: Modelled view of square Hybrid DSTC base model

3.2 Cyclic Loading Program for Square Hybrid DSTC Base Model

The cyclic loading program was adopted as per specifications of ATC 24. The cyclic loading program adopted has 27 cycles. With the help of Ansys software, the cyclic loading was given to analyze the behaviour of square Hybrid DSTC base model. Fig 6 shows the cyclic loading program adopted for square Hybrid DSTC base model.

Fig -6: Cyclic loading program for square Hybrid DSTC base model [16]

4. PARAMETER STUDIES ON CIRCULAR HYBRID DSTC's

The parameter studies were conducted on circular Hybrid DSTC's. The key parameters studied, include void ratio, steel tube thickness, different FRP's, and H/t_c ratio. The influence of each parameter on the behaviour of circular Hybrid DSTC's were studied. For every parameter investigation the circular Hybrid DSTC base model was kept as a reference model for comparison

4.1 Void Ratio (VR)

The void ratio is defined as the ratio between the inner diameter and outer diameter of the annular concrete section of Hybrid DSTC. Void ratio is said to be an important parameter that affects the performance of Hybrid DSTC's. The void ratio of circular Hybrid DSTC base model was 0.57. The void ratios studied were 0.53, 0.51, 0.48, 0.46, and 0.43. The height of the circular VR models is kept as 400 mm. The thicknesses of GFRP tube and steel tube is taken as 0.17 mm and 5 mm respectively. Table 1 shows the specifications of the void ratio models of circular Hybrid DSTC's used for the study.

Table -1: Specifications of different VR models of circular Hybrid DSTC's

Model name	Void ratio	Outer diameter of GFRP tube (mm)	Inner diameter of steel tube (mm)
C-VR 0.57	0.57	156.8	88.9
C-VR 0.53	0.53	166.7	88.9
C-VR 0.51	0.51	173.9	88.9
C-VR 0.48	0.48	186	88.9
C-VR 0.46	0.46	190.5	88.9
C-VR 0.43	0.43	205.3	88.9

The cyclic loading program for VR models were adopted as per the specifications of ATC 24. The cyclic loading program adopted has 27 cycles. Fig 7 shows the cyclic loading program adopted for void ratio models of circular Hybrid DSTC's.
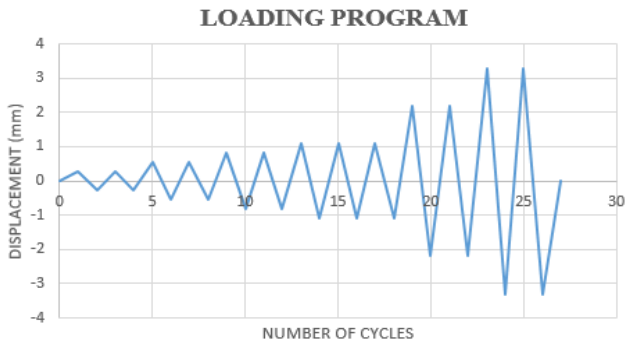
Fig -7: Cyclic loading program for void ratio models of circular Hybrid DSTC's [16]

4.2 Steel Tube Thickness (ST)

The steel tube thickness is the thickness of the steel tube which acts as main reinforcement in Hybrid DSTC's. Steel tube also prevents the concrete from inward spalling thus the thickness of steel tube plays an effective role in the performance of Hybrid DSTC's. The steel tube is of circular cross section. The thicknesses of steel tube used for the study are 1.6 mm, 2.3 mm, 3.2 mm, 3.6 mm, 4 mm, 5 mm and 6 mm. A circular model was also modelled with no steel tube denoted as C-WST. All other circular steel tube thickness models were compared with C-WST model. Table 2 shows the specifications of steel tube thickness models of circular Hybrid DSTC's used for the study. The height of the ST models is kept as 400 mm. The thicknesses of GFRP tube is taken as 0.17 mm.

Table -2: Specifications of different ST models of circular Hybrid DSTC's

Model name	Steel tube thickness (mm)	Outer diameter of GFRP tube (mm)	Inner diameter of steel tube (mm)
C-ST 1.6	1.6	156.8	88.9
C-ST 2.3	2.3	156.8	88.9
C-ST 3.2	3.2	156.8	88.9
C-ST 3.6	3.6	156.8	88.9
C-ST 4	4	156.8	88.9
C-ST 5	5	156.8	88.9
C-ST 6	6	156.8	88.9
C-WST	-	156.8	-

The cyclic loading program for Steel tube thickness (ST) models were adopted as per specifications of ATC 24. The cyclic loading program adopted has 27 cycles. Fig 8 shows the cyclic loading program adopted for steel tube thickness models of circular Hybrid DSTC's. The cyclic loading program adopted for C-WST is different from those of steel tube thickness models. Fig 9 shows the cyclic program adopted for C-WST model.
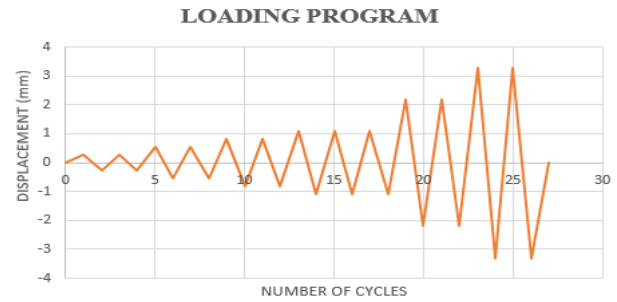

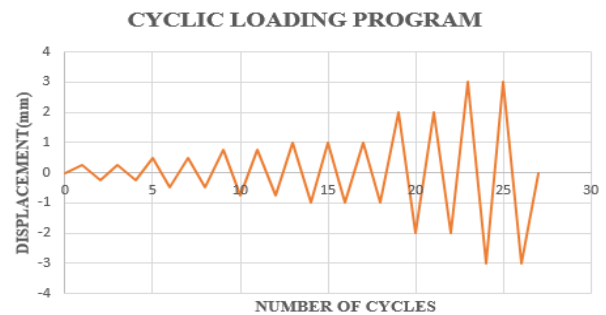**Fig -8:** Cyclic loading program for ST models of circular Hybrid DSTC's [16]

Fig -9: Cyclic loading program for C-WST model [16]

4.3 Different FRP's

The FRP used for circular Hybrid DSTC base model was glass fiber reinforced polymer (GFRP). The other FRPs used for the study were carbon fiber reinforced polymer (CFRP), aramid fiber reinforced polymer (AFRP) and basalt fiber reinforced polymer (BFRP). Table 3 shows the material properties of each FRP's used for the study. The height of the different FRP models is kept as 400 mm. The thicknesses of GFRP tube and steel tube is taken as 0.17 mm and 5 mm respectively.

Table -3: Material properties of different FRP's used

FRP used	Density (kg/m³)	Modulus of elasticity (GPa)	Poissons ratio	Tensile strength (MPa)
GFRP	2550	80.1	0.3	1825.5
CFRP	1600	251	0.3	3626
AFRP	1450	128.7	0.3	2390
BFRP	2650	87	0.3	2900

Table 4 shows the specifications of different FRP models of circular Hybrid DSTC's. After modelling different FRP models, each FRP's material properties were assigned to the models using Ansys software.

Table -4: Specifications of different FRP models of circular Hybrid DSTC's

Model name	FRP used	Outer diameter of GFRP tube (mm)	Inner diameter of steel tube (mm)
C-GFRP	GFRP	156.8	88.9
C-CFRP	CFRP	156.8	88.9
C-AFRP	AFRP	156.8	88.9
C-BFRP	BFRP	156.8	88.9

The cyclic loading program for different FRP models were adopted as per the specifications of ATC 24. The cyclic loading program adopted has 27 cycles. Fig 10 shows the cyclic loading program adopted for different FRP models of circular Hybrid DSTC's.
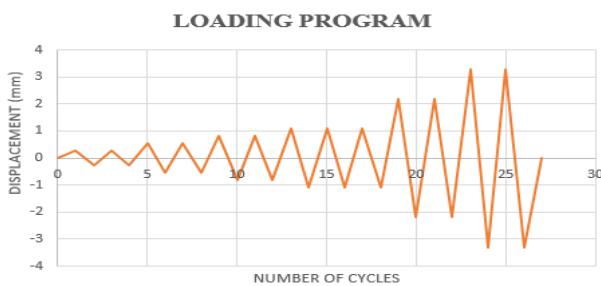

Fig -10: Cyclic loading program for different FRP models of circular Hybrid DSTC's [16]

4.4 H/t_c Ratio

The H/t_c ratio is defined as ratio of height of Hybrid DSTC's to the thickness of annular concrete section of Hybrid DSTC's. The thickness of annular concrete section is constant whereas changing parameter is the height of Hybrid DSTC's. The H/t_c ratio of circular Hybrid DSTC base model is 5.9. The other H/t_c ratios used for the study were 4.6, 5.3, 5.9, 6.6, 7.2 and 7.9. The height of circular Hybrid DSTC's used for the study were 310 mm, 360 mm, 400 mm, 450 mm, 490 mm and 540 mm respectively. Table 5 shows the specifications of different H/t_c ratio models of circular Hybrid DSTC's used for the study. The thicknesses of GFRP tube and steel tube is taken as 0.17 mm and 5 mm respectively.

Table -5: Specifications of different H/t_c ratio models of circular Hybrid DSTC's

Model name	H/t_c ratio	Height ,H (mm)	Thickness of annular concrete section, t_c (mm)
C- H/t_c 4.6	4.6	310	67.9
C- H/t_c 5.3	5.3	360	67.9
C- H/t_c 5.9	5.9	400	67.9
C- H/t_c 6.6	6.6	450	67.9
C- H/t_c 7.2	7.2	490	67.9
C- H/t_c 7.9	7.9	540	67.9

The cyclic loading program for different H/t_c ratio models were adopted per the specifications of ATC 24. The cyclic loading program adopted has 27 cycles. Fig 11 shows the cyclic loading program adopted for different H/t_c ratio models of circular Hybrid DSTC's.
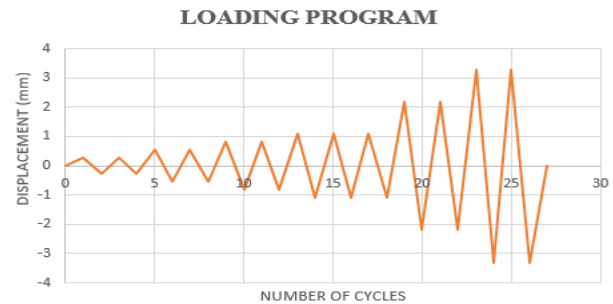

Fig -11: Cyclic loading program for different H/t_c ratio models of circular Hybrid DSTC's [16]

5. PARAMETER STUDIES ON SQUARE HYBRID DSTC's

The parameter studies were also conducted on square Hybrid DSTC's. The key parameters studied, include void ratio, steel tube thickness, different FRP's, and H/t_c ratio. The influence of each parameter on the behaviour of square Hybrid DSTC's were studied. For every parameter investigation the square Hybrid DSTC base model was kept as a reference model for comparison.

5.1 Void Ratio (VR)

The void ratio is defined as the ratio between the inner diameter and outer diameter of the annular concrete section of Hybrid DSTC. Void ratio is said to be an important parameter that affects the performance of Hybrid DSTC's. In case of square Hybrid DSTC's there is no outer diameter thus the face area of circular void ratio models were found out and the square void ratio models were made with the same face area as that of circular void ratio models. Table 6 shows the specifications of the void ratio models of square Hybrid DSTC's used for the study. The height of the square VR models is kept as 400 mm. The thicknesses of GFRP tube and steel tube is taken as 0.17 mm and 5 mm respectively.

Table -6: Specifications of different VR models of square Hybrid DSTC's

Model name	Steel tube thickness (mm)	Side length of GFRP tube (mm)	Inner diameter of steel tube (mm)
S-ST 1.6	1.6	156.8	88.9
S-ST 2.3	2.3	156.8	88.9
S-ST 3.2	3.2	156.8	88.9
S-ST 3.6	3.6	156.8	88.9
S-ST 4	4	156.8	88.9
S-ST 5	5	156.8	88.9
S-ST 6	6	156.8	88.9
S-WST	-	156.8	-

The cyclic loading program for VR models were adopted as per the specifications of ATC 24. The cyclic loading program adopted has 27 cycles. Fig 12 shows the cyclic loading program adopted for void ratio models of square Hybrid DSTC's.
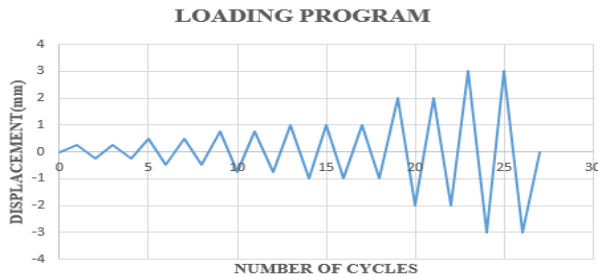

Fig -12: Cyclic loading program for void ratio models of square Hybrid DSTC's [16]

5.2 Steel Tube Thickness (ST)

The steel tube thickness is the thickness of the steel tube which acts as main reinforcement in Hybrid DSTC's. Steel tube also prevents the concrete from inward spalling thus the thickness of steel tube plays an effective role in the performance of Hybrid DSTC's. The steel tube is of circular cross section. The thicknesses of steel tube used for the study are 1.6 mm, 2.3 mm, 3.2 mm, 3.6 mm, 4 mm, 5 mm and 6 mm. A square model was also modelled with no steel tube denoted as S-WST. All other square steel tube thickness models were compared with S-WST model. Table 7 shows the specifications of steel tube thickness models of square Hybrid DSTC's used for the study. The height of the ST models is kept as 400 mm. The thicknesses of GFRP tube is taken as 0.17 mm.

Table -7: Specifications of different ST models of square Hybrid DSTC's

Model name	Steel tube thickness (mm)	Side length of GFRP tube (mm)	Inner diameter of steel tube (mm)
S-ST 1.6	1.6	140.6	88.9
S-ST 2.3	2.3	140.6	88.9
S-ST 3.2	3.2	140.6	88.9
S-ST 3.6	3.6	140.6	88.9
S-ST 4	4	140.6	88.9
S-ST 5	5	140.6	88.9
S-ST 6	6	140.6	88.9
S-WST	-	140.6	-

The cyclic loading program for Steel tube thickness (ST) models were adopted as per specifications of ATC 24. The cyclic loading program adopted has 27 cycles. Fig 13 shows the cyclic loading program adopted for steel tube thickness models of square Hybrid DSTC's. The cyclic loading program adopted for S-WST is different from those of square

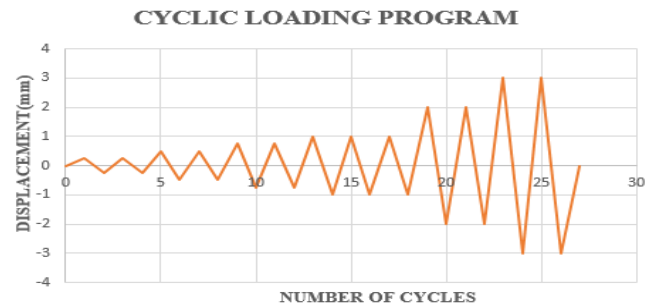steel tube thickness models. Fig 14 shows the cyclic program adopted for S-WST model.

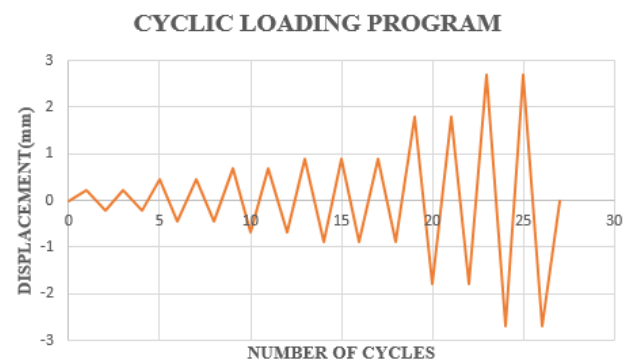**Fig -13:** Cyclic loading program for ST models of square Hybrid DSTC's [16]

Fig -9: Cyclic loading program for S-WST model [16]

5.3 Different FRP's

The FRP used for square Hybrid DSTC base model was glass fiber reinforced polymer (GFRP). The other FRPs used for the study were carbon fiber reinforced polymer (CFRP), aramid fiber reinforced polymer (AFRP) and basalt fiber reinforced polymer (BFRP). Table 3 shows the material properties of each FRP's used for the study. The height of the different FRP models is kept as 400 mm. The thicknesses of GFRP tube and steel tube is taken as 0.17 mm and 5 mm respectively. Table 8 shows the specifications of different FRP models of square Hybrid DSTC's. After modelling different FRP models, each FRP's material properties were assigned to the models using Ansys software.

Table -8: Specifications of different FRP models of square Hybrid DSTC's

Model name	FRP used	Side length of GFRP tube (mm)	Inner diameter of steel tube (mm)
S-GFRP	GFRP	140.6	88.9
S-CFRP	CFRP	140.6	88.9
S-AFRP	AFRP	140.6	88.9
S-BFRP	BFRP	140.6	88.9

The cyclic loading program for different FRP models were adopted as per the specifications of ATC 24. The cyclic loading program adopted has 27 cycles. Fig 15 shows the cyclic loading program adopted for different FRP models of square Hybrid DSTC's.
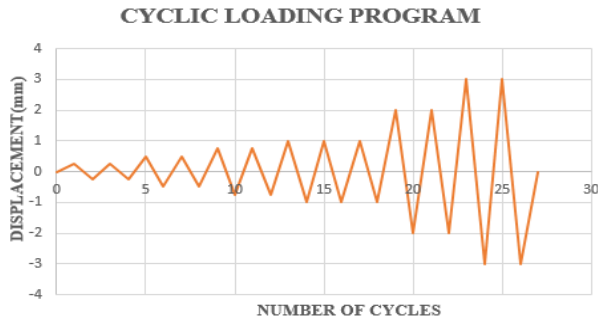

Fig -13: Cyclic loading program for different FRP models of square Hybrid DSTC's [16]

5.4 H/t_c Ratio

The H/t_c ratio is defined as ratio of height of Hybrid DSTC's to the thickness of annular concrete section of Hybrid DSTC's. The thickness of annular concrete section is constant whereas changing parameter is the height of Hybrid DSTC's. The H/t_c ratio of square Hybrid DSTC base model is 5.9. The other H/t_c ratios used for the study were 4.6, 5.3, 5.9, 6.6, 7.2 and 7.9.The height of square Hybrid DSTC's used for the study were 310 mm, 360 mm, 400 mm, 450 mm, 490 mm and 540 mm respectively. Table 9 shows the specifications of different H/t_c ratio models of square Hybrid DSTC's used for the study. The thicknesses of GFRP tube and steel tube is taken as 0.17 mm and 5 mm respectively.

Table -9: Specifications of different H/t_c ratio models of square Hybrid DSTC's

Model name	H/t_c ratio	Height ,H (mm)	Thickness of annular concrete section, t_c (mm)
S- H/t_c 4.6	4.6	310	67.9
S- H/t_c 5.3	5.3	360	67.9
S- H/t_c 5.9	5.9	400	67.9
S- H/t_c 6.6	6.6	450	67.9
S- H/t_c 7.2	7.2	490	67.9
S- H/t_c 7.9	7.9	540	67.9

The cyclic loading program for different H/t_c ratio models were adopted per the specifications of ATC 24. The cyclic loading program adopted has 27 cycles. Fig 14 shows the cyclic loading program adopted for different H/t_c ratio models of square Hybrid DSTC's.
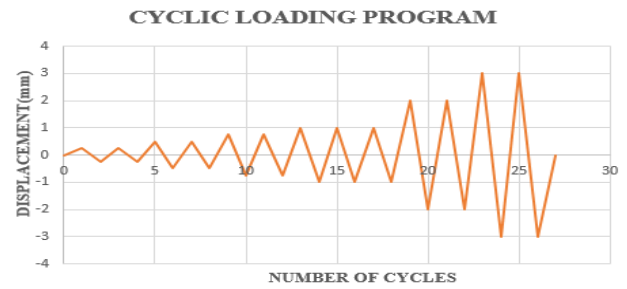

Fig -14: Cyclic loading program for different H/t_c ratio models of square Hybrid DSTC's [16]

6. RESULTS AND DISCUSSIONS

Static analysis of circular and square Hybrid DSTC's with axial cyclic loading was done using ANSYS 16.2 WORKBENCH. After the axial cyclic loading, the total deformation and hysteresis curves of circular and square Hybrid DSTC's were obtained from the ANSYS 16.2 WORKBENCH. From the hysteresis curves the energy absorption was calculated by calculating the area under the hysteresis curves. The effect of void ratio, steel tube thickness, different FRP's, H/t_c ratio on circular and square Hybrid DSTC's were also examined.

6.1 Total Deformation of circular Hybrid DSTC base model

Total deformation of circular Hybrid DSTC base model was determined. Fig 10 shows the total deformation of circular Hybrid DSTC base model obtained from ANSYS 16.2 WORKBENCH. The total deformation obtained for circular Hybrid DSTC base model was 0.15276 mm.
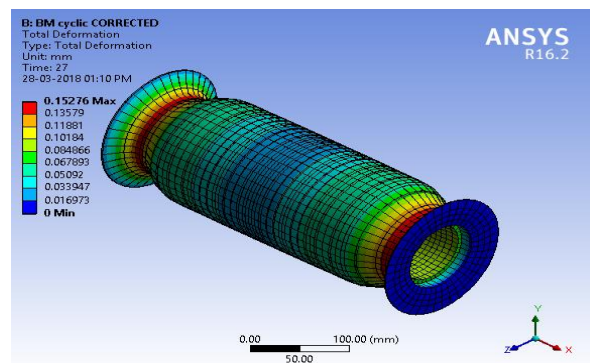

Fig -10: Total deformation of circular Hybrid DSTC base model

6.2 Energy Absorption of Circular Hybrid DSTC Base Model

From the ANSYS 16.2 WORKBENCH, the hysteresis curve for circular Hybrid DSTC base model was obtained. The Fig 11 shows the hysteresis curve of circular Hybrid DSTC base model obtained from Ansys software.
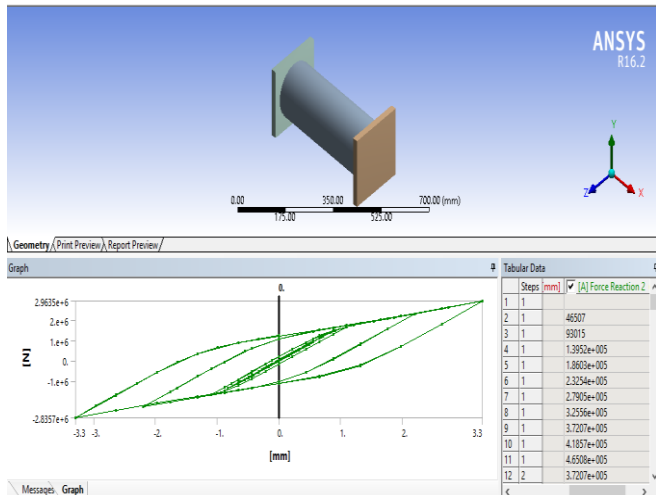
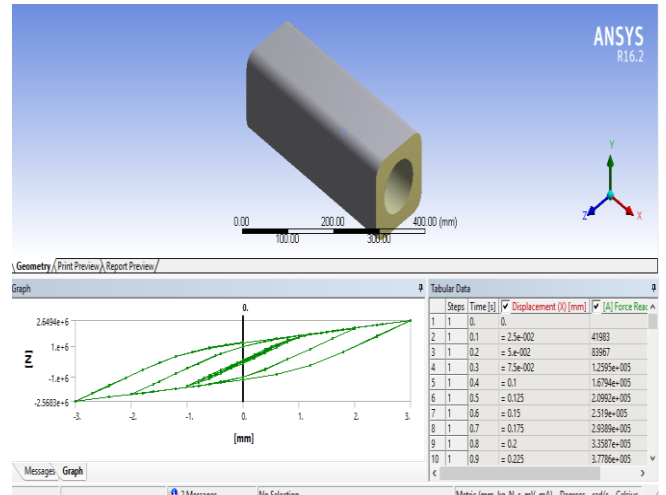**Fig -11:** Hysteresis curve of circular Hybrid DSTC base model

The area under the hysteresis curve gives the energy absorption. The energy absorption of circular Hybrid DSTC base model calculated from hysteresis curve was 33.026 kJ.

6.3 Total Deformation of square Hybrid DSTC base model

Total deformation of square Hybrid DSTC was determined. Fig 12 shows the total deformation of square Hybrid DSTC base model obtained from Ansys software. The total deformation obtained for square Hybrid DSTC base model was 0.19517 mm.
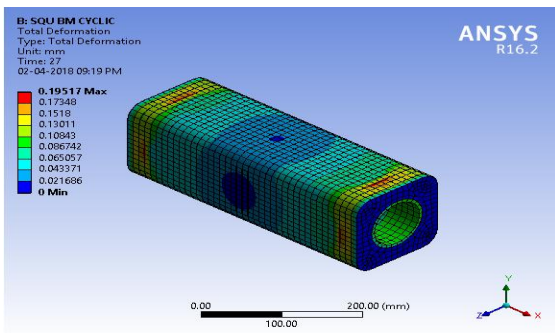

**Fig -12:** Total deformation of square Hybrid DSTC base model

6.4 Energy Absorption of square Hybrid DSTC Base Model

From the ANSYS 16.2 WORKBENCH, the hysteresis curve for square Hybrid DSTC base model was obtained. The Fig 13 shows the hysteresis curve of square Hybrid DSTC base model obtained from Ansys.

Fig -13: Hysteresis curve of square Hybrid DSTC base model

6.5 Effect of Void Ratio (VR) on Circular Hybrid DSTC's

Total deformation

The Total deformation for different void ratios such as 0.57, 0.53, 0.51, 0.48, 0.46, 0.43 of circular Hybrid DSTC's were obtained. Fig 14 shows the total deformation obtained from Ansys software for different void ratio of circular Hybrid DSTC's.
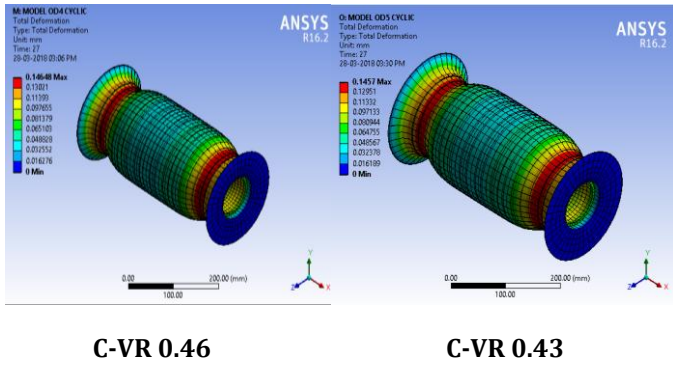

C-VR 0.57 BM   **C- VR 0.53**

C-VR 0.51   **C-VR 0.48**

C-VR 0.46   **C-VR 0.43**
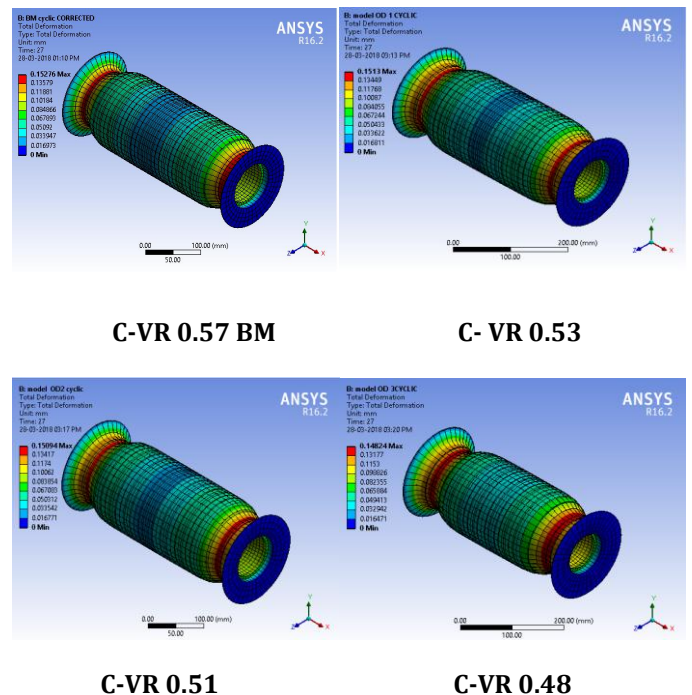
Fig -14: Total deformation for different void ratios of circular Hybrid DSTC's

From the results it was inferred that the total deformation is decreasing with decrease in void ratios. And it was found that for the void ratio of 0.43 is having the least total deformation of 0.1457 mm.

Energy Absorption

From the ansys, the hysteresis curves for different void ratios of circular Hybrid DSTC's were obtained. The area under the hysteresis curve gives the energy absorption. Energy absorption of circular Hybrid DSTC's with different void ratios were calculated from hysteresis curves. Table 10 shows the results of energy absorption of circular Hybrid DSTC's with different void ratios. Chart 1 shows the comparison of hysteresis curves of different void ratios of circular Hybrid DSTC's.

Table -10: Energy absorption of circular Hybrid DSTC's with different void ratios

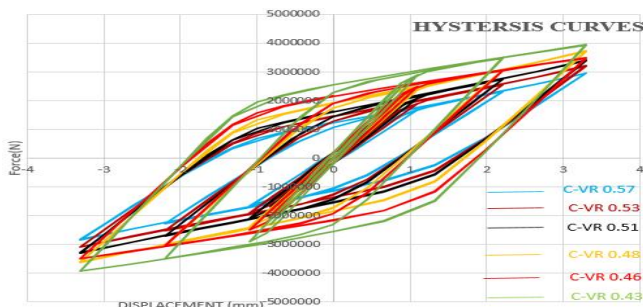| Model name	Void ratio	Energy absorption (kJ)
C-VR 0.57	0.57	33.026
C-VR 0.53	0.53	38.827
C-VR 0.51	0.51	43.207
C-VR 0.48	0.48	51.198
C-VR 0.46	0.46	55.742
C-VR 0.43	0.43	65.311

Chart -1: Comparison of hysteresis curves of different void ratios of circular Hybrid DSTC's

From the results we can infer that, the energy absorption capacities of circular Hybrid DSTC's were increasing with decrease in void ratios. And also found that the circular Hybrid DSTC of void ratio 0.43 has the highest energy absorption capacity. This increase in energy absorption capacity might be due to increase in annular concrete section.

6.6 Effect of Steel Tube Thickness (ST) on Circular Hybrid DSTC's

Total deformation

The Total deformation for different Steel tube thicknesses 0 mm, 1.6 mm, 2.3 mm, 3.2 mm, 3.6 mm, 4 mm, 5 mm and 6 mm of circular Hybrid DSTC's were obtained. Fig 15 shows the total deformation obtained from Ansys software for different steel tube thicknesses of circular Hybrid DSTC's
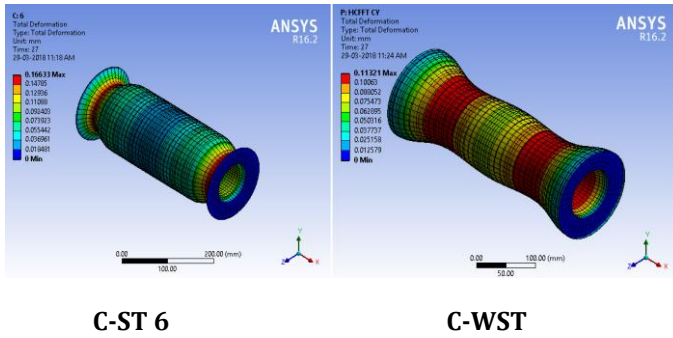

C-ST 1.6   **C-ST 2.6**

C-ST 3.2   **C-ST 3.6**

C-ST 4   **C-ST 5**

C-ST 6   **C-WST**
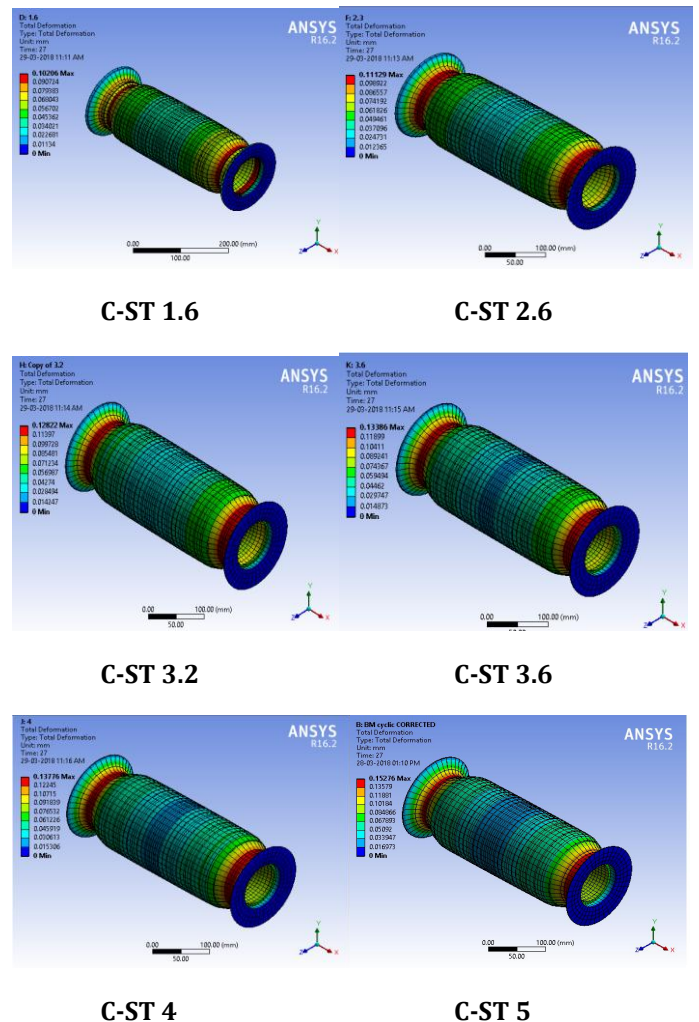
Fig -15: Total deformation for different steel tube thickness of circular Hybrid DSTC's

From the results it was inferred that, the total deformation of circular Hybrid DSTC's with different steel tube thicknesses were increasing with increase in steel tube thickness. And it was found that, the circular Hybrid DSTC with the steel tube thickness of 1.6 mm is having the least total deformation of 0.10206 mm. The total deformation of 0 mm steel tube thickness circular DSTC denoted as C-WST is 0.11321 mm.

Energy Absorption

From the ansys, the hysteresis curves for different steel tube thicknesses of circular Hybrid DSTC's were obtained. The area under the hysteresis curve gives the energy absorption. Energy absorption of circular Hybrid DSTC's with different steel tube thicknesses were calculated from hysteresis curves. Table 11 shows results of energy absorption of circular Hybrid DSTC's with different steel tube thicknesses. Chart 2 shows the comparison of hysteresis curves of circular Hybrid DSTC's with different steel tube thicknesses.

Table -11: Energy absorption of circular Hybrid DSTC's with different steel tube thicknesses

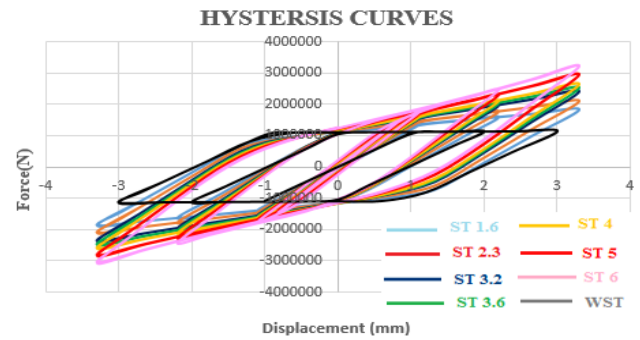| Model name	Steel tube thickness (mm)	Energy absorption (kJ)
C-ST 1.6	1.6	25.37
C-ST 2.3	2.3	30.88
C-ST 3.2	3.2	31.182
C-ST 3.6	3.6	31.795
C-ST 4	4	32.086
C-ST 5	5	32.36
C-ST 6	6	33.026
C-WST	-	33.677

Chart -2: Comparison of hysteresis curves of circular Hybrid DSTC's with different steel tube thicknesses

From the results we can infer that, the introduction of steel tube increases the energy absorption capacities of circular Hybrid DSTC's. The energy absorption capacities of circular Hybrid DSTC's were increasing with increase in steel tube thicknesses. This increase might be due to the additional stiffness contributed by steel tube. And also found that the circular Hybrid DSTC of steel tube thickness of 6 mm has the highest energy absorption capacity of 33.677 kJ. And the energy absorption capacity of C-WST is very lower when compared circular Hybrid DSTC's with different steel tube thicknesses.

6.7 Effect of Different FRP's on Circular Hybrid DSTC's

Total deformation

The Total deformation for different FRP's such as GFRP, CFRP, AFRP and BFRP of circular Hybrid DSTC's were obtained from ansys. Fig 16 shows the total deformation obtained from Ansys software for circular Hybrid DSTC's with different FRP's.
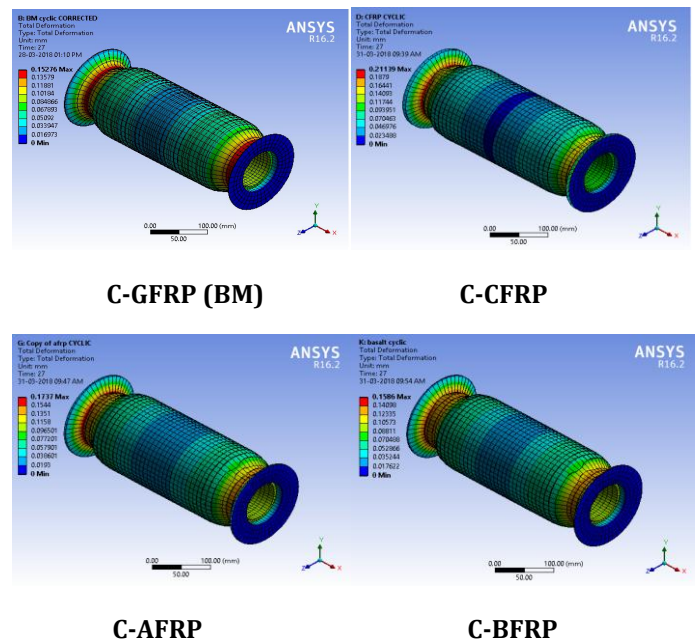

C-GFRP (BM)   **C-CFRP**

C-AFRP   **C-BFRP**

Fig -16: Total deformation for circular Hybrid DSTC's with different FRP's

Energy Absorption

From the ansys, the hysteresis curves for different FRP's of circular Hybrid DSTC's were obtained. The area under the hysteresis curve gives the energy absorption. Energy absorption of circular Hybrid DSTC's with different FRP's were calculated from hysteresis curves. Table 12 shows the results of energy absorption of circular Hybrid DSTC's with different FRP's. Chart 3 shows the comparison of hysteresis curves of circular Hybrid DSTC's with different FRP's.

Table -12: Energy absorption of circular Hybrid DSTC's with different FRP's

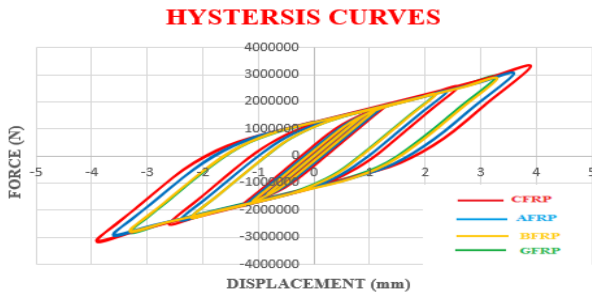| Model name	FRP used	Energy absorption (kJ)
C-GFRP	GFRP	33.026
C-CFRP	CFRP	45.613
C-AFRP	AFRP	39.641
C-BFRP	BFRP	33.885

Chart -3: Comparison of hysteresis curves of circular Hybrid DSTC's with different FRP's

From the results we can infer that, the circular Hybrid DSTC's with CFRP tube has the highest energy absorption capacity of 45.613 kJ than other FRP tubes. And also found that the circular Hybrid DSTC with GFRP tube has the least energy absorption capacity of 33.026 kJ.

6.8 Effect of H/t_c Ratio on Circular Hybrid DSTC's

Total Deformation

The Total deformation for different H/t_c ratios 4.6, 5.3, 5.9, 6.6, 7.2 and 7.9 of circular Hybrid DSTC's were obtained. Fig 17 shows the total deformation obtained from Ansys software for different H/t_c ratios of circular Hybrid DSTC's.
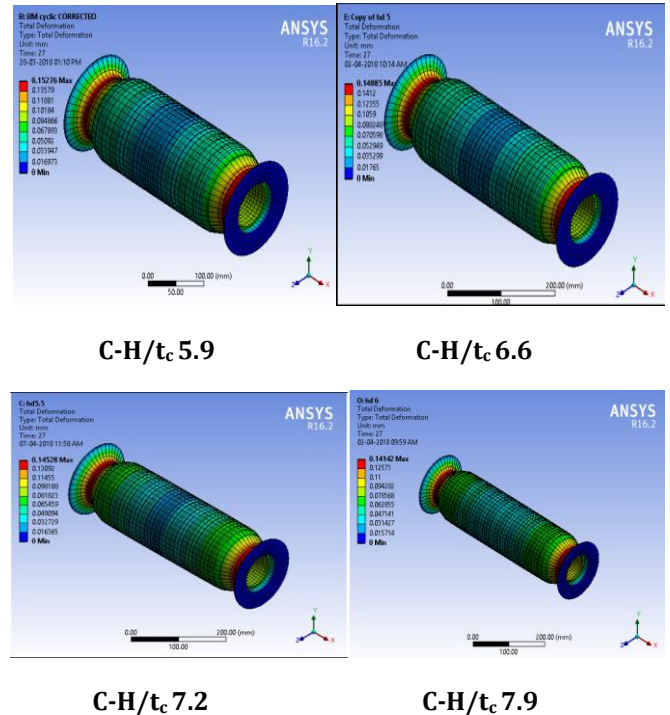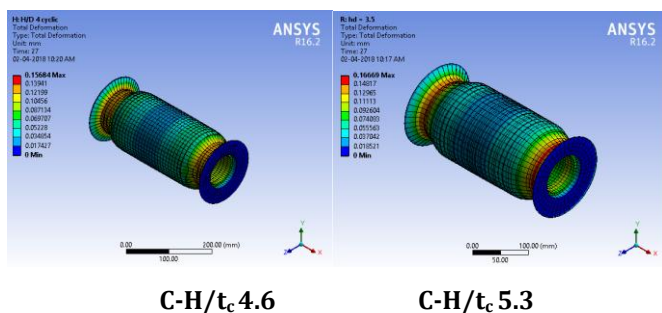

C-H/t_c 4.6   **C-H/t_c 5.3**

C-H/t_c 5.9   **C-H/t_c 6.6**

C-H/t_c 7.2   **C-H/t_c 7.9**

Fig -17: Total deformation for circular Hybrid DSTC's with different H/t_c ratios

From the results it was inferred that, the total deformation of circular Hybrid DSTC's with different H/t_c ratios were decreasing with increase in H/t_c ratios. And it was found that, the circular Hybrid DSTC with H/t_c ratio of 7.9 is having the least total deformation of 0.14142 mm.

Energy Absorption

From the ansys, the hysteresis curves for different H/t_c ratios of circular Hybrid DSTC's were obtained. The area under the hysteresis curve gives the energy absorption. Energy absorption of circular Hybrid DSTC's with different H/t_c ratios were calculated from hysteresis curves. Table 13 shows the results of energy absorption of circular Hybrid DSTC's with different H/t_c ratios. Chart 4 shows the comparison of hysteresis curves of circular Hybrid DSTC's with different H/t_c ratios.

Table -13: Energy absorption of circular Hybrid DSTC's with different H/t_c ratios

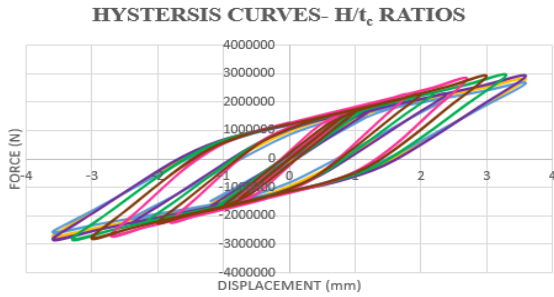| Model name	H/t_c ratio	Energy absorption (kJ)
C- H/t_c 4.6	4.6	29.251
C- H/t_c 5.3	5.3	30.373
C- H/t_c 5.9	5.9	33.026
C- H/t_c 6.6	6.6	34.996
C- H/t_c 7.2	7.2	32.351
C- H/t_c 7.9	7.9	29.239

Chart -4: Hysteresis curves for circular Hybrid DSTC with different H/t$_c$ ratios

From the results we can infer that, the energy absorption capacities of circular Hybrid DSTC's were increasing with increase in H/t$_c$ ratio up to 6.6, beyond H/t$_c$ ratio 6.6 the energy absorption capacities were decreasing. And also found that the circular Hybrid DSTC's of H/t$_c$ ratio 6.6 has the highest energy absorption capacity of 34.996 kJ. For H/t$_c$ ratios 7.2 and 7.9 the energy absorption capacities of circular Hybrid DSTC's were found to be decreasing. This decrease in energy absorption capacities may be due to the change in the performance of short column to intermediate column and also the change in failure mode from crushing to bending. As the height of column increases, the energy absorption capacity also increases but up to a limit, beyond the limit the energy absorption capacity decreases due to the change in column type from short column to intermediate column.

6.9 Effect of Void Ratio (VR) on Square Hybrid DSTC's

Total Deformation

The Total deformation for different void ratios 0.57, 0.53, 0.51, 0.48, 0.46, 0.43 of square Hybrid DSTC's were obtained. The Fig 18 shows the total deformation obtained from Ansys software for different void ratios of square Hybrid DSTC's.

S-VR 0.57   **S-VR 0.53**

S-VR 0.51   **S-VR 0.48**
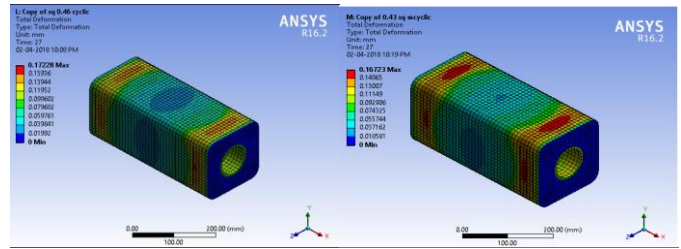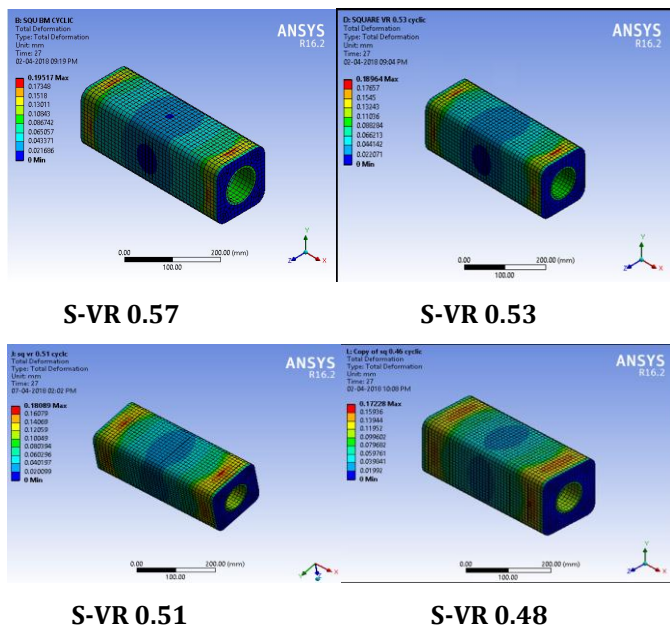
S-VR 0.46   **S-VR 0.43**

Fig -18: Total deformation for square Hybrid DSTC's with different void ratios

From the results it was inferred that, total deformation is decreasing with decrease in void ratios. And it was found that for the square Hybrid DSTC with void ratio of 0.43 is having the least total deformation of 0.16723 mm.

Energy Absorption

From the ansys, the hysteresis curves for different void ratios of square Hybrid DSTC's were obtained. The area under the hysteresis curve gives the energy absorption. Energy absorption of square Hybrid DSTC's with different void ratios were calculated from hysteresis curves. Table 14 shows the results of energy absorption of square Hybrid DSTC's with different void ratios. Chart 5 shows the comparison of Hysteresis curves of different void ratios of square Hybrid DSTC's.

Table -14: Energy absorption of square Hybrid DSTC's with different void ratios

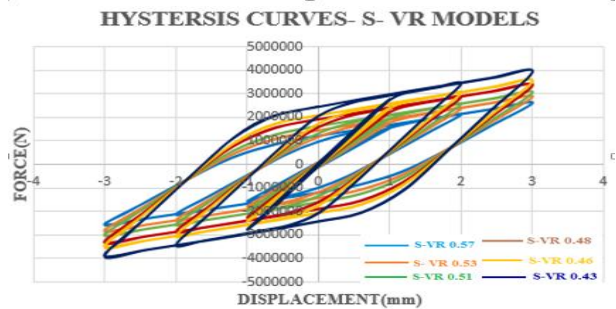| Model name	Void ratio	Energy absorption (kJ)
S-VR 0.57	0.57	28.334
S-VR 0.53	0.53	33.106
S-VR 0.51	0.51	36.940
S-VR 0.48	0.48	45.532
S-VR 0.46	0.46	47.342
S-VR 0.43	0.43	55.295

Chart -5: Hysteresis curves for square Hybrid DSTC with different void ratios

From the results we can infer that, the energy absorption capacities of square Hybrid DSTC's were increasing with decrease in void ratios. And also found that the square Hybrid DSTC of void ratio 0.43 has the highest energy absorption capacity of 55.295 kJ. This increase in

energy absorption capacity might be due to increase in annular concrete section.

6.10 Effect of Steel Tube Thickness (ST) on Square Hybrid DSTC's

Total Deformation

The total deformation for different Steel tube thicknesses 0 mm, 1.6 mm, 2.3 mm, 3.2 mm, 3.6 mm, 4 mm ,5 mm and 6 mm of square Hybrid DSTC's were obtained. The Fig 19 shows the total deformation obtained from Ansys software for different steel tube thicknesses of square Hybrid DSTC's.
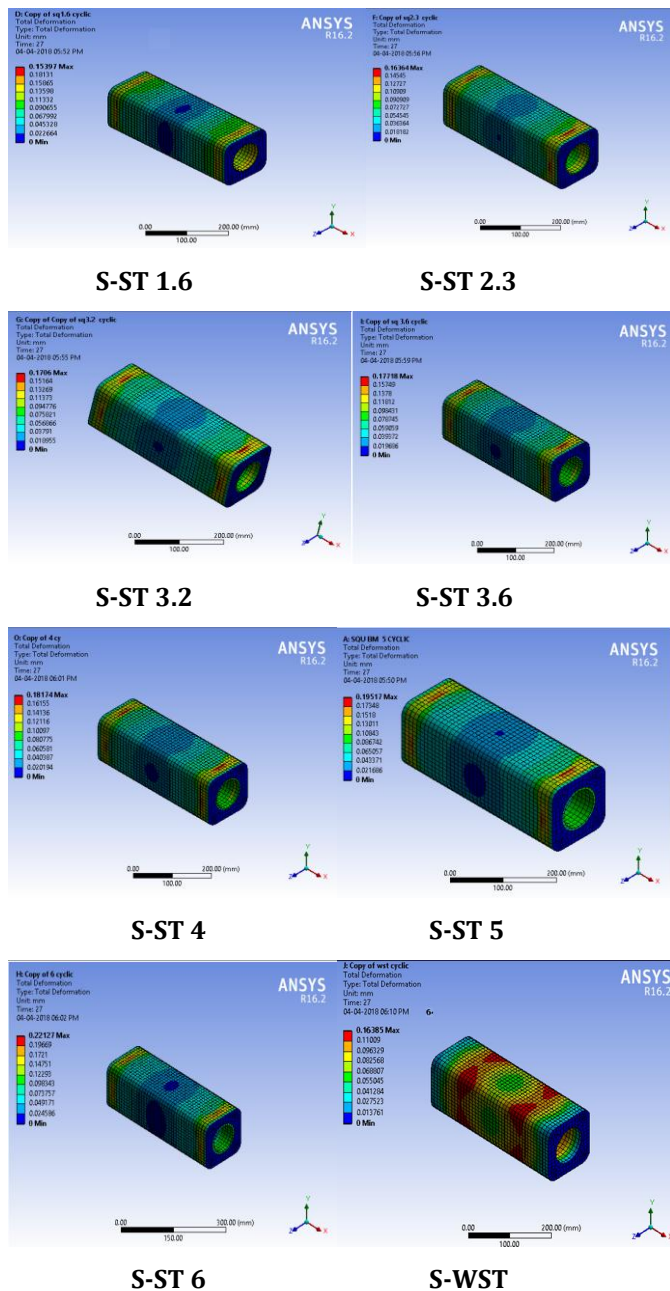

S-ST 1.6   **S-ST 2.3**

S-ST 3.2   **S-ST 3.6**

S-ST 4   **S-ST 5**

S-ST 6   **S-WST**

Fig -19: Total deformation for square Hybrid DSTC's with different steel tube thicknesses

From the results it was inferred that, the total deformation of square Hybrid DSTC's with different steel tube thicknesses were increasing with increase in steel tube thickness. And it was found that, the square Hybrid DSTC with the steel tube thickness of 1.6 mm is having the least total deformation of 0.15397 mm. The total deformation of 0 mm steel tube thickness of square DSTC denoted as S-WST is of 0.16385 mm.

Energy Absorption

From the ansys, the hysteresis curves for square Hybrid DSTC's with different steel tube thicknesses were obtained from ansys. The area under the hysteresis curve gives the energy absorption. Energy absorption of square Hybrid DSTC's with different steel tube thicknesses were calculated from hysteresis curves. Table 15 shows the Results of energy absorption of square Hybrid DSTC's with different steel tube thicknesses. Chart 6 shows the comparison of hysteresis curves of square Hybrid DSTC's with different steel tube thicknesses.

Table -15: Energy absorption of square Hybrid DSTC's with different steel tube thicknesses

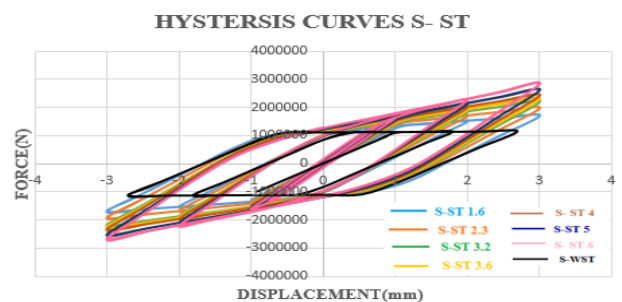| Model name	Steel tube thickness (mm)	Energy absorption (kJ)
S-ST 1.6	1.6	20.927
S-ST 2.3	2.3	25.975
S-ST 3.2	3.2	26.213
S-ST 3.6	3.6	26.847
S-ST 4	4	27.205
S-ST 5	5	27.552
S-ST 6	6	28.334
S-WST	-	29.013

Chart -6: Hysteresis curves for square Hybrid DSTC with different steel tube thicknesses

From the results we can infer that, the introduction of steel tube increases the energy absorption capacities of square Hybrid DSTC's. The energy absorption capacities of square Hybrid DSTC's were increasing with increase in steel tube thicknesses. And also found that the square Hybrid DSTC of steel tube thickness of 6 mm has the highest energy absorption capacity of 29.013 kJ. And the energy absorption capacity of S-WST is very lower when compared to square hybrid DSTC's with different steel tube thicknesses.

6.11 Effect of Different FRP's on Square Hybrid DSTC's

Total Deformation

The Total deformation for different FRP's such as GFRP, CFRP, AFRP and BFRP of square Hybrid DSTC's were obtained. Fig 20 shows the total deformation obtained from Ansys software for square Hybrid DSTC's with different FRP's.
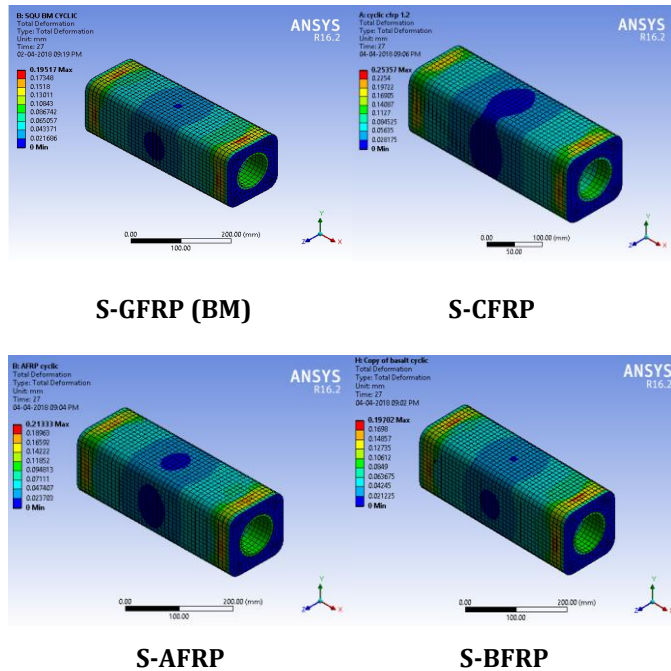

S-GFRP (BM)   **S-CFRP**

S-AFRP   **S-BFRP**

Fig -20: Total deformation for square Hybrid DSTC's with different FRP's

From the results it was inferred that, the total deformation of square Hybrid DSTC's with GFRP tube has the least deformation of 0.19517 mm and with CFRP tube has the highest deformation of 0.25357 mm.

Energy Absorption

From the Ansys software, the hysteresis curves for different FRP's of square Hybrid DSTC's were obtained. The area under the hysteresis curve gives the energy absorption. Energy absorption of square Hybrid DSTC's with different FRP's were calculated from hysteresis curves. Table 16 shows results of energy absorption of square Hybrid DSTC's with different FRP's. Chart 7 shows the comparison of hysteresis curves of square Hybrid DSTC's with different FRP's.

Table -16: Energy absorption of square Hybrid DSTC's with different FRP's

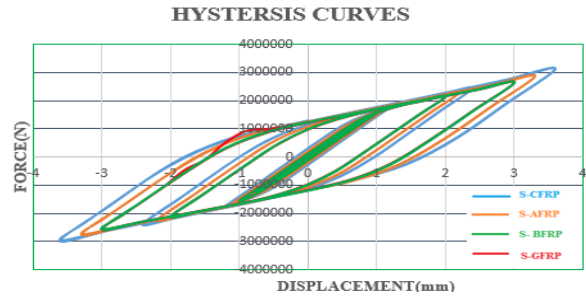| Model name	FRP used	Energy absorption (kJ)
S-GFRP	GFRP	39.672
S-CFRP	CFRP	33.960
S-AFRP	AFRP	28.812
S-BFRP	BFRP	28.334

Chart -7: Hysteresis curves for square Hybrid DSTC with different FRP's

From the results we can infer that, the square Hybrid DSTC's with CFRP tube has the highest energy absorption capacity of 39.672 kJ compared to other FRP tubes. And also found that the square Hybrid DSTC with GFRP tube has the least energy absorption capacity of 28.334 kJ.

6.12 Effect of H/t_c Ratio on Square Hybrid DSTC's

Total Deformation

The Total deformation for different H/t_c ratios 4.6, 5.3, 5.9, 6.6, 7.2 and 7.9 of square Hybrid DSTC's were obtained. Fig 21 shows the total deformation obtained from ansys for different H/t_c ratios of square Hybrid DSTC's.
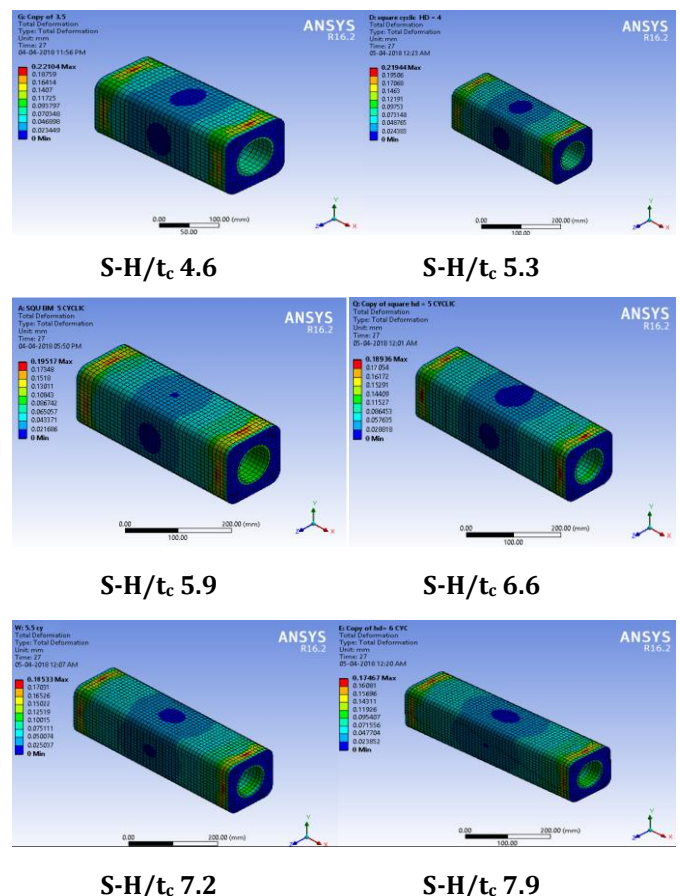

S-H/t_c 4.6   **S-H/t_c 5.3**

S-H/t_c 5.9   **S-H/t_c 6.6**

S-H/t_c 7.2   **S-H/t_c 7.9**

Fig -20: Total deformation for square Hybrid DSTC's with different H/t_c ratios

Energy Absorption

From the ansys, the hysteresis curves for different H/t_c ratios of square Hybrid DSTC's were obtained. The area under the hysteresis curve gives the energy absorption. Energy absorption of square Hybrid DSTC's with different H/t_c ratios were calculated from hysteresis curves. Table 17 shows the results of energy absorption of square Hybrid DSTC's with different H/t_c ratios. Chart 8 shows the comparison of hysteresis curves of square Hybrid DSTC's with different H/t_c ratios.

Table -17: Energy absorption of square Hybrid DSTC's with different H/t_c ratios

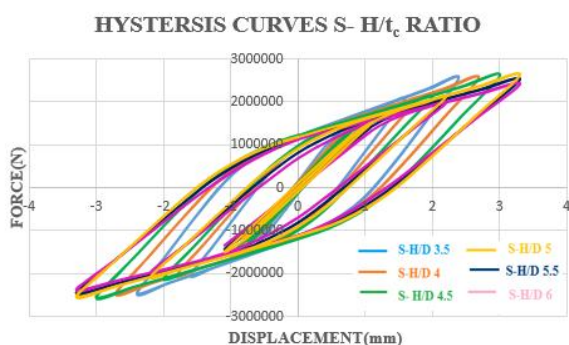| Model name	H/t_c ratio	Energy absorption (kJ)
S- H/t_c 4.6	4.6	22.501
S- H/t_c 5.3	5.3	24.491
S- H/t_c 5.9	5.9	28.334
S- H/t_c 6.6	6.6	29.096
S- H/t_c 7.2	7.2	26.582
S- H/t_c 7.9	7.9	23.81

Chart -8: Hysteresis curves for square Hybrid DSTC with different H/t_c ratios

From the results we can infer that, the energy absorption capacities of square Hybrid DSTC's were increasing with increase in H/t_c Ratio up to 6.6, beyond H/t_c Ratio 6.6 the energy absorption capacities were decreasing. And also found that the square Hybrid DSTC of H/t_c Ratio 6.6 has the highest energy absorption capacity of 29.096 kJ. For H/t_c Ratios 7.2 and 7.9 the energy absorption capacities of square Hybrid DSTC's were found to be decreasing. This decrease in energy absorption capacities may be due to the change in the performance of short column to intermediate column and also the change in failure mode from crushing to bending. As the height of column increases, the energy absorption capacity also increases but up to a limit, beyond the limit the energy absorption capacity decreases due to the change in column type from short column to intermediate column.

7. COMPARISON OF RESULTS OF CIRCULAR AND SQUARE HYBRID DSCTC's

7.1 Circular and Square Hybrid DSTC's Base Models

The energy absorption capacities of circular and square Hybrid DSTC's base models were compared. Chart 9 shows the comparison of energy absorption of circular and square base models.
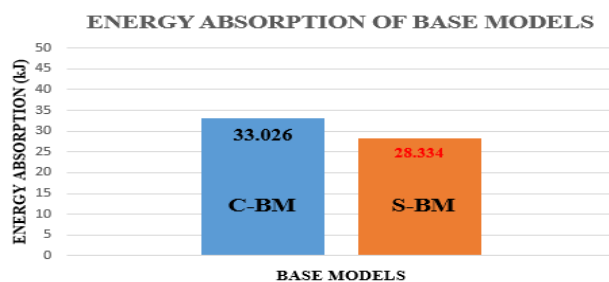

Chart -9: Comparison of energy absorption of circular and square base models

From the results, it is found that energy absorption capacity of circular base model is higher than that of square base model. Thus it is inferred that circular Hybrid DSTC base model is effective over square Hybrid DSTC base model in terms of energy absorption capacity.

7.2 Void Ratios of Circular and Square Hybrid DSTC's

The energy absorption capacities of circular and square Hybrid DSTC's with different void ratios were compared. Chart 10 shows the comparison of energy absorption of circular and square Hybrid DSTC's with different void ratios.
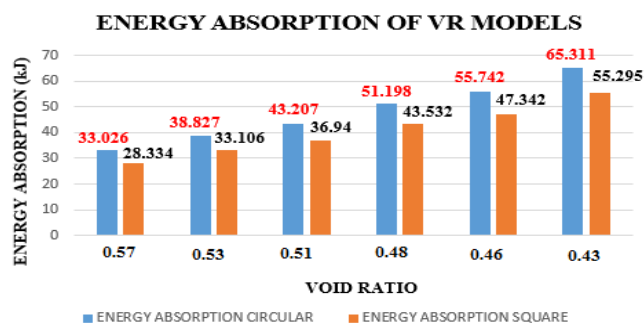

Chart -10: Comparison of energy absorption of circular and square Hybrid DSTC's with different void ratios

From the results, it is inferred that circular Hybrid DSTC's with different void ratios is very effective over square Hybrid DSTC's with different void ratios in terms of energy absorption. The square Hybrid DSTC's with different void ratios has energy absorption capacities lower than that of circular Hybrid DSTC's with different void ratios.

7.3 Steel Tube Thicknesses of Circular and Square Hybrid DSTC's

The energy absorption capacities of circular and square Hybrid DSTC's with different steel tube thicknesses were compared. Chart 11 shows the comparison of energy absorption of circular and square Hybrid DSTC's with different steel tube thicknesses.
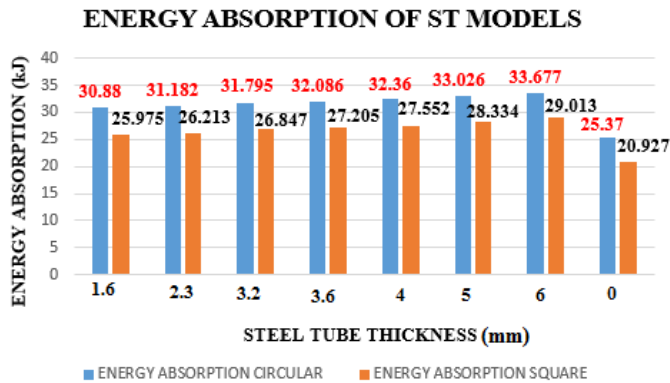

Chart -11: Comparison of energy absorption of circular and square Hybrid DSTC's with different steel tube thicknesses

From the results, it is inferred that circular Hybrid DSTC's with different Steel tube thicknesses is very effective over square Hybrid DSTC's with different Steel tube thicknesses. The square Hybrid DSTC's with different steel tube thicknesses has energy absorption capacities lower than that of circular Hybrid DSTC's with different Steel tube thicknesses.

7.3 Different FRP's of Circular and Square Hybrid DSTC's

The energy absorption capacities of circular and square Hybrid DSTC's with different FRP's were compared. . Chart 12 shows the comparison of energy absorption of circular and square Hybrid DSTC's with different FRP's.
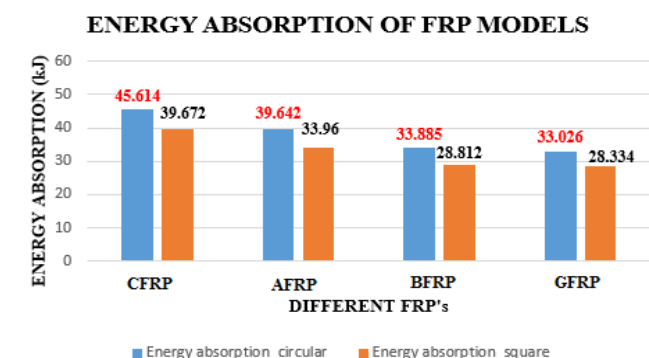

Chart -12: Comparison of energy absorption of circular and square Hybrid DSTC's with different FRP's

From the results, it is inferred that circular Hybrid DSTC's with different FRP's is very effective over square Hybrid DSTC's with different FRP's. The square Hybrid

DSTC's with different FRP's has energy absorption capacities lower than that of circular Hybrid DSTC's with different FRP's.

7.4 H/t_c Ratios of Circular and Square Hybrid DSTC's

The energy absorption capacities of circular and square Hybrid DSTC's with different H/t_c ratios were compared. Chart 13 shows the comparison of energy absorption of circular and square Hybrid DSTC's with different H/t_c ratios.
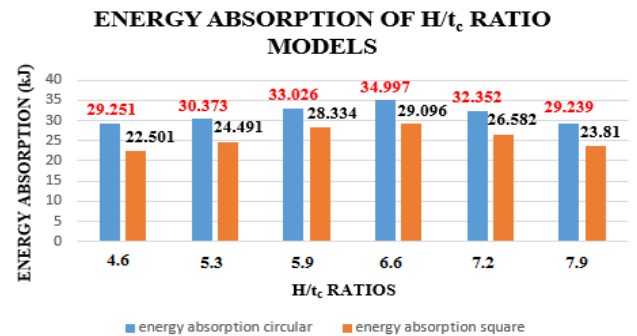

Chart -13: Comparison of energy absorption of circular and square Hybrid DSTC's with different H/t_c ratios

From the results, it is inferred that circular Hybrid DSTC's with different H/t_c ratios is very effective over square Hybrid DSTC's with different H/t_c ratios. The square Hybrid DSTC's with different H/t_c ratios has energy absorption capacities lower than that of circular Hybrid DSTC's with different H/t_c ratios.

8. CONCLUSIONS

The strength behaviour of circular and square Hybrid DSTC's under axial cyclic loading were studied using numerical analysis. The influence of parameters such as void ratios, steel tube thickness, different FRP's and H/t_c ratios on circular and square Hybrid DSTC's were also studied. The circular Hybrid DSTC's were also compared with square Hybrid DSTC's.

The following are the conclusions derived from the studies conducted as part of this study:

Energy absorption

- Circular Hybrid DSTC's are superior to square Hybrid DSTC's.

- Increases with decrease in Void Ratios. This increase may be due to increase in annular concrete section.

- Circular Hybrid DSTC's showed improved performance than square Hybrid DSTC's with different Void Ratios.

- Increases with increase in steel tube thicknesses. This increase may be due to the additional stiffness provided by the steel tube.

- Circular Hybrid DSTC's showed superior performance than square Hybrid DSTC's with different Steel tube thicknesses.

- Increases when CFRP tubes are used in Hybrid DSTC's. This increase may be due to high value of modulus of elasticity of CFRP.

- Hybrid DSTC's with CFRP tubes showed superior performance than Hybrid DSTC's with GFRP tubes.

- Circular Hybrid DSTC's are superior to square Hybrid DSTC's with different FRP tubes.

- H/t_c ratios is an influencing parameter that affects circular and square Hybrid DSTC's.

- Increases up to H/t_c ratio of 6.6

- Decreases beyond H/t_c ratio of 6.6. This decrease may be due to change in the performance of short column to intermediate column, thereby changes the failure mode from crushing to bending.

- From the study it was found that Performance of tube sections can be enhanced by providing inner stiffening steel tubes.

Finally it can be concluded that, Performance of circular Hybrid DSTC's are very effective over square Hybrid DSTC's under axial cyclic loading. Thus the circular Hybrid DSTC's are well suited for seismic regions than square Hybrid DSTC's.

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