AKADÉMIAI KIADÓ

Performance of steel bridge piers filled with lightweight concrete under cyclic loading

Abou Hamza Taha[1*] and Zoltán Orbán[2]

[1] Department of Civil Engineering, Institute of Smart Technology and Engineering, Faculty of Engineering and Information Technology, University of Pécs, Pécs, Hungary

[2] Structural Diagnostics and Analysis Research Group, Faculty of Engineering and Information Technology, University of Pécs, Pécs, Hungary

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ABSTRACT

Concrete-filled steel tube columns are widely used in civil engineering structures due to their excellent ductility, energy absorption capacity, ultimate load-bearing capacity, and seismic behavior. In this paper, a numerical study modeling of eight lightweight concrete and conventional concrete filled steel tubes was carried out using ABAQUS software, and the lateral load-carrying capacity of square and circular steel tubes under cyclic load was compared. The quarter and one-third height of the tubes was filled with concrete with respect to the pier's height, to improve the base performance of the piers. The results show that the capacity of steel tubes filled with lightweight concrete increased by 40%–70% regarding energy absorption. The square tubes showed better performance than the circular tubes in terms of yielding load, yielding displacement, and energy dissipation.

KEYWORDS

lightweight concrete, ABAQUS software, finite element analysis, concrete-filled steel tube, steel bridges piers

1. INTRODUCTION

A concrete filled steel tube Fig. 1 is a composite system that ideally combines the advantages of steel and concrete materials, providing a higher load-bearing capacity due to the superposition of axial strength of the concrete core [1], and the encased steel tube. In addition to high load-bearing capacity, Concrete-Filled Steel Tube (CFST) columns also have high strength, high ductility, and good energy absorption capacities. For these reasons these column systems are widely utilized in modern engineering works for example high-rise buildings and bridges [2]. Because concrete prevents the local buckling of hollow steel sections and increases ductility significantly, steel tubes act as longitudinal and lateral reinforcement for concrete cores making them preferable in high seismic regions [3]. No additional reinforcement is needed for CFST piers apart from the steel tube, which encases the concrete core, and enhances the core's strength, ductility and prevents the concrete from crashing.

2. RESEARCH SIGNIFICANCE

Many researchers of CFST, were considered filling the whole steel tubes with concrete to get higher resistance, and capacity due to the applied loads. Hence this method shows a new attempt aims to increase the capacity of the steel tubes, by filling the critical parts only with Conventional Concrete (CC) or LightWeight Concrete (LWC) where plastic hinges formed, which is the lower part of the piers due to the huge base shear, and bending moment, so by this will not cause an extra vertical loads on the Pier's foundation or the bridge itself as a

*Corresponding author.
E-mail: tahaabouhamza94@gmail.com

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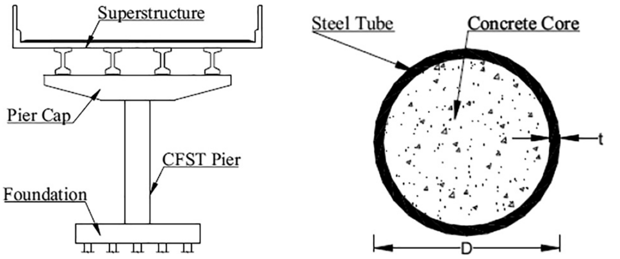

Fig. 1. Cross-section of the concrete-filled steel tube of a bridge pier

whole in case of filling the entire steel tube besides, using LWC, which considered less weight than CC, in brief this method leads to higher capacity with less amount of concrete and less vertical weight.

3. MATERIALS AND METHODS

3.1. Properties of the materials used

C50 and C50.4 grade concrete was used for the modeling of the CC, and LWC respectively, the Poisson ratio is considered as 0.2 for both grades of concrete, and the density of the conventional concrete used was 2,400 kg m^{-3} and 1,400 kg m^{-3} for lightweight concrete, Young's modulus was 33,400 N mm^{-2} and 21,400 N mm^{-2}, respectively. The properties of conventional concrete were derived according to [4] and for the lightweight concrete according to [5].

S355 was the steel grade used in all the modeling, with 18 mm walls, according to Eurocode [6], the yield and ultimate stress of the steel are 355 and 470 MPa, respectively; the Young's modulus of steel is 210,000 MPa. No reinforcement was used in the models because the concrete acted as the filling material.

3.2. Model's specification and detailing

As stated previously there were two types of concrete used and, in addition, there were two heights of concrete inside the tube. The height of the piers was 5 m for all models, quarter height = 0.25 H =1.25 m and one-third height = 0.333 H = 1.65 m, were the two heights of concrete inside the steel tubes. In order to simplify the model's results, Table 1 shows the model Identification (ID), category, and abbreviation.

The concrete was modeled using Finite Element Analysis (FEM) software ABAQUS and to simulate the plastic behavior of the concrete considered in FEM software concrete damage plasticity is used. Hence the stress-strain behavior for both CC and LWC were included in the analysis as well as described in [7].

As it is shown in Table 1, the two types of steel profile are shown in Fig. 2 (all dimensions are in millimeters).

4. ANALYTICAL STUDY

4.1. Finite element modeling

All models either filled or not with concrete, are shown in Figs 3–5 with a longitudinal cross-section for each. The steel part was taken as a shell element with rectangular mesh, and

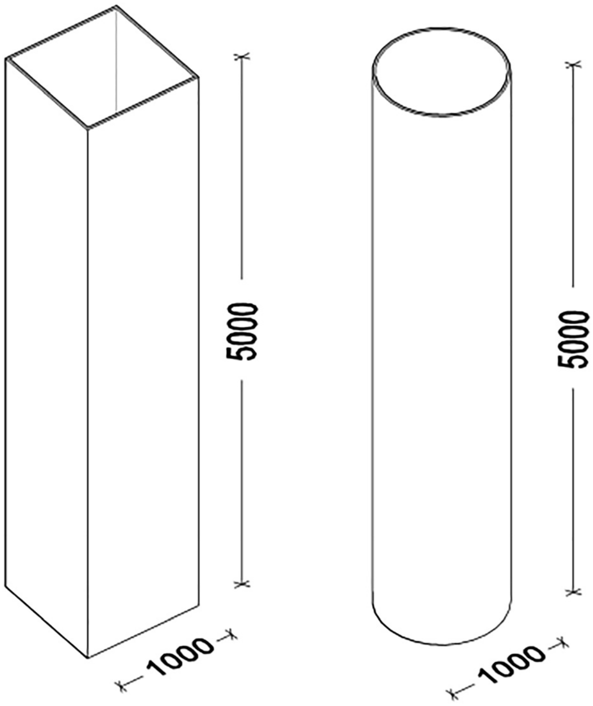

Fig. 2. Square and circle steel dimensions

Table 1. State of all types with ID and abbreviation

Model ID	Category	Abbreviation
SST	Steel (NC)	Square Steel Tube
CST		Circular Steel Tube
CCL4S	Conventional concrete (CC)	Conventional Concrete Filled Steel Tube -(Length/4 = quarter) - Square Steel Tube
CCL4C		Conventional Concrete Filled Steel Tube -(Length/4 = quarter) - Circular Steel Tube
CCL3S		Conventional Concrete Filled Steel Tube - (Length/3 = one-third) - Square Steel Tube
CCL3C		Conventional Concrete Filled Steel Tube -(Length/3 = one-third) - Circular Steel Tube
LWCL4S	Lightweight concrete (LWC)	Lightweight Concrete Filled Steel Tube -(Length/4 = quarter) - Square Steel Tube
LWCL4C		Lightweight Concrete Filled Steel Tube -(Length/4 = quarter) - Circular Steel Tube
LWCL3S		Lightweight Concrete Filled Steel Tube -(Length/3 = one-third) - Square Steel Tube
LWCL3C		Lightweight Concrete Filled Steel Tube -(Length/3 = one-third) - Circular Steel Tube

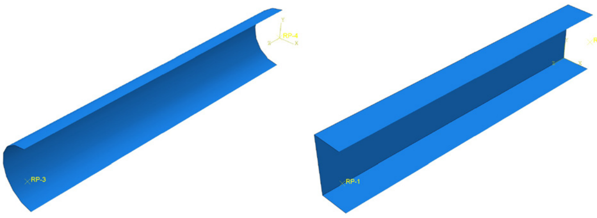

Fig. 3. SST and CST model cross-sections

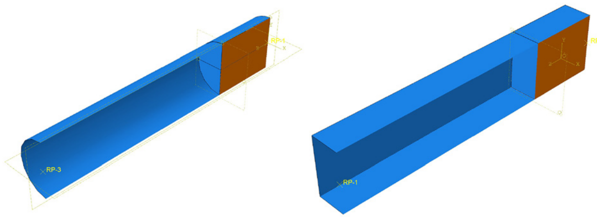

Fig. 4. CCL4C, LWCL4C and CCL4S, LWCL4S models cross-sections

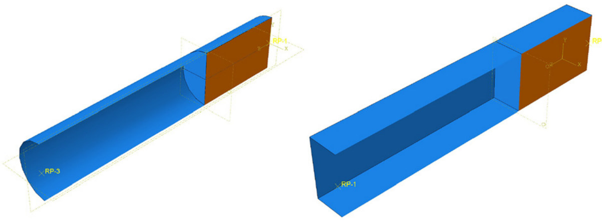

Fig. 5. CCL3C, LWCL3C and CCL3S, LWCL3S models cross-sections

the concrete part as a solid element with hexahedral mesh, with considering matching the size and joints between shells and solids elements.

The interaction between the concrete and steel was taken in normal direction as a hard contact, and in the tangential direction as a friction contact with 0.3 friction factor according to Ding et al. [8] and Li [9]. The same cyclic load as Yadav [10] shown in Fig. 6 was applied on all models at the top of the bridge piers. The bottom side had fixed support.

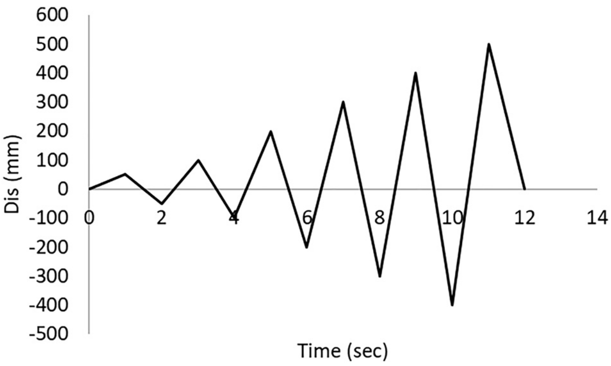

Fig. 6. Cyclic load profile

5. RESULTS AND DISCUSSION

Each variation, shown in Table 1, was modeled and a stress-strain graph computed for the steel and concrete section.

Figure 7 shows the stress of the steel tubes for both square and circular tubes respectively.

For the concrete-filled steel tube using lightweight concrete, the stress of the steel and concrete elements are shown in terms of Von-Mises principles in Figs 8 and 9. Generally, the maximum deformed part near the bottom side as Vulcu et al. [11] and Danku et al. [12], which has red color in the

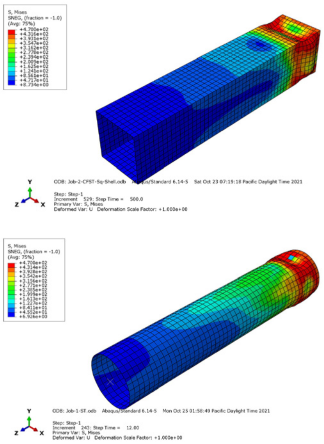

Fig. 7. SST and CST stress contour

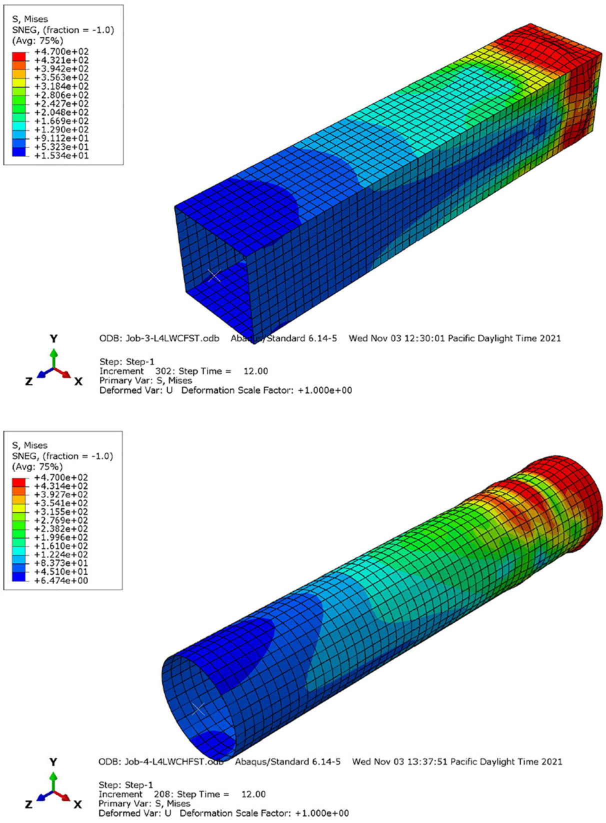

Fig. 8. LWCL4S and LWCL4C steel stress contour

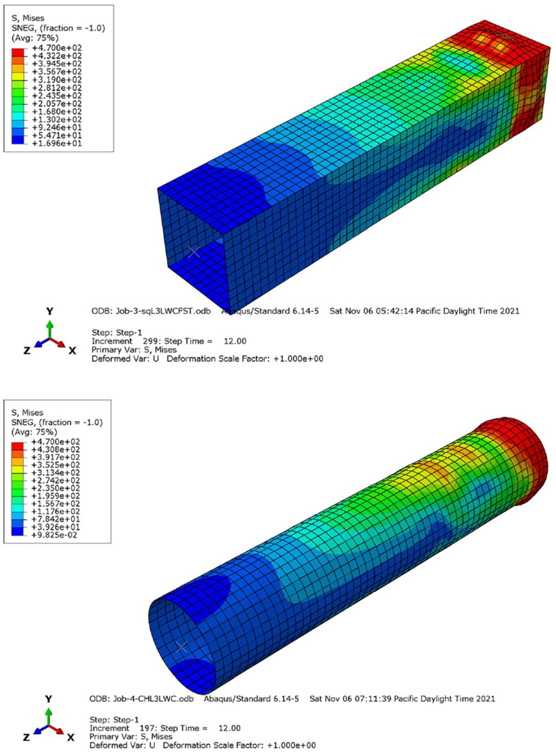

Fig. 9. LWCL3S and LWCL3C steel stress contour

figures referred to the part of steel tube and concrete, which reached their ultimate stress limit of failure, 470 MPa for steel and 50 MPa for concrete.

The square and circular steel tubes deformed at the bottom part of the piers where they were fixed but had different characteristics. The square concrete profile inside the square steel tubes shows the stresses under compression were concentrated at the corners on the upper face of the concrete as it can be seen in Fig. 10, which shows the concentration of stresses at the corners only in red color then the stresses decrease inward, so these corners has reached to the ultimate limit. In contrast, Fig. 11 shows the circular concrete profile inside the circular steel tube and here the stress of compression from the cyclic load was spread over a wider area on the concrete bottom face, and completely different compare to the cubic profile.

Table 2 shows the proportions and mass of materials used in the study. Square profiled steel sections were slightly heavier than the circular profiles, but the biggest difference was whether lightweight concrete or conventional concrete was used. As it is shown in Table 2 LWC was 41.67% lighter than CC.

Along with the cyclic load applied on each model, Table 3 shows the results in terms of the yielding load, ultimate load, yielding displacement, ultimate displacement and energy dissipation, where dissipated energy is calculated

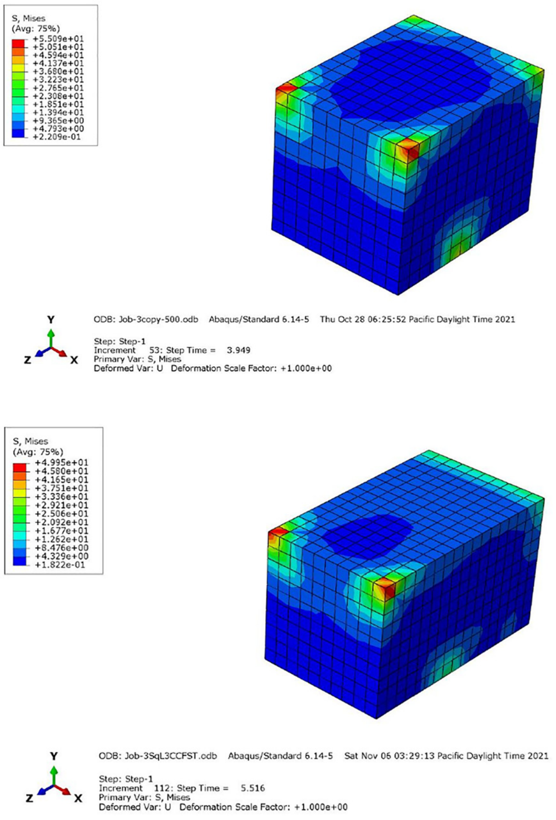

Fig. 10. Concrete stress in case of quarter's and one-third height of the square piers

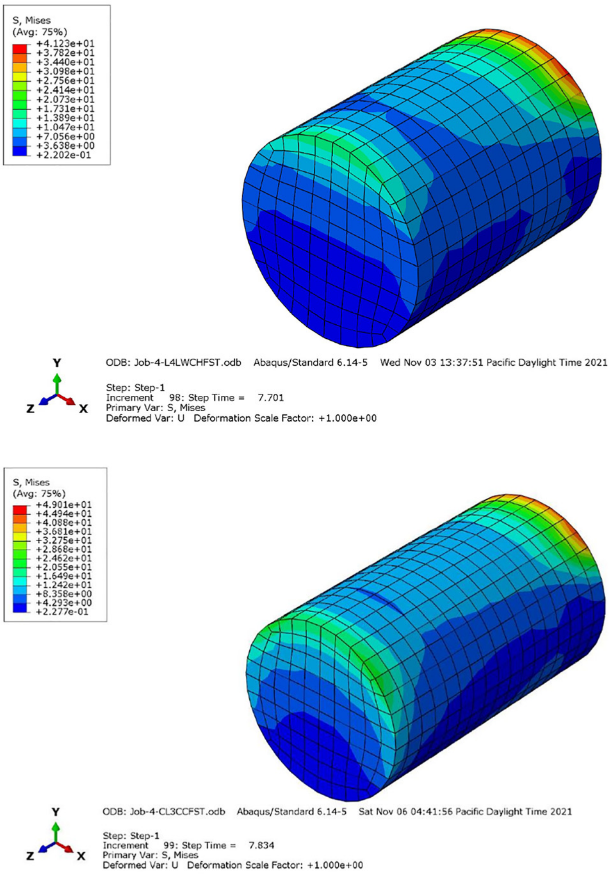

Fig. 11. Concrete stress in case of quarter's and one-third height of the circular piers

Table 2. Weight of steel, concrete and the reduction in weight

Model ID	Weight of Steel (kg)	Weight of Concrete (kg)	Reduction in Weight %
SST	128.6	-	0
CST	101.3	-	0
CCL4S	128.6	2017.2	0
CCL4C	101.3	1584	0
CCL3S	128.6	2664	0
CCL3C	101.3	2088	0
LWCL4S	128.6	1176.7	41.67
LWCL4C	101.3	924	41.67
LWCL3S	128.6	1554	41.67
LWCL3C	101.3	1218	41.67

Table 3. Yielding and ultimate load, displacement and energy dissipation

Model ID	Fy (kN)	Fu (kN)	Dy (mm)	Du (mm)	Energy dissipation
SST	1609.9	2003.3	30.5	49.01	1.67
CST	1140.1	1301.5	37.5	56.25	1.52
CCL4S	1878.7	1893.6	37.2	40.6	2.39
CCL4C	1322.7	1361.8	50.0	59.3	2.28
CCL3S	1968.4	1961.01	40.4	47.82	2.86
CCL3C	1239.1	1412.5	39.1	68.3	2.26
LWCL4S	1875.7	1895.4	33.6	38.4	2.35
LWCL4C	1198.4	1377.9	39.1	68.3	2.27
LWCL3S	1924.2	1925.1	40.6	49.4	2.85
LWCL3C	1230.8	1406.9	39.6	68.5	2.25

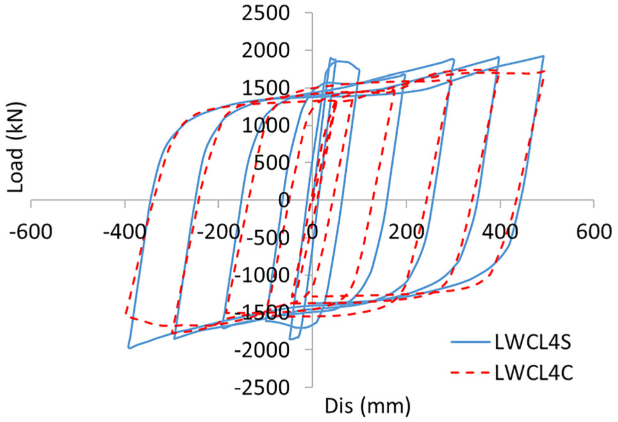

Fig. 13. Cyclic loops of LWCL4S and LWCL4C

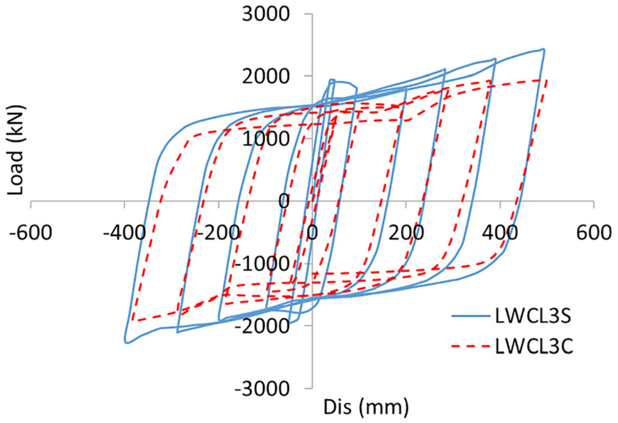

Fig. 14. Cyclic loops of LWCL3S and LWCL3C

by measuring the area of the loops for each model using AutoCAD software.

Table 3 shows that LWC gives similar results to the CC models with the same cross-section, which means that using lightweight concrete has the same capacity for absorbing the cyclic applied load but has 41.67% less weight in concrete.

Comparing the circular cross-section with the square cross-section results in Fig. 12, the circular piers give less capacity in terms of yielding load compared to the square profile.

Figures 13 and 14 compare the square and circular profiles for both quarter and one-third heights of tubes filled with concrete. The square profile gives a higher-yielding capacity and also higher energy absorption, the circular section shows 97% of the energy absorption compared with square tubes in the case of quarter height of tubes filled with concrete and 80% for one-third height of tubes filled with concrete.

Figure 15 shows the effectiveness of filling the steel tube with LWC, which means the bottom part of the tube has higher friction between the concrete and the steel, which

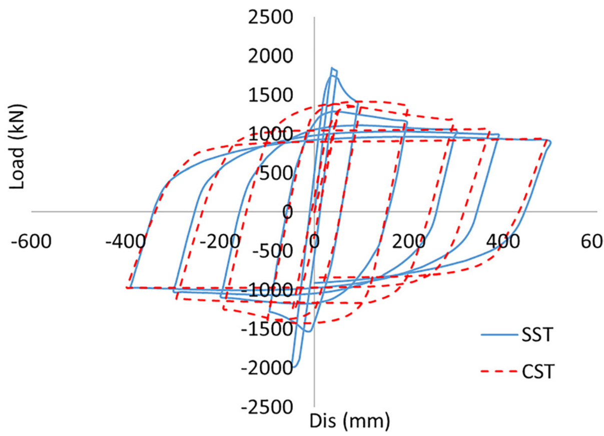

Fig. 12. Cyclic loops of SST and CST

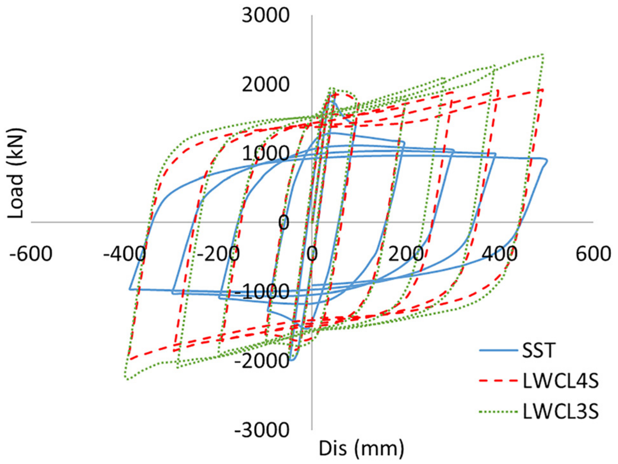

Fig. 15. Cyclic loops of SST, LWCL4S and LWCL3S

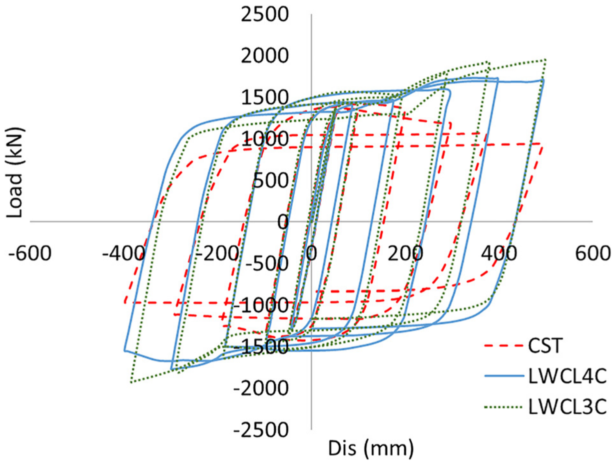

Fig. 16. Cyclic loops of CST, LWCL4C and LWCL3C

means the cyclic loop of model LWCL4S is 40% higher than the square steel tube without it, and 70% higher for LWCL3S model.

Similarly, Fig. 16 shows the effectiveness of filling the circular tube with LWC, both LWCL4C and LWCL3C models give 49% higher capacity than the ordinary circular steel tube.

6. CONCLUSION

This study involves the analytical investigation on CFST using ABAQUS software, The following conclusions are drawn based on finite element analysis:

- Lightweight concrete gives almost similar performance to conventional concrete models for both square and circular tubes;
- Square tubes show higher capacity in terms of yielding load compared to circular tubes;
- Circular tubes show higher capacity in yielding displacement compared to square tubes;
- CCL3S shows the highest capacity in terms of energy dissipation compared to others;
- Absorbed energy of CCL4C is equal to 97% from the CCL4S capacity and 80% in the case of CCL3C compare to CCL3S;
- Absorbed energy of LWCL4C is equal to 96% from the LWCL4S capacity and 78% in the case of LWCL3C compare to LWCL3S;
- Introducing lightweight concrete in construction as a filler material reduce the vertical loads of the bridge piers by 41.7% in addition getting similar performance compare to conventional concrete which leads to lower costs for a project as whole.

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