Investigation of Effects of the Angles of Carbon Fibers for the Strengthening of Thin-Walled Cylinders under Compressive Loads

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1. Introduction

Thin-walled steel cylinders (TSCs) have been widely used in many fields of civil engineering and play an important role in the development of infrastructures and the economy. Because TSCs have very thin thicknesses, they are susceptible to buckling when subjected to loading. These structures need to be strengthened to ensure the sustainable development of infrastructures and the economy. Recently, the use of Carbon Fiber Reinforced Polymers (CFRPs) for strengthening in civil infrastructure applications has been popular because CFRPs have many advanced properties such as high specific strength, lightweight and high corrosion resistance. In this study, the effects of the angles of carbon fibers for the strengthening of TSCs under compressive loads are investigated by the experiments and finite element analysis (FEA).

2. Specimen preparation and experimental setup

Two kinds of carbon fiber sheets (CF) are employed: unidirectional CF (UT70-20) and bi-directional CF (BT70-20). The CF UT70-20 is used to strengthen in 0 degrees (UT0) or 90 degrees (UT90), whereas, CF BT70-20 is used for 0 and 90 degrees strengthening (BT0/90). The epoxy E2500 (a product of Konishi, Japan) is used to connect the CF sheets to TSCs. E2500 has elastic modulus and Poisson's ratio values of 4.1 GPa and 0.37, respectively. The material properties of CFRP layers are calculated from the lamination theory, as shown in Table 1. In the table, t_f, t_m, and t_c are the thickness of carbon fiber, epoxy, and CFRP layer, respectively; V_f and V_m are the volume fraction of carbon fiber and epoxy, respectively; E_x and E_y are the elastic modulus of CFRP layers in x and y direction (circumferential and vertical direction); G_{xy} is the shear modulus of CFRP layer.

Table 1. Thickness and mechanical properties of CFRP layers

CFRP layer	t_f [mm]	t_m [mm]	t_c [mm]	V_f [%]	V_m [%]	E_x [MPa]	E_y [MPa]	G_{xy} [MPa]	Poisson's ratio
UT0	0.222	0.41	0.63	35	65	88415	6251	2283	0.3
UT90	0.222	0.41	0.63	35	65	6251	88415	2283	0.3
BT0/90	0.224	0.42	0.64	35	65	47562	47562	2283	0.04

TSCs used in the experiments are machined from the seamless mild steel pipes (STKM13A, the original outside diameter of 267.4 mm and original thickness of 8 mm). After machined by numerically controlled lathe, these TSCs have 200 mm heights, 2.0 mm thicknesses and 260mm outside diameters. TSCs have the average yield tress of 286 (MPa), which is determined from material tests. Two CFRP layers are covered within 140mm height at the bottom of the TSCs; while three CFRP layers are covered within 50mm height at the top of the TSCs. The purpose of this work is to prevent the elephant foot bulge's (EFB) occurrence at the top of the TSCs. Figure 1 shows the experimental setup for bare TSC and strengthened TSCs.

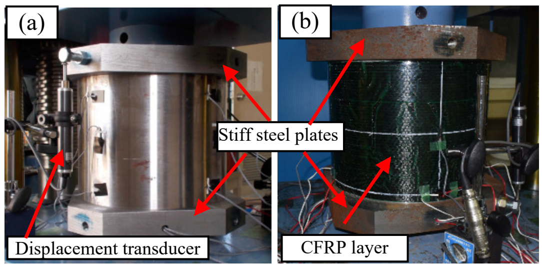

Figure 1: Experimental setup for (a) bare TSC specimen and (b) CFRP-reinforced TSC specimens

3. Finite element analysis (FEA)

Three-dimensional (3D) nonlinear analysis (LUSAS package) is used to analyze the failure buckling modes and the ultimate strength of CFRP-strengthened TSCs under compressive loads. Figure 2 shows the models of TSCs in FEA. In these models, the tank walls are simulated using 3D quadratic 20-node higher-order solid elements (HX20). The CFRP layers are modeled as 8-node higher-order shell elements (QSL8) outside the TSCs with orthotropic materials. Half models are applied because the TSCs are symmetry through the meridional direction. Three elements are applied in the thickness direction of TSCs. In the tank walls, 50 and 120 elements are presented in the half-circumferential direction and in the height direction, respectively (where meshing sizes are approximately 1.66×8mm on the circumferential surfaces). The analysis iteration increments are set to the values of 0.6% maximum loading for the experiments.

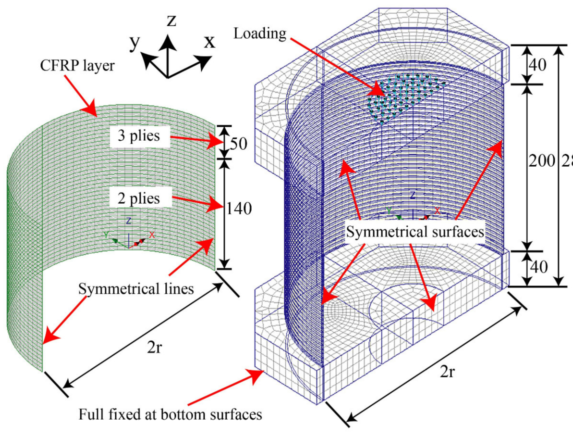

Figure 2. TSC models in FEA

Initial geometric imperfections are considered in FEA. The initial geometric imperfections for TSCs are assumed following Equation 1 (Teng, 2007).

$$w = w_0 \sin(\pi y / L) \cos n\phi, \quad L = 1.728\sqrt{r_0 t_s} \qquad (1)$$

where y is the axial coordinate from one end of the TSC, ϕ is the circumferential angle (radian), w_0 is the amplitude of the imperfection (w_0=2%), L is the half-wavelength of the imperfection in the meridional direction, r_0 is the radius of TSC middle surface, t_s is the TSC's thickness, and n is the number of circumferential waves of the imperfection.

Keywords: Thin-walled steel cylinders, compressive load, CFRP
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4. Results and discussions

Figure 3 shows the failure modes of TSCs. The failure modes are different when the cylinders strengthened by different types of CFRP layers. The failure mode is diamond buckling at the center in specimen UT0 when strengthened with circumferential CFRP layers; whereas, EFB occurs at the base of the tank in the case of UT90 specimen. Debonding also occurs between the CFRP layer and steel for the UT90 specimen. There is a combination of EFB and diamond buckling (DB) in the case of the BT0/90 specimen.

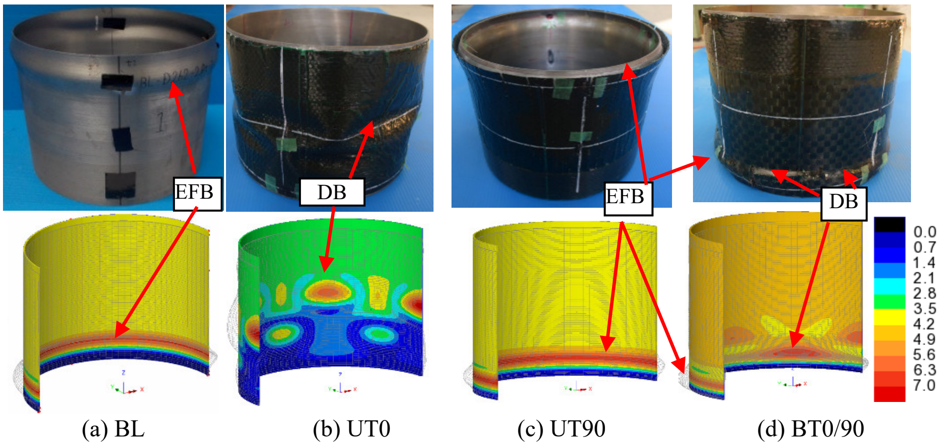

Figure 3. Deformation of TSCs specimens in experiments and FEA. Unit (mm)

The main failure mode is EFB at the base of the cylinder in BT0/90specimen. However, some DB occurred at the bottom corner parts of the cylinder in the case of the BT0/90 specimen. There are good agreements between FEA and experimental results about failure modes. However, the debonding failure between the CFRP layer and steel cannot perfectly be analyzed in FEA because of the capacity of the software.

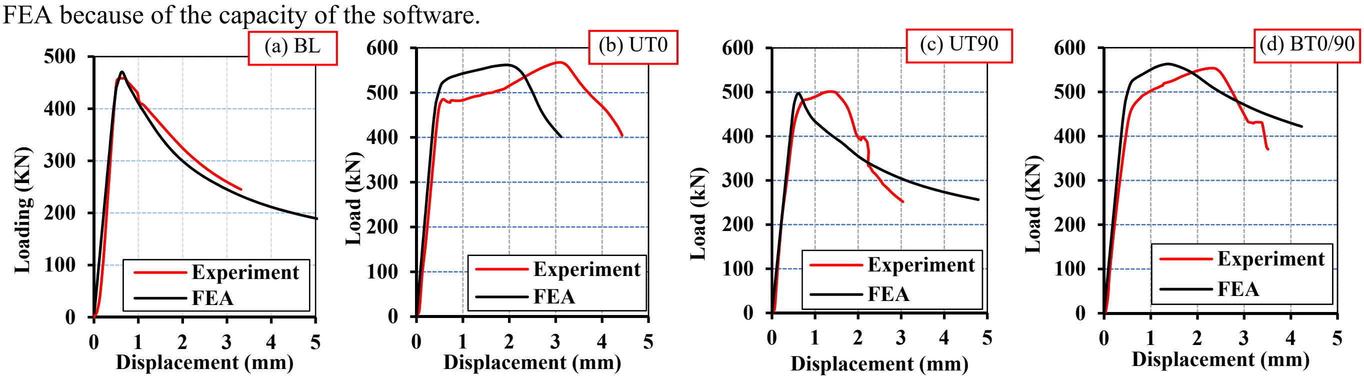

Figure 4. Load-displacement relations of all specimens

Figure 4 shows the load-displacement relations obtained from experiments and FEA. The displacements are measured from the displacement transducers, as shown in Figure 1. There are quite good correspondences between experimental and FEA results. The load-displacement relations are different after steel passing the yield stress until reaching the maximum loading. The reason is that some minor damage likely occurs between CFRP and steel after steel passing yield stress and before the breaking of CFRP layers. However, out-of-plane deformation can be confined by circumferential CFRP even if the bonding layer is damaged. So, loading was continuously increased after out-of-plane deformation reached enough value for fixing again the connection between CFRP and steel wall. Then, the maximum loads obtained from FEA are good correspondences with experimental results.

Table 2. The maximum loads and strengthening effects of CFRP for TSCs

Specimen	Experiment				FEA			
	BL	UT0	UT90	BT0/90	BL	UT0	UT90	BT0/90
Maximum load (KN)	449.46	567.52	501.24	553.74	456.01	564.5	496.94	563.11
Strengthening effect (%)		26.27%	11.52%	23.20%		25.60%	10.56%	25.29%

Tables 2 shows the maximum loads and strengthening effects obtained from experiments and FEA. There are good agreements between FEA and experimental results. It can be seen that the circumferential CFRP layer (UT0) has the best strengthening effect, following by the BT0/90 CFRP layer. This is because the main failure mode of the cylinder is EFB, so circumferential can be effectively constraint the buckling and increase the load-carrying capacity. Only 90 degrees CFRP layer has a low strengthening effect if the cylinders subjected to axial compression.

5. Conclusions

In this study, the effects of the angles of carbon fibers for the strengthening of TSCs under compressive loads are experimentally and numerically investigated. The results show that circumferential CFRP layers reveal their significant effects on the increased load-carrying capacity of TSCs under axial compression. The appearance of circumferential CFRP layers will bring higher strengthening effects for buckling restraint of TSCs under axial compression. Only 90 degrees of CFRP layers should not be used to strengthen the TSCs under axial compression. In addition, FEA can be used effectively to investigate the strengthening effects of CFRP for TSCs under compressive load.

Reference

Teng JG, Hu YM: Behaviour of FRP-jacketed circular steel tubes and cylindrical shells under axial compression, Construction and Building Materials, Vol.21, pp.827–838, 2007.

