Effects of the Carbon Fiber Orientations for the Strengthening of Thin-Walled Steel Cylinders under Compressive Loads and Bending Shear Loads

P V Nhut¹, Y Matsumoto², T Matsui³, and H Nakamura⁴

¹ Graduate student, Department of Architecture and Civil Engineering, Toyohashi University of Technology, Tempaku-cho, Toyohashi, 441-8580 Japan
² Associate Professor, Department of Architecture and Civil Engineering, Toyohashi University of Technology, Tempaku-cho, Toyohashi, 441-8580 Japan
³ ACM Technology Dept., TORAY Industries, Inc., Nihonbashi-muromachi, Chuoh-ku, Tokyo, 103-8666, Japan
⁴ Associate Professor, Department of Civil and Environmental Engineering, Tokyo Metropolitan University, Minami-Osawa, Hachioji-shi, 192-0397 Japan

Email: phan.viet.nhut.yu@tut.jp

Abstract. In this study, the effects of carbon fiber orientations on the strengthening of small-scale thin-walled steel cylinders (TSCs) under axial compression were experimentally and numerically investigated. Besides, the strengthening effects of various types of carbon fiber reinforced polymers (CFRPs) on the load-carrying capacity of full-scale TSCs were numerically investigated. The results showed that circumferential CFRP layers (0°) have significant effects on the increased load-carrying capacity of TSCs under axial compression, whereas, only 90° CFRP layers had small strengthening effects for TSCs under axial compression. When the TSCs subjected to bending shear loads with high values of internal pressures, the appearances of circumferential fibers also brought better strengthening effects than only the angled fibers for TSCs.

1. Introduction

Large thin-walled steel cylinders (TSCs) are used as fluid tanks, chemical, electric power, food engineering, etc., in many fields of industry and infrastructures. Many of them were constructed a long time ago and suffered degradation because of aging or corrosion. Moreover, a large number of earthquakes with highly recorded magnitudes in recent years, especially in the Pacific Ocean, threaten the safety of not only degraded tanks but also existing healthy tanks [1, 2]. As a result, the strengthening of the tanks against buckling and enhance the ultimate strength of the tanks is necessary to improve performance against seismic events. Recently, carbon fiber reinforced polymers (CFRPs) that are lightweight, very strong, and are resistant to corrosion have been used to increase the load capacity and ductility of steel structures, thus proving to be an economical and reliable strengthening solution [3-7]. However, the study about the use of CFRP for the strengthening of TSCs is limited. Therefore, clear research about the strengthening effects of CFRP on the load-carrying capacity of TSCs is the important work to develop this application.

Some research has been conducted to investigate the strengthening effects of bonded CFRP layers on the increase of the load-carrying capacity of TSCs [8-11]. All the above research focused on the use...
of circumferential CFRP layers for the strengthening of TSCs under axial compression. The results showed that circumferential CFRP layers can restrain the elephant foot bucking (EFB) at the base of TSCs and increase the load-carrying capacity of TSCs. Nhut et al. [12] experimentally investigated the effects of circumferential CFRP layer (0°) and bi-directional CFRP layer (0°/90°) on the strengthening of TSCs against dynamic loads. They concluded that the 0° CFRP layer has better effects than the 0°/90° CFRP layer under dynamic loads. In this study, the effects of carbon fiber orientations on the strengthening of small-scale TSCs under axial compression were experimentally and numerically investigated. Moreover, finite element analysis (FEA) was performed to analyze the strengthening effects of different types of CFRP layers with various fiber angles on the load-carrying capacity of full-scale TSCs under bending shear loads. The use of FEA has been proven to bring good correspondence between experimental and numerical results [11, 13]. Therefore, FEA is a suitable solution to investigate the strengthening effects of CFRP layers for full-scale TSCs under bending shear loads.

2. Carbon fiber sheets and resin

Two kinds of carbon fiber (CF) sheets, products of Toray Industries, Inc., were employed: unidirectional CF (UT70-20) and bi-directional CF (BT70-20). The CF UT70-20 was used to strengthen in 0° (UT0) or 90° (UT90), whereas, CF BT70-20 was used for 0°/90° strengthening (BT0/90) or ±45° strengthening (BT45). ±45° CF sheets were applied by rotating the 0°/90°CF sheets to 45°. The CFRP-strengthened specimens were molded following the next two steps: First, we applied primer resin (E810LS, Konishi, Osaka, Japan) for the strengthened positions and waited around 24 hours for the curing. Second, the CFRP layers were bonded and molded on the outside surfaces of TSCs using impregnation epoxy (E2500-Konishi, Osaka, Japan) by hand lay-up molding method. E2500 has elastic modulus and Poisson’s ratio values of 4.1 GPa and 0.37, respectively.

The CF sheets were bonded onto the outside surfaces of TSCs for strengthening. The CF sheets after impregnating with E2500 resin created CFRP layers. The material properties of one CFRP layer were calculated from the lamination theory, as shown in Table 1. In the table, \( t_f \) and \( t_c \) are the thickness of carbon fiber and CFRP layer, respectively; \( V_f \) is the volume fraction of carbon fiber and epoxy; \( E_x \) and \( E_y \) are the elastic modulus of CFRP layers in \( x \) and \( y \) direction (circumferential (0°) and vertical direction(90°)); \( G_{xy} \) is the shear modulus of CFRP layer.

| Type | CFRP layer | Carbon Fiber Orientation | \( t_f \) (mm) | \( t_c \) (mm) | \( V_f \) (%) | \( E_x \) (MPa) | \( E_y \) (MPa) | \( G_{xy} \) (MPa) | Poisson’s ratio |
|------|------------|-------------------------|---------------|---------------|--------------|-------------|-------------|----------------|----------------|
| A    | UT0        | 0°                      | 0.222         | 0.63          | 35           | 88415       | 6251        | 2283           | 0.3            |
| B    | BT45       | ±45°                    | 0.224         | 0.64          | 35           | 8360        | 8360        | 22874          | 0.83           |
| C    | BT0/90     | 0°/90°                  | 0.224         | 0.64          | 35           | 47562       | 47562       | 2283           | 0.04           |
| D    | UT90       | 90°                     | 0.222         | 0.63          | 35           | 6251        | 88415       | 2283           | 0.3            |

3. Investigation models

Figure 1 shows two types of models using for the investigation. Small-scale TSCs were subjected to compressive loads, whereas, full-scale TSCs were subjected to bending shear loads (horizontal shear load and inside internal pressures). In the figure, \( h \) is the height of TSC, \( h_{CF} \) is the height of the strengthened CFRP layer, \( d \) is the outside diameter of TSC, and \( l \) is the distance from the base of TSC to the point that horizontal loading is applied (top of the rigid roof).

The effects of carbon fiber orientations on the strengthening of small-scale TSCs were investigated by both experiments and FEA. Three different types of CFRP layers, including Type A, C, and D, were used to consider the effects of carbon fiber angle for the small-scale models. The small-scale TSCs used in the experiments were 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 had 200 mm heights, 2.0 mm thicknesses, and 260mm outside diameters. The material of small-scale TSCs had an average yield tress of 286 (MPa), which was determined from material tests. Two CFRP layers were covered within 140mm height at the bottom of the TSCs; while three CFRP
layers were covered within 50mm height at the top of the TSCs. The purpose of this work was to prevent the elephant foot bulge (EFB) occurrence at the top of the TSCs. EFB was a main failure mode of TSC under compressive loading. In the experiment, the EFB could occur at the top or bottom of TSCs if the same CFRP layers were applied on the TSC’s walls because symmetrical loading conditions were applied at the top and bottom of TSCs. Therefore, covering three CFRP layers could prevent the EFB occurrence at the top of TSCs, making the investigation of the effects of carbon fiber orientations easier.

For the second type model, full-scale TSC with the dimension $l/h/r/t$ (mm) = 6200/5000/4990/10 was used for the strengthening of CFRP layers. Here, $r$ is the inside radius of TSC and $t$ is the thickness of TSC. The materials of the full-scale TSCs are assumed using SS400 steel (Japanese Industrial Standard) with a yield stress of 235 MPa and an elastic modulus of 205 GPa. FEA was used for the analysis of 36 models with different types of CFRP layer strengthening, which were divided following the notation $D_{n;0^\circ \rightarrow 100}$. Figure 2 describes the parameters of this notation. Internal pressures were applied onto the inside surfaces of TSCs. Two types of internal pressures were assigned in the analysis with the ratios $\sigma_h/\sigma_y = 0.5$ and $\sigma_h/\sigma_y = 0.7$. Here, $\sigma_h$ is the tensile hoop stress and $\sigma_y$ is the yield stress of SS400 steel. From the tensile hoop stress $\sigma_h$, the values of the internal pressures are defined by equation (1) with $r_1$ is the mean radius of the TSC. Three types of CFRP layers: Type A, B, and C with different orientations of carbon fibers were used to strengthen the TSCs. Every type of CFRP layers was used to strengthen 20%, 50%, and 100% of the height of TSC and subjected to two levels of internal pressures. Tables 2 and 3 show the kinds of TSCs analyzed by FEA.

$$p = \sigma_h t / r_1 \tag{1}$$

The numbers of CFRP layers

The direction of the CFRP layers ($D$= $0^\circ; 45^\circ; 0^\circ; 90^\circ$ or $D$=Type A; Type B; Type C)

4. Effects of the angles of carbon fibers on the strengthening of TSCs under compressive load

4.1. Experimental setup

All small-scale TSCs were tested using a 1000 kN universal testing machine (Maekawa Testing Machine MFG Co., Ltd., Tokyo, Japan), as shown in Figure 3. Bare small-scale TSC (NS) and three small-scale TSCs strengthened with Type A, C, and D CFRP layers (namely UT0, UT0/90, and UT90) were used for compressive tests. These specimens were held in a groove fitted to a steel cylinder at a depth of 2 mm on the top and bottom ends and were sandwiched by the loading steel plate (see Figure 3).
Table 2. Models in FEA in the cases of $\sigma_h/\sigma_y = 0.5$.

| Model | (NS1) Without strengthening | (A6-1) | (B6-1) | (C6-1) | (A12-1) | (B12-1) | (C12-1) |
|-------|-----------------------------|--------|--------|--------|---------|---------|---------|
|       |                             | ($0^\circ$)$_{0,20}$ | ($\pm 45^\circ$)$_{0,20}$ | ($0^\circ$/90$^\circ$)$_{0,20}$ | ($0^\circ$)$_{12,20}$ | ($\pm 45^\circ$)$_{12,20}$ | ($0^\circ$/90$^\circ$)$_{12,20}$ |
| Model | (A6-2)                      | ($0^\circ$)$_{0,50}$ | ($\pm 45^\circ$)$_{0,50}$ | ($0^\circ$/90$^\circ$)$_{0,50}$ | ($0^\circ$)$_{12,50}$ | ($\pm 45^\circ$)$_{12,50}$ | ($0^\circ$/90$^\circ$)$_{12,50}$ |
| Model | (A6-3)                      | ($0^\circ$)$_{0,100}$ | ($\pm 45^\circ$)$_{0,100}$ | ($0^\circ$/90$^\circ$)$_{0,100}$ | ($0^\circ$)$_{12,100}$ | ($\pm 45^\circ$)$_{12,100}$ | ($0^\circ$/90$^\circ$)$_{12,100}$ |

Table 3. Models in FEA in the cases of $\sigma_h/\sigma_y = 0.7$.

| Model | (NS2) Without strengthening | (A6-4) | (B6-4) | (C6-4) | (A12-4) | (B12-4) | (C12-4) |
|-------|-----------------------------|--------|--------|--------|---------|---------|---------|
|       |                             | ($0^\circ$)$_{0,20}$ | ($\pm 45^\circ$)$_{0,20}$ | ($0^\circ$/90$^\circ$)$_{0,20}$ | ($0^\circ$)$_{12,20}$ | ($\pm 45^\circ$)$_{12,20}$ | ($0^\circ$/90$^\circ$)$_{12,20}$ |
| Model | (A6-5)                      | ($0^\circ$)$_{0,50}$ | ($\pm 45^\circ$)$_{0,50}$ | ($0^\circ$/90$^\circ$)$_{0,50}$ | ($0^\circ$)$_{12,50}$ | ($\pm 45^\circ$)$_{12,50}$ | ($0^\circ$/90$^\circ$)$_{12,50}$ |
| Model | (A6-6)                      | ($0^\circ$)$_{0,100}$ | ($\pm 45^\circ$)$_{0,100}$ | ($0^\circ$/90$^\circ$)$_{0,100}$ | ($0^\circ$)$_{12,100}$ | ($\pm 45^\circ$)$_{12,100}$ | ($0^\circ$/90$^\circ$)$_{12,100}$ |

4.2. Finite element analysis

Three-dimensional (3D) nonlinear analysis (LUSAS package) was used to analyze the failure buckling modes and the ultimate loads of CFRP-strengthened TSCs under compressive loads. Figure 4 shows the models of TSCs in FEA. In these models, the TSC walls were simulated using 3D quadratic 20-node higher-order solid elements (HX20). The CFRP layers were modeled as 8-node higher-order shell elements (QSL8) outside the TSCs with orthotropic materials. Half models were applied because the TSCs were symmetrical through the meridional direction. Three elements were applied in the thickness direction of TSCs. In the TSC walls, 50 and 120 elements were 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 were set to the values of 0.6% maximum loading for the experiments.

![Figure 3: Experimental setup for (a) bare TSC specimen and (b) CFRP-reinforced TSC specimens.](image)

![Figure 4: Small-scale TSC models in FEA. Unit: mm.](image)

Initial geometric imperfections were considered in FEA. The initial geometric imperfections for TSCs were assumed following equation (2) [14].

$$w = w_0 \sin(\pi y / L) \cos\phi,$$

$$L = 1.728\sqrt{\frac{d}{f}},$$

where $y$ is the axial coordinate from one end of the TSC, $\phi$ 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.

4.3. Experimental and FEA results

Figure 5 shows the failure modes of TSCs under compressive loads. The failure modes were different when the cylinders were strengthened by different types of CFRP layers. The failure mode was diamond buckling at the center in specimen UT0 when strengthened with circumferential CFRP layers; whereas, EFB occurred at the base of the TSC in the case of the UT90 specimen. Debonding occurred between the CFRP layer and steel for the UT90 specimen. There was a combination of EFB and diamond buckling (DB) in the case of the BT0/90 specimen. The main failure mode was EFB at the base of the cylinder in the BT0/90 specimen. However, some DB occurred at the bottom corner parts of the cylinder in the case of the BT0/90 specimen. There were good agreements between FEA and experimental results about failure modes. However, the debonding failure between the CFRP layer and steel could not perfectly be analyzed in FEA.

![Figure 5 Deformation of TSCs specimens in experiments and FEA. Unit (mm)](image)

Figure 6 shows the load-displacement relations obtained from experiments and FEA. The displacements were measured from the displacement transducers, as shown in Figure 3. There were quite good correspondences between experimental and FEA results. The load-displacement relations were different after steel passing the yield stress until reaching the maximum loading. The reason is that some minor damage likely occurred between CFRP and steel after steel passing yield stress and before the breaking of CFRP layers. However, out-of-plane deformation could be confined by circumferential CFRP even if the bonding layer was 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 were good correspondences with experimental results.

Table 4 shows the maximum loads and strengthening effects obtained from experiments and FEA. There were good agreements between FEA and experimental results. It can be seen that the circumferential CFRP layer (UT0) had the best strengthening effect, following by the BT0/90 CFRP layer. This is because the main failure mode of the cylinder was EFB, so circumferential can be effectively constrained the buckling, leading to an increase of the load-carrying capacity. Only 90° CFRP layer had a low strengthening effect if the cylinders were subjected to axial compression.
5. Effects of the angles of carbon fibers on the strengthening of TSCs under bending shear loads

5.1. Finite element analysis models

Figure 7 shows the FEA models for full-scale TSCs. A total of 38 models were analyzed in FEA, as shown in Tables 2 and 3. Half models were used because of symmetrical conditions. In these models, the TSC’s walls were simulated with 3D quadratic solid elements and the TSC’s roofs were used the surface elements with rigid materials. These rigid elements can help the load transfer from the top of the TSC to the TSC’s walls easily. Mesh sizing and the number of analysis iterations play important roles in the analysis. In the TSC’s walls, there were 170 elements in the circumferential direction, 80 elements in the height direction, and 2 elements in the thickness direction. The mesh sizing was divided smaller at the bottom of the TSC so that the convergence of the analysis occurred easily.

In this study, the analysis was stopped when getting one of the two conditions. Firstly, the maximum displacement at the top of the TSC’s wall was constrained to the value of one percent of the TSC’s height (50mm). This is because the big displacement may affect the equipment connected to the TSCs. Secondly, in the cases of strengthening with CFRP layers, the analysis results considered the damage of CFRP layers. The analysis was stopped when the strain in the CFRP layers reached the breaking strain of CFRP layers in fiber direction (1.4%). This breaking strain value was calculated from the properties of the CFRP layer.
The loads were applied to two steps. In the first step, only the internal pressure was applied to the analysis. After finishing this step, the results were fixed and then the horizontal loading was assigned. The values of internal pressures were defined according to the ratios of $\sigma_h/\sigma_y$. Two levels of $\sigma_h/\sigma_y$ (0.5 and 0.7) were surveyed. From the tensile hoop stress $\sigma_h$, the values of the internal pressure were defined by equation (1). The values of internal pressure were 0.235 (MPa) for $\sigma_h/\sigma_y = 0.5$ and 0.329 (MPa) for $\sigma_h/\sigma_y = 0.7$.

Geometrical initial imperfections were neglected in the FEA for full-scale models because these TSCs have very large dimensions and high values of internal pressures. The internal pressures create pressures that can balance the initial geometrical imperfections.

5.2. Buckling modes

Figures 8 and 9 show the buckling modes and von Mises stress of TSCs with all the cases of non-strengthened models and strengthened models. The main buckling mode of TSCs without CFRP layers is EFB. EFB usually appears at the bottom of the TSCs (20% of the height of the TSCs). The EFB occurs easily at the bottom if the ratio $\sigma_h/\sigma_y$ is larger. When strengthening with CFRP layers, the EFB at the bottom of the TSCs was limited and the shear buckling occurred at the TSC’s walls. EFB was moved upper if the numbers of CFRP layers in the circumferential direction was thick enough to restrain this buckling at the bottom as TSCs: A12-1, C12-1, A6-4, C6-4, A12-4, C12-4, A12-5, and C12-5. The prevention of EFB did not occur when using (±45°) CFRP layers. After strengthening with CFRP layers, although EFB was partly prevented, the main failures of TSCs were also EFB while more shear buckling occurred on the TSC’s walls.

Figure 8 The von Mises stress of TSCs in the cases of $\sigma_h/\sigma_y = 0.5$. 
Figure 9 The von Mises stress of TSCs in the cases of $\sigma_h/\sigma_y = 0.7$.

5.3. The strengthening effects of CFRP layers on the increase of the load-carrying capacity of TSCs

The maximum horizontal loads depend on the values of internal pressure, the numbers of strengthening CFRP layers, the strengthening height, and the angle of CFRP layers. Figures 10 and 11 show the maximum loads (for half models) and strengthening effects when TSCs were strengthened with 6 and 12 CFRP layers, respectively.

5.3.1. The effects of the numbers of CFRP layers for the strengthening

The maximum loading decreased when the values of the internal pressure increased with all cases of TSCs. When strengthening with CFRP layers, the maximum horizontal loads of strengthened models increased comparing with non-strengthened models having the same values of internal pressures. Moreover, the increase in maximum loading was corresponding to the increase in the number of CFRP layers. However, when increasing the thickness of strengthening CFRP layers to twice, the increasing effects were not double increase. For example, the increasing effect was 38% for 6-ply CFRP strengthening layer but only 61% for 12-ply CFRP layers ($\sigma_h/\sigma_y = 0.7$).

5.3.2. The effects of the height of strengthening CFRP layers

The results showed that the strengthening effects highly depend on the values of internal pressures. The strengthening effects were higher with higher values of internal pressures in the same strengthening heights. The strengthening effects were nearly the same with 20% and 50% strengthening heights if the ratios $\sigma_h/\sigma_y$ equal to 0.5, whereas, the strengthening effects were a little bit changed if the ratios between hoop stress and yield stress of TSCs were increased ($\sigma_h/\sigma_y = 0.7$). From the results, it is better to choose the method of 20% of heights for strengthening because of economical effectiveness if the ratios $\sigma_h/\sigma_y$ are small. It can be seen that the strengthening effects were highly increased when strengthening with 100% of heights in the cases of Type A and C CFRP layers, especially with higher values of the ratios $\sigma_h/\sigma_y$. 
5.3.3. The effects of the angles of fibers of strengthening CFRP layers

The strengthening effects of different types of CFRP-strengthened layers are related closely to the buckling restraint of the TSCs. The unidirectional CFRP layers can restrain the EFB effectively; whereas the angle-CFRP layers have significant impacts on SB restraint. The failure modes were EFB in the TSCs without strengthening. When strengthening with CFRP layers, SB occurred on the TSC’s walls but the dominant modes were also EFB. This is because the high values of $\sigma_h/\sigma_y$ were focused on this study. That is the reason Type A (0°) and C (0°/90°) CFRP layers had high strengthening effects for the TSCs. From the results, it is better to choose the circumferential (0°) or (0°/90°) CFRP layers to strengthen for TSCs that are subjected to high values of internal pressures under bending shear loads.

6. Conclusion

In this study, the effects of the angles of carbon fibers for the strengthening of TSCs under compressive loads and bending shear loads were investigated. Some following main points are highlighted.

- Circumferential CFRP layers revealed their significant effects on the increased load-carrying capacity of TSCs under axial compression. The appearance of circumferential CFRP layers would 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.
The main buckling failure of full-scale TSCs without CFRP strengthening was EFB. When strengthening with CFRP layers, the EFB at the bottom of the TSCs was limited and the SB occurred at the TSC’s walls.

- The EFB at the bottom of the TSCs could be prevented when using enough CFRP layers at the bottom of the TSCs (20% of heights) with Type A and C CFRP layers. The EFB moved upward if the thickness of the CFRP layer was enough to prevent the EFB.
- When TSCs were subjected to internal pressure with the ratios $\sigma_h/\sigma_y = 0.5$, the strengthening effects were nearly the same with 20% and 50% strengthening heights. Therefore, it is better to choose 20% strengthening heights because of economic benefit.
- Type A and C had better strengthening effects than Type B CFRP layers for TSCs under bending shear loads because the main failure modes of TSCs were EFB. It is recommended that only angled fiber of CFRP layers should not be used to strengthen when the TSCs are subjected to high values of internal pressures and bending shear loads.

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