The Effects of Carbon Fiber Reinforced Polymer Strengthening on Cylindrical Steel Storage Tanks under Bending Shear Load

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Abstract. Large thin-walled cylindrical steel storage tanks play important roles in the development of economy and infrastructures. Storage tanks subjected to internal pressure can cause buckling modes, especially elephant foot bulge at the bottom of the tanks. The design of tanks against buckling is very necessary. In this paper, the load-carrying capacity and the failure modes of the storage tanks subjected to internal pressure under bending shear load will be calculated by the finite element analysis. The results will be compared with the design method from Architectural Institute of Japan. Moreover, this paper will also consider the effects of the use of carbon fiber reinforced polymer layers to strengthen storage tanks against buckling and the increase of the load-carrying capacity of the tanks under bending shear load.

1. Introduction

Large thin-walled cylindrical steel storage tanks (CSSTs) have an extremely important role in the development of economy and infrastructures. They have been widely used in fluid tanks, chemical, electric power, food engineering, etc. CSSTs are also often used as key facilities in the whole production system. The destruction of CSSTs will cause the interruption of the production process, even lead to disaster. Therefore, the evaluation the load-carrying capacity of CSSTs is very necessary. In addition, the most common failure mode of CSSTs subjected to internal pressure is buckling and capacity to buckling resist is an important evaluation item in the design of cylindrical storage tanks. Buckling is a serious failure mode for tanks, which drastically lowers their structural strength and collapses their geometries [1,3]. One of the design standards, which related to cylindrical steel tanks against buckling was introduced by the design recommendation of Architectural Institute of Japan [2]. However, the small-scale tanks were used in the experiments and the accuracy of these small-scale tanks’ results with the large real tanks has not been verified. Actually, the performance of the large real tank’s experiments against buckling is very difficult and costly. In this paper, the finite element analysis (FEA) will be used to analyze the large real CSSTs subjected to internal pressure and the results will be compared with small-scale ones in the design recommendation [2].

Another problem is that a large number of CSSTs have appeared increasing signs of deterioration and reducing load-carrying capacity because of corrosion or aging degradations. For achieving sustainable development of infrastructure and economy, these structures need to be repaired to improve the performance. The conventional method of repairing or strengthening these aging structures often involves bulky and heavy plates that are difficult to fix and prone to corrosion. Moreover, this method
could cause business interruption and the damage of materials. In recent years, the use of carbon fiber reinforced polymers (CFRPs) with many outstanding characteristics such as lightweight, high strength, and high corrosion resistance to increase the load capacity and ductility of steel structures proved to be an economical and reliable strengthening solution [5,6]. In this paper, the authors will consider the effectiveness of CFRP strengthening on buckling restraining of CSSTs subjected to internal pressure under bending shear load using finite element analysis. CFRP layers are unidirectional materials; therefore, they will be applied to the circumferential direction of the tanks. CSSTs strengthened by CFRP layers in this way can restrain the deformation of the tanks in the horizontal direction and limit the elephant foot bulge in the bottom of the tanks. Three models with different geometrical parameters with two values of internal pressure will be surveyed by finite element analysis to investigate the load-carrying capacity and buckling modes of CSSTs. After that, these models with CFRP strengthening will also be simulated by FEA to consider the effects of CFRP layers on buckling protest of CSSTs under bending shear load.

2. Material properties of CFRP layers and steel storage tanks

2.1. CFRP layers
CFRP layers contain CFRP fiber layer and matrix. The volume fraction of fiber \( v_f \) and of matrix \( v_m \) are 50% and 50% respectively. One layer of CFRP and matrix has the thickness of 0.444 mm. The longitudinal modulus of the CFRP fiber and matrix are \( E_f = 245000 \) (MPa) and \( E_m = 4100 \) (MPa) respectively. These properties are calculated by typical carbon fiber properties [4]. From these parameters, the material properties of CFRP layers are determined by the composite rules. Table 1 shows the evaluated properties of CFRP layers. In the table, \( E \) and \( E \) are the longitudinal and transverse elastic modulus of CFRP layers, \( G_{xy} \) is the shear modulus of CFRP layers. \( E_x \) and \( E_y \) are also elastic modulus of CFRP layers in the circumferential (x) and vertical (z) direction in FEA.

| \( E_x \) (MPa) | \( E_y \) (MPa) | \( G_{xy} \) (MPa) |
|----------------|----------------|-----------------|
| 124550         | 8065           | 2946            |

2.2. Steel storage tanks
The tanks use the SS400 steel with the material properties as shown in Figure 1. The yield stress of SS400 steel is 235 (MPa). This is the lowest value of SS400 steel. The stress-strain relationship of steel used for the tanks has the tri-linear shape.

![Figure 1. Material properties of steel.](image)

3. Theory of buckling of CSSTs under bending shear load
According to design recommendation, the buckling of CSSTs subjected to internal pressure depends on the ratio of tensile hoop stress \( \sigma \) caused by internal pressure to the yield point stress of the tank's material \( \sigma_y \). In the region below \( \sigma/\sigma_y = 0.3 \), the buckling occurs in inextensional modes, whereas beyond \( \sigma/\sigma_y = 0.3 \), the buckling occurs in elephant foot bulge mode. In this paper, the design of tanks against the elephant foot bulge will be focused because this kind of failure is very dangerous and remarkably affects the load-carrying capacity of CSSTs.
In the case of the ratio of $\sigma_h/\sigma_y$ over 0.3, the equivalent bending stress $\sigma_c$ of cylindrical steel storage tanks is determined by equations (1) to (4). In these equations, $r$ is the inside radius of the tank, $t$ is the thickness of the tank, and $E$ is the elastic modulus of the tank's material.

$$\sigma_c = \sigma_{cr0} \left(1 - \frac{\sigma_h}{\sigma_y}\right)$$  \hspace{1cm} (1)

$$\frac{r}{t} < 0.069 \frac{E}{\sigma_y} \rightarrow \sigma_{cr0} = \sigma_y$$  \hspace{1cm} (2)

$$\frac{r}{t} > 0.807 \frac{E}{\sigma_y} \rightarrow \sigma_{cr} = \frac{0.8E}{\sqrt{3(1-v^2)}} \left(\frac{t}{r}\right)$$  \hspace{1cm} (3)

$$0.069 \frac{E}{\sigma_y} < \frac{r}{t} < 0.807 \frac{E}{\sigma_y} \rightarrow \text{interpolating } \sigma_{cr0} \text{ from (2) and (3)}$$  \hspace{1cm} (4)

4. Finite element analysis

4.1. Description and generation of 3D finite element models

3D nonlinear analysis (LUSAS package) was used to analyze the failure buckling modes and the ultimate strength of cylindrical steel storage tanks subjected to internal pressure under bending shear load with two cases: without CFRP strengthening and having CFRP strengthening. The simulated models in FEA were followed to the experimental tests of Akiyama in recommendation book [2] so that the results can be compared and evaluated. The configuration of the models is described in Figure 2.

![Figure 2. Half model in finite element analysis and boundary conditions.](image-url)

The simulated tanks had two parts: the tank’s wall and the tank’s roof. In the cases of tanks with CFRP-strengthened layers, CFRP layers are modelled as surface elements at the outside of the tank’s walls as shown in Figure 2. In this paper, three kinds of tanks were modelled with different ratios of inside radius to the thickness of the tank ($r/t$), the height of the tank to the inside radius ($l/r$), and the distance between the lower edge of tank where horizontal loading is applied to the inside radius ($h/r$) (Table 2).
Table 2. Three kinds of models in FEA.

| Parameter | r/t | l/r | h/r | t(mm) | l(mm) |
|-----------|-----|-----|-----|-------|-------|
| Tank 1    | 999 | 0.5 | 0.621 | 10    | 5000  |
| Tank 2    | 749 | 0.668 | 0.828 | 10    | 5000  |
| Tank 3    | 499 | 1    | 1.24 | 10    | 5000  |

Every kind of tank subjected to internal pressure under bending shear loads was considered in three cases: without CFRP strengthening, 5-ply CFRP strengthening, and 12-ply CFRP strengthening. The internal pressure with the ratios $\sigma_h/\sigma_y = 0.5$ and 0.7 was focused on the analysis because the main buckling failure is elephant foot bulge in these cases. In total, there were 18 models in finite element analysis.

In these models, the tank’s walls were simulated with 3D quadratic solid elements and the tank’s roofs were used the surface elements with rigid materials. These rigid elements can help the load transfer from the top of the tanks to the tanks easily. Mesh sizing and the number of analysis iterations play important roles in the analysis. The mesh sizing and the analysis iteration increment must small enough so that the convergence can occur. Also, small mesh sizing assures the accuracy of the analysis results and collapse behavior of the tanks. In this analysis, half models were applied for all the tanks because of symmetrical conditions. In the tank’s walls, there were 170 elements in the circumferential direction, 80 elements in the height direction, and 3 elements in the thickness direction.

4.2. Boundary conditions

The tanks were fixed at the bottom surface, two surfaces on the tank’s walls and two lines on the tank’s roofs were applied symmetrical conditions as shown in Figure 2.

4.3. Loading conditions

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 pressure were defined according to the ratios of the tensile hoop stress $\sigma_h$ to the yield point stress of the tank’s material $\sigma_y$ ($\sigma_h/\sigma_y$). Two levels of $\sigma_h/\sigma_y$ were surveyed 0.5 and 0.7. From the tensile hoop stress $\sigma_h$, the values of the internal pressure were defined by equation (5). The values of internal pressure were presented in Table 3.

$$ p = \frac{\sigma_h l}{r} $$  

(5)

Table 3. The values of internal pressure in three kinds of tanks.

| Internal pressure (MPa) | Tank 1 | Tank 2 | Tank 3 |
|------------------------|--------|--------|--------|
| $\sigma_h/\sigma_y=0.5$ | 0.11762 | 0.1569 | 0.2355 |
| $\sigma_h/\sigma_y=0.7$ | 0.16466 | 0.21963 | 0.32966 |

5. Buckling modes and ultimate strength of cylindrical steel storage tanks in FEA

5.1. Ultimate strength

Table 4 shows the maximum horizontal loading $P_{\text{max}}$ obtained from FEA in the cases of tanks without CFRP strengthening and with 5-ply and 12-ply CFRP-strengthened layers. In the case of tanks without CFRP strengthening, the maximum horizontal loads decreased when the values of the internal pressure increased. When strengthening with CFRP layers, the maximum horizontal loads increased comparing with the cases without strengthening that having the same values of internal pressure. Moreover, the increase of maximum loading is corresponding to the increase of the number of CFRP layers.

Figure 3 and 4 present the relationships between the horizontal loading and the displacement at the top of the tank's wall for all the models. In the cases of tanks without CFRP strengthening, the loading
decreased rapidly after the tanks reached the maximum load capacity. This is very dangerous for the working of the structures. However, when strengthening with CFRP layers, the loading decreased slowly and more stable. This is because the CFRP layers helped to keep the loading decrease slowly. This is very important thing for the buckling restraining of the tanks under the loading, especially seismic loading.

In this paper, the analysis will be stopped when getting one of two conditions. Firstly, the maximum displacement at the top of the tank’s wall was constrained to the value of one percent of the tank’s height (50mm). This is because the big displacement may affect the equipment connected to the tanks.

Secondly, in the cases of strengthening with CFRP layers, the analysis results will consider the damage of CFRP layers. The analysis will be stopped when the strain in the CFRP layers reaches the breaking strain of CFRP layers in fiber direction (1.4%). This breaking strain value was calculated from the properties of CFRP layer (TORAYCA) [4].

### Table 4. The maximum horizontal loading obtained from FEA.

| P<sub>max</sub> (kN) | σ<sub>y</sub>/σ<sub>γ</sub> = 0.5 | σ<sub>y</sub>/σ<sub>γ</sub> = 0.7 |
|---------------------|-----------------|-----------------|
|                     | Tank 1 | Tank 2 | Tank 3 | Tank 1 | Tank 2 | Tank 3 |
| Without strengthening | 18226 | 13833 | 8799 | 16186 | 11417 | 6356 |
| 5-ply CFRP strengthening | 19183 | 14720 | 9871 | 18658 | 13862 | 8098 |
| 12-ply CFRP strengthening | 20091 | 15926 | 10718 | 20743 | 15903 | 10356 |

5.2. Buckling modes

Figure 5 and 6 show the buckling modes and Von Mises stress of tanks without CFRP strengthening and the tanks with 5-ply CFRP-strengthened layers and 12-ply CFRP-strengthened layers in two levels of internal pressure. The main buckling failure of tanks without CFRP strengthening was elephant foot bulge. When strengthening with CFRP layers, the elephant foot bulge at the bottom of the tanks was limited and the shear buckling occurred at the tank’s walls.

6. The correspondence of analysis results compared with theory and strengthening effects of CFRP layers on storage tanks

6.1. The correspondences of analysis results compared with theory in the cases of tanks without CFRP-strengthened layers

In the cases of tanks without CFRP strengthening, the main buckling modes were elephant foot bulge. These results are good correspondence with the design recommendation.

Equations (6) and (7) show the calculation process of the equivalent bending stress σ<sub>cr</sub> of cylindrical steel storage tanks, which was determined from FEA. In these equations, P<sub>max</sub> is the maximum horizontal loading obtained from FEA and A is the sectional area of the half tank.

\[
\tau = \frac{P_{\text{max}}}{A} \tag{6}
\]

\[
\sigma_{cr, FEA} = \tau \frac{h}{r} \tag{7}
\]

Table 5 shows the equivalent bending stress calculated from FEA compared with these values calculated by theoretical equations from the design recommendation. There were large differences in the results between FEA and theory in the case of the ratio σ/σ<sub>γ</sub> = 0.5. With the ratio σ/σ<sub>γ</sub> = 0.7, the results were more accurate with the theoretical equations. This is because the tanks, which were used in the experimental tests in design recommendation were made of very thin shells, whereas, the thickness of the tanks in FEA is much larger. This causes the differences in the behavior under buckling modes. In the case of the ratio σ/σ<sub>γ</sub> = 0.7, the analysis results were approximately same with the results of experimental tests.
6.2. The strengthening effects of CFRP layers on storage tanks

From Figure 3 and 4, it is clear that when strengthening the tanks with CFRP layers, the ultimate strength of the tanks was increased and the increased level of ultimate strength was corresponding with the increase of the numbers of CFRP - strengthened layers. On the other hand, the strengthening would be more effective if the ratio $r/t$ was smaller and the ratio $l/r$ was larger as shown in Figure 7.
6.3. The impact of CFRP strengthening on the decrease of internal pressure inside the storage tanks

When strengthening storage tanks by CFRP layers, the value of internal pressure inside the tanks will be decreased. This is the reason for the increase of the ultimate strength in the tanks with CFRP-strengthened layers. The decrease value of internal pressure can be calculated from the decrease of tensile hoop stress $\sigma_h$ as shown from equations (8) and (9). In these equations, $p$ is internal pressure, $t$ is the thickness of the tank’s wall, $E_{FRP}$ is the elastic modulus of CFRP layers, $t_F$ is the thickness of CFRP layers, and $\sigma_{h,eq}$ is the equivalent tensile hoop stress.

$$\sigma_h = \frac{p \cdot r}{t}$$  \hspace{1cm} (8)

$$\sigma_{h,eq} = \frac{p \cdot r}{t + \frac{E_{FRP}}{E} t_F}$$  \hspace{1cm} (9)

![Figure 6. The Von Mises stress of tanks in the case of $\sigma_h/\sigma_y=0.7$. Unit: MPa.](image)

Figure 8 shows the decrease of the value of internal pressure inside the tanks when strengthening with CFRP layers. In finite element analysis, the same tanks with and without CFRP layers were applied the same value of internal pressure according to the ratio $\sigma_h/\sigma_y$. After analysis completion, the decreased value of internal pressure will be considered and presented by equivalent tensile hoop stress $\sigma_{h,eq}$. From Figure 8, it can be seen that when strengthening with CFRP layers, the ratios $\sigma_h/\sigma_y$ of 0.7 and 0.5 were decreased to ratios $\sigma_{h,eq}/\sigma_y$ of 0.53 and 0.38 respectively. Along with the decrease, the loading was increased with various levels depending on the kinds of models. The increase of the loading was higher with the models which have the ratio $r/t$ smaller and the ratio $l/r$ larger. Besides, the strengthening effects of CFRP layers in the case of $\sigma_h/\sigma_y=0.7$ was remarkably higher compared with the case of $\sigma_h/\sigma_y=0.5$. If using the theoretical equations from design recommendation, the increase of loading when the values of the ratio $\sigma_h/\sigma_y$ decrease from 0.7 to 0.53 and 0.5 to 0.38 would be higher compared with the results in FEA.
Table 5. The values of equivalent bending stress from FEA compared with theoretical equations.

| Equivalent bending stress (KN/cm²) | $\sigma_{cr}/\sigma_y=0.5$ | $\sigma_{cr}/\sigma_y=0.7$ |
|-----------------------------------|---------------------------|---------------------------|
| $P_{max}$ (KN)                    | Tank 1 | Tank 2 | Tank 3 | Tank 1 | Tank 2 | Tank 3 |
| Theory                            | 4.968  | 6.625  | 10.52  | 2.981  | 3.975  | 6.132  |
| FEA                               | 3.604  | 4.865  | 6.97   | 3.201  | 4.016  | 5.035  |
| Variation (%)                     | -27.46% | -26.57% | -33.75% | 7.38%  | 1.03%  | -17.89% |

Figure 7. The strengthening effects of CFRP layer on the increase the ultimate strength of tanks.

Figure 8. The impact of CFRP strengthening on the decrease of internal pressure inside the storage tanks. (1) Without CFRP strengthening, (2) 5-ply CFRP strengthening, and (3) 12-ply CFRP strengthening.

7. Conclusion
In this paper, finite element analysis was used to survey the load-carrying capacity and buckling modes of cylindrical steel storage tanks under bending shear load with and without CFRP strengthening. Three models with different geometry parameters were simulated with two levels of internal pressure. Moreover, the strengthening effects of CFRP layers on the ultimate strength of the tanks was also considered. Based on the analysis and calculated results, some following main points may be highlighted:

- In the case of without CFRP strengthening, the main buckling modes of storage tanks obtained from FEA were elephant foot bulge. These failure modes were very corresponding with the design recommendation of Architectural Institute of Japan. However, there were some differences in ultimate strength of the tanks because the differences in steel materials used. When the ratio of the tensile hoop stress to the yield point stress of the tank’s material was 0.5, the results had about 26% to 33% variation, whereas if this ratio increased to 0.7, the analysis results were more accurate with the design recommendation.
The strengthening effects of CFRP layers on the increase of ultimate strength of storage tanks were clear in this study. The increase of ultimate strength of the tanks corresponds to the increase of the numbers of CFRP layers. On the other hand, the effectiveness of strengthening depends on the ratio of the tank’s radius to the tank’s thickness and the ratio of the height of the tanks to the tank’s radius. If the first ratios were lower and the second ratios were higher, the strengthening by CFRP layer would be remarkably effective. Another issue when strengthening the tanks by the CFRP layers is about the buckling modes of tanks after strengthening. The elephant foot bulge was limited and the shear buckling occurred in the tank’s wall. This is because the CFRP-strengthened layers are unidirectional materials; therefore, the strengthening effects of CFRP layers on the circumferential directions were clear. This restrained the elephant foot bulge in the tanks. However, the effectiveness of strengthening against shear buckling was limited.

When strengthening the tanks by CFRP layers, the impact of internal pressure on the tanks was decreased. This is also the reason for the increase of ultimate strength of the tanks and makes them more safety in the working and production.

8. Future works
The authors will consider the effective and reasonable height of CFRP layers for the strengthening of CSSTs. The results will have important contributions to enlarge this strengthening method in the future.

9. References
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