Effect of Hydrochloric Acid Corrosion and CFRP Coating on the Buckling Behavior of Cylindrical Shells Under External Pressure

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Abstract: Thin walled cylindrical shells are being widely used as silos, liquid tanks, marine structures, and industrial chemical plants. In such applications, the shells are mostly exposed to liquids. When shells filled with low-pH-liquids, corrosion occurs at the surface. Corroded material loss, causes the thickness of the shells to decrease, and it reduces the buckling capacity of shells. Purpose of this study is to investigate the effects of corrosion on the buckling capacity of thin walled cylindrical shells subjected to uniform external pressure. The model shells were half or full filled with 5\% and 10\% HCl (Hydrochloric Acid) solutions for corrosion. To tolerate the negative effects of corrosion, the cylinders were coated with varying sizes of carbon fiber reinforced polymer (CFRP) sheets. Total of 12 models with the dimensions of 800x400x0.45 mm was investigated in this research. The perfect non-corroded models were used to compare the behavior of all the models. Results show that corrosion causes a significant decrease on the buckling capacity of thin walled cylindrical shells. Acid ratio, filling rate and surface area coated with CFRP fabrics affects the buckling capacity of cylinders. Coating the cylinders with one layer of CFRP resulted with tolerating the buckling capacity loss.

Keywords: Cylindrical Shell; HCl; CFRP; Experimental; uniform external pressure.
1. INTRODUCTION

Corrosion is the process of unstable metals returning to their original state in atmospheric environment. When a metal interacts with hydrochloric acid, hydrogen ions take the electrons that the metal loses by oxidation. In this electron exchange on the surface of the metal, the regions where the electrons are being given up are called anodes and the areas where the electrons are being absorbed are called cathodes. Negatively charged ions move from the anode to cathode and positively charged hydrogen ions move from cathode to anode, causing corrosion on the metal surface [1]. The most common effect of corrosion on steel is causing material loss on the surface. This loss causes strength of material to decrease [2-4]. Sharifi and Rahgozar [5] examined the corrosion damage on three steel I beams used in petrochemical industry. They stated that the shear capacity of steel profiles decreased due to corrosion. Lugauskas et al. [6] studied the corrosion behavior of low carbon steel and aluminum in the external environment in rural, marine and industrial areas. Corrosion of steel and aluminum materials depends on the atmospheric corrosion level of the environment. Çelik [7] examined the corrosion behavior of austenitic stainless steels in his study. Local corrosion resistance of austenitic stainless steels such as pitting and crevice corrosion are low. Corroding of this material in the body causes health problems. Qiao [8] examined pipelines with small diameter and observed that the corrosion reduced the thickness of pipelines over time, leading to cracks and failures. Manliza [9] examined the corrosion and cavitation of water pipes in Hong Kong. The corrosion damages the pipe material and poses a health risk, if it interacts with drinking water. Becerra et al. [10] examined the effect of oil content on corrosion of AISI-SAE 1010 carbon steel in oil-in-water emulsions. Electrochemical activity decreases as oil content increases. They stated that in low emulsions with a low content of oil (<20-40%), as the oil content increases, the corrosion rate increases. Patané et al. [11] examined an air cylinder damaged by corrosion. The CO₂ content in the condensed water in the pressurized gas storage tanks decreases the pH value of the water and water with increased acidity causes corrosion in the tank. Kong et al. [12] investigated the galvanic corrosion behavior of the underwater joint in their study. Since the weld metal and base metal are different from each other, the junction areas are vulnerable to galvanic corrosion. Chegeni et al. [13] studied the
effects of corrosion depth and corrosion shape on the performance of thin-walled steel tubes by numeric and experimental methods. The tubes were subjected to combined internal pressure and four-point bending load. They stated that the bending capacity decreased as the depth of corrosion increased. It has been stated that as the surface area affected by corrosion increases, the bending capacity decreases. Zhao et al. [14] investigated the effects of pitting corrosion on the bending capacity of thin-walled cylindrical tubes by nonlinear numerical analysis. They simulated corrosion by reducing the thickness of the cylinder. The corrosion shape affected the bending capacity and buckling caused by corrosion caused a decrease in bending capacity.

Shells are often used in the submarines, missiles, tanks and liquid reservoirs [15-16]. Therefore, it is important to examine buckling behavior under various effects [17]. Maali et al. [18] and Kılıç [19] investigated the effect of size and imperfections on the buckling capacity of shells in their study. It has been observed that the effect of imperfection's increases even more as the height increases. Fatemi et al. [20] examined the buckling behavior of four groups of specimens with varying measures and imperfection magnitudes in their study. As the depth of the initial imperfection's increases, the buckling capacity decreases. Such structures are quite sensitive and are significantly affected by the initial imperfections. Niloufari et al. [21] examined the effect of weld-induced geometric imperfections on the buckling capacity of shells. They studied 12 specimens with different ratios of t/R (where R is the radius of the tanks, and t is the thickness) were tested under hydrostatic pressure. Geometrical imperfections at different t/R ratios may have been decreasing or increasing effect on the buckling capacity of the cylinders.

Fiber-reinforced polymer (FRP) composites are being widely used to strengthen the materials with their high strength to weight ratio and high corrosion resistance [22-25]. FRP's with fibers oriented in the circumferential direction can be used to prevent possible buckling of shells. For circular steel tubes, external FRP confinement is an effective method [26]. Using CFRP for strengthening damaged steel structures is an effective method [27]. Li et al. [28] examined the bond between CFRP plates and corroded steel plates. They stated that the effect of the thickness of the adhesive on the
deformation was higher than the effect of the corrosion time by examining samples at
different corrosion times and adhesive thickness. For corrosion, sodium chloride
solution was sprayed for 5 minutes every four hours. Maali et al. [29] investigated the
effect of dent and CFRP on the buckling behavior of thin-walled steel cylindrical shells.
They studied 14 specimens in two groups with and without CFRP. Dents are placed in
different directions. Buckling behaviors were examined under external pressure. It was
observed that the buckling capacity of the cylinders increased with CFRP reinforcement.
Teng and Hu [30] examined the reinforcement of steel pipes with FRP. Steel pipes were
coated with FRP up to three layers and tested under axial pressure. As the thickness of
the FRP reinforcement increases, the ductility of the steel pipes has increased
significantly. However, since this increase in thickness loses its effect when the pipes
start to buckle from the inside, there is a limited increase in buckling capacities.
Ghazijahani et al. [31] investigated the effect of CFRP on the buckling capacity of timber
filled thin walled steel cylinders. The CFRP reinforced the cylinder against external
buckling. Inward buckling behavior took the control because CFRP couldn’t be effective
as it was in external buckling. The CFRP roller strengthened the cylinders against the
buckling style known as elephant foot buckling.
In this study, the buckling behavior of 12 thin walled cylindrical shells subjected to
uniform external pressure investigated. 10 models corroded with 5% and 10% HCl
solutions and two model tested without corrosion. CFRP's with different lengths
(800mm, 400mm, 100mm) coated to cylinders to tolerate the effects of corrosion.
Cylinders were weighed before and after corrosion and total weight loss observed. All
tests in this research were conducted by the authors in the Steel Structural Lab of
Atatürk University, Erzurum, Turkey. The buckling loads were compared and estimated
according to the theoretical loads of Jawad [32], Venstel and Krauthammer [33], and
Ross [34]. However, the mentioned theories are not designed to determine the corroded
steel tanks, as in this work.

2. Test setup and models

2.1. Preparation of the test setup and cylinders

In this research, an experimental setup is prepared for this work by the authors and
used as shown in Fig. 1. Test setup consists of two steel plates with dimensions of
1500x1500mm and thickness of 30 mm. These plates were cut to exact dimensions with the help of CNC cutting machine. Circular supports were then welded to the plates where the rollers would be placed. Two holes were opened in the middle of the top plate, one for the vacuum pipe and the other in the load cell. In order to control the movement of the upper plate, total of six holes were opened, four are on the corners of the plates, and two are in the middle of the edges. Bolts were placed in these holes. After the preparation of the test setup, the preparation of the test models was started. Three tensile coupon test were performed to obtain the properties of the material. With tests results in the failure and yield stresses were found 342.4 MPa and 198.8 MPa. Modulus of elasticity 210 GPa and the Poisson ratio was 0.29. To prepare 12 cylinder models with the dimensions of 800x400x0.45 mm, rectangular steel sheets with the dimensions of 1260x800 mm and thickness of 0.45 mm were used. The sheets were rolled by the machine used by Maali et al. [35] and Aydin et al. [36]. The joints of the cylinders were attached to each other by soldering. The reason of using the soldering method for the joints is as it provides an advantage in the construction and experiment phases. Soldering is both economic and prevents the possible damage to the thin material [17].

2.2. Corrosion Tests

After the preparation of the cylinders, the preparation phase in the corrosion test was started. First, the rollers weighed before corrosion and noted. To keep the aqueous acid solution in the cylinders without any leaks, cylinders were put on the foam boards. The foam boards were used, because they are impermeable, and they aren’t affected by hydrochloric acid. The cylinders were put on the foam boards firmly and the contact area of the cylinder and foam board were glued with silicon from inside and outside to ensure there are not any leaks. After waiting for the 24-hours period for silicon glue to get dry, cylinder’s impermeability was checked by filling the cylinder with some water. Then, water and acid were filled with the determined ratios as shown in Fig. 2. In this study, hydrochloric acid with a purity of 30-32% and a density of 1.15-1.16 g/cm$^3$ was used to corrode the cylinders. The ratio of hydrochloric acid used is presented in Table 1. The reason for using the acid as 5% and 10% solutions is that it is the general acidic effect taken under consideration for varying purposes at the literature [1, 4, 7, 9, 10]. After filling the cylinders with solutions, the cylinders were kept at room temperature
for a day to complete the corrosion. At the end of the period, the solution was safely emptied, and the cylinders were cleaned. After cleaning, cylinders weighed again and the weight loss caused by corrosion was determined.

### 2.3 Applying CFRP to the cylinders

After the corrosion is completed, Master Brace P 3500 branded special epoxy primer was applied to the outer surface of the cylinders with the help of roller to make CFRP coating. The two parts of the epoxy primer were mixed in the ratio of 1:2.22. After waiting 24 hours for primer to dry, MasterBrace 4500 branded special epoxy adhesive was applied to the cylinders’ surface. Properties of the epoxies used in this research is given in Table 2. Then, appropriate sizes of CFRP were cut and placed on the surface of the model cylinders. The CFRP was wrapped on the surface and epoxy adhesive was applied again. Like the epoxy primer, it takes 24 hours for epoxy adhesive to get dry. In this study, cylinders were only coated with one layer of CFRP. CFRP fabrics used in this study are made of unidirectional and continuous fibers. Other properties of the CFRP fabrics used in this research are presented in Table 3.

### 2.4. The buckling tests

At the last stage, models were placed in the test setup and the contact areas of the rollers with the set setup were glued with silicon to prevent air leaks. External pressure was applied to the cylinders with a vacuum pump that has a hydrostatic pressure capacity of 600 kPa, shown in Fig. 3. Four SDP-300 branded linear variable displacement transducers (LVDT) used to measure the displacements on the cylinders that will occur at different points with external pressure. The LVDT’s used in this research can measure the displacements up to 300mm. LVDT’s are labeled as LVDT 1, LVDT 2, LVDT 3, LVDT 4 and the location of LVDT’s are shown in Fig. 3. Furthermore, the height of LVDT’s are presented in Table 4.

Two TML YEFLA-5 (5mmx3mm dimensions, resistance value 121 Ω ± 0.5%, sensitivity
coefficient $2.1 \pm 2\%$) model strain gauges were used to determine the strain changes in the system. Strain gauges are labeled as VS and HS (VS: Vertical Strain and HS: Horizontal Strain). Heights of Strain Gauges are presented in Table 4. Since strain gauges measure the strains in the elastic region, they play an important role with determining the initial buckling of the cylinders. The cylinder surface was carefully cleaned before the strain gauges were glued. Then, the strain gauges were glued vertically and horizontally with fast adhesive. During the experiment, the behavior of the models was recorded with the camera. The exact time of when the initial, overall, and collapse buckling took place and the locations of the buckling were determined by strain gauges, LVDTs and camera recordings. The mentioned experimental settings are designed according to considerations of Teng et al. [37].

3. Test Results

3.1. Theories for obtaining the buckling load and approximate waves

Buckling loads of the cylinders were calculated with Jawad, Venstel and Krauthammer, Ross theories and compared with the values obtained as a result of the experiment.

According to Jawad’s Theory [32]:

$$P_{cr} = \frac{0.92E\left(\frac{t}{e}\right)^{2.5}}{L\frac{e}{R}}$$

(1)

According to Venstel and Krauthamer’ Theory [33]:

$$P_{cr} = 0.92 \frac{E_t}{L} \left(\frac{t}{r_m}\right)^{1.5}$$

(2)

According to Ross’ Theory [34]:

$$P_{cr} = \frac{2.6E\left(\frac{t}{d}\right)^{2.5}}{H - 0.45\left(\frac{t}{d}\right)^{0.5}}$$

(3)

where;
P_{cr} expresses the critical buckling load for the cylinders,

E expresses modulus of elasticity (young’s modulus) = 210 GPa,

t\equiv t_e expresses the effective thickness= 0.45 mm,

d expresses the diameter of the cylinder=400 mm,

R=r_m expresses the radius of the cylinder=200 mm,

H=L_e=L expresses the length of the cylinder=800 mm.

Buckling load was found 11.6- 11.6- 11.72 kPa according to equations 1-2-3-4 relatively. Approximate number of circumferential buckling waves with external pressure calculated by [20, 37]:

\[ n = 2.74 \frac{R}{L} \sqrt{\frac{R}{t}} \]  \hspace{1cm} (4)

In equation 4, n expresses the approximate buckling waves, R expresses the Radius of the cylinder, t expresses the thickness and L expresses the height of the cylinder. From equation 4 approximate number of buckling waves calculated as 6.29≈ 6-7 and shown in Table 5.

3.2. Buckling load of the models

The photos of the models before and after the tests are given in Figure 4. Pressure-displacement and buckling load-strain curves of all the models are shown in Figure 5 and Figure 6. Each of the breaks in the buckling load-displacement curves represents one or more waves. Initial buckling is the first buckling wave that occurs at the end of the elastic zone. The first break of the curves in Figure 5 shows the initial buckling of cylinders. After initial buckling, cylinders resisted and carried more load without any air leaks. The buckling capacity of cylinders has kept increasing until overall buckling. Overall buckling load expresses the ultimate carrying capacity of cylinders, and it’s the highest value on the buckling load-displacement curves in Figure 5. Between the initial and overall buckling process, more buckling waves have occurred. First break of the curves in load-displacement figures after overall buckling represents the collapse buckling of cylinders. A figure which shows the location of these buckling phases on a graphic is given in Figure 7. The initial buckling, overall buckling and collapse buckling
values of the cylinders are given in the Table 5 and shown in Figure 8. In Figure 8, arrows near the columns shows the increase and decrease between the bucking loads. Under external pressure, it has been observed that horizontal strains are bigger than vertical strains. This can be explained by the size and corrosion effect. Strains were elastic until collapse and at the point of collapse, it is observed that the strains changed from elastic to plastic. The cylinders did not show any buckling behavior before the first buckling, and after the first buckling, they moved to the post-buckling stage. The rate of the increase in buckling capacity, varies between 1.38 times and 4.78 times of the initial buckling. The overall buckling loads range from 27.46% to 79.07% compared to the initial buckling. The collapse buckling loads were ranged between -4.09% and 57.5% compared to initial buckling.

The initial buckling load of the perfect model is presented in Table 5. and Fig. 5. Table 6 shows the change of buckling loads compared to the initial buckling for each model. The overall buckling capacity of the perfect model is 2.34 times greater than the initial buckling, and the collapse buckling is 2.28 times greater than the initial buckling load. The overall buckling is increased by 57.28%, and the collapse buckling load is increased by 56.1% compared to the first buckling. At the perfect model with whole surface CFRP; the overall buckling load is 1.38 times greater than the initial buckling, and the collapse buckling are 0.96 times greater than the initial buckling. The overall buckling capacity increased by 27.46%, the collapse buckling capacity decreased by 4.1% compared to the initial buckling. For this group, the perfect model without CFRP had the greatest increase in the post buckling phase. The initial buckling capacity of the perfect model without CFRP decreased by 66% compared to perfect model with CFRP. When these two models are compared, it is seen that the initial buckling capacity of the cylinder with CFRP is 2.94 times greater than the initial buckling capacity of the cylinder without CFRP. According to these data, the application of CFRP to the cylinders can increase the initial buckling capacity up to 300%.

For the M1-F-A10-CN model, which is fully filled with 10% acid solution, the overall buckling was found to be 3 times greater than the initial buckling, and the collapse buckling was 2.21 times greater than the initial buckling. The overall buckling increased by 66.69%, and the collapse buckling increased by 54.69% compared to the initial
buckling. The initial buckling capacity of M1-F-A10-CN is decreased by 21.66% compared to the perfect one without CFRP. The corrosion decreased the initial buckling capacity of the model. For the model M2-F-A10-CF, which was filled with the same amount of acid solution, but tested with CFRP reinforcement on the entire surface, overall buckling was found 4.78 times of the initial buckling and collapse buckling was found 2.49 times of the initial buckling. For this model, the overall buckling is increased by 79.07% and the collapse buckling increased by 59.89% compared to the initial buckling. For this group, model M2-F-A10-CF had the greatest increase in the post buckling phase. Initial buckling capacity of M2-F-A10-CF decreased by 63.93% compared to perfect model with CFRP. When these two models are compared, it is seen that the initial buckling capacity of the model with CFRP is 1.35 times more than the model without CFRP.

For the M3-F-A5-CN, which is fully filled with the acid ratio 5%, the overall buckling was found 2.37 times of the initial buckling, and the collapse buckling was 1.86 times of the initial buckling. The overall buckling increased by 57.74%, and the collapse buckling increased by 46.14% compared to the initial buckling. Initial buckling capacity of the M3-F-A5-CN model decreased by 15.72% compared to model without CFRP. For the M4-F-A5-CF model, which was filled with the same amount of acid solution but tested with CFRP reinforcement on the entire surface, overall buckling was found to be 3.4 times of initial buckling and collapse buckling was found to be 1.85 times of the initial buckling. The overall buckling increased by 70.62% and the collapse buckling increased by 45.95% compared to the initial buckling, for this model. The initial buckling capacity of the M4-F-A5-CF model decreased by 52.08% compared to the perfect one with CFRP. For this group of models, the model M4-F-A5-CF had the greatest increase in the post buckling phase. When these two models are compared, it is seen that the initial buckling capacity of the model with CFRP is 1.67 times more than the one without CFRP.

The M5-H-A10-CH model, which was half-filled with 10% acid solution and coated with CFRP along the corroded part (up to half the cylinder height), the overall buckling was found to be 2.97 times of the initial buckling and collapse buckling was found to be 1.76 times of the initial buckling. The overall buckling increased by 66.33%, and the collapse
buckling increased by 43.16% compared to the initial buckling. Initial buckling capacity of the M5-H-A10-CH increased by 14.48% and decreased by 60.25%, when compared to perfect model without CFRP, and the perfect one with CFRP, respectively. For the model M6-H-A10-CF, which was half-filled with the same amount of acid solution, but tested with CFRP strengthening on the entire surface of the cylinder, the overall buckling was found to be 3.34 times of the initial buckling and collapse buckling was found to be 2.35 times of the initial buckling. The overall buckling increased by 70.05%, and the collapse buckling increased by 57.5% compared to the initial buckling, for this model. The initial buckling capacity of the M6-H-A10-CF is increased by 42.34% and decreased by 41.04% compared to the perfect model without CFRP, and the perfect model with CFRP respectively. For the model M7-H-A10-C100, the overall buckling was found 2.4 times of the initial buckling, and the collapse buckling was found to be 2.01 times of the initial buckling. The overall buckling increased by 58.41%, and the collapse buckling increased by 50.3% compared to the initial buckling. With 100 mm CFRP coating, the initial buckling capacity increased by 5.92% and decreased by 63.87% compared to perfect model without CFRP and perfect model with CFRP respectively. When these three models are compared, it is seen that the initial buckling capacity of the model with full CFRP is 1.48 times greater than the model with half surface CFRP and 1.63 times more than the model with 100 mm CFRP. Initial buckling capacity of the M5-H-A10-CH decreased by 32.57% compared to the M6-H-A10-CF. The initial buckling capacity of the M7-H-A10-C100 is decreased by 38.71% and 9.1% compared to the M6-H-A10-CF and the M5-H-A10-CH, respectively. For this group, the model M6-H-A10-CF and the M7-H-A10-C100 had the greatest and least increase in the post buckling phase.

For the model M8-H-A5-C100, which was tested by half filling with 5% acid solution and strengthened with 100 mm CFRP, overall buckling was found 2.24 times of the initial buckling and collapse buckling was found 1.88 times of the initial buckling. For this model, overall buckling is increased by 55.4% of the initial buckling, and the collapse buckling is increased by 46.75% of the initial buckling. The initial buckling capacity of the M8-H-A5-C100 is increased by 18.4% and decreased by 58.35% compared to perfect model without CFRP and perfect one with CFRP, respectively. For the M9-H-A5-CH, which the CFRP reinforcement was applied only to corroded zones (half length of the
cylinder) the overall buckling was found 2.23 times of the initial buckling, and the collapse buckling was found 1.84 times of the initial buckling. The overall buckling increased by 55.18% and the collapse buckling are increased by 45.5% when compared to initial buckling. The initial buckling capacity of the model M9-H-A5-CH is increased by 42.88% and decreased by 40.49% compared to the perfect model without CFRP and the perfect one with CFRP, respectively. For the M10-H-A5-CF model, which was half-filled with 5% acid solution and tested with whole surface CFRP, overall buckling was found 2.3 times of the initial buckling and collapse buckling was found 1.6 times of the initial buckling. The overall buckling is increased by 56.48%, and the collapse buckling is increased by 37.36% compared to initial buckling, respectively. The initial buckling capacity of the M10-H-A5-CF is increased by 52.72% and decreased by 28.1% compared to the perfect one without CFRP and the perfect model with CFRP, respectively. When these three models are compared, it was observed that the initial buckling capacity of the model with full CFRP is 1.21 times greater than the model with half CFRP, and 1.73 times more than the model with 100 mm CFRP. The initial buckling of M10-H-A5-CF is increased by 42.06% and 17.23% compared to the model M8-H-A5-C100 and the model M9-H-A5-CH, respectively. The initial buckling capacity of the M9-H-A5-CH is increased by 30% compared to the model M8-H-A5-C100. For this group, the model M10-H-A5-CF and M9-H-A5-CH had the greatest and least increase in the post buckling phase.

3.4. Comparison of the Models with Same Height of CFRP
The initial buckling of the models without CFRP, presented a decrease about 7% for the increasing acid solution ratio from 5 to 10%, for the models M3-F-A5-CN and M1-F-A10-CN. However, this decrease is about 25% for the wholly CFRP covered the M4-F-A5-CF and the M2-F-A10-CF models.

As expected, the decrease for the models covered with only 100 mm is about 13%, for the M7-H-A10-C100 and the M8-H-A5-C100. Furthermore, the models with half-length coated with CFRP, presented a similar behavior for the models M9-H-A5-CH and M5-H-A10-CH, as 33% decrease of the initial buckling, with the acid solution increase. Nevertheless, this decrease is about 18% for the fully coated, but half-acid-solution-filled models, the M10-H-A5-CF and the M6-H-A10-CF. According to these results, increasing the ratio of acid to 10% increased the damage caused by corrosion. As the acid ratio
increases, initial buckling capacity of thin walled cylindrical shells decreases, as expected.

3.3. Comparison of the Models with Same Acid Ratio

Among the models containing 10% acid, M2-F-A10-CF and M7-H-A10-C100, had the greatest and least increase at post-buckling capacity after the initial buckling. The initial buckling capacity of the model M2-F-A10-CF is decreased by 38.31%, when compared to the M6-H-A10-CF. Among the models, containing 5% acid, M4-F-A5-CF and M9-H-A5-CH, had the greatest and least increase at post-buckling capacity after initial buckling. The initial buckling capacity of the model M4-F-A5-CF decreased by 33.36%, when compared to the model M10-H-A5-CF. These results show that as the fulness of the cylinders' increases, the buckling capacity decreases. The models, filled with more HCl solutions have been lower buckling capacities, as expected.

3.5. Failure Modes

Number of experimental waves and approximate waves according to [20,37] are presented in Table 5. The waves were ranged between 3 and 5. Theoretically calculated number of waves are greater than experimental waves. The models after the test are shown in Fig. 4. The buckling failure of all models occurred at the bottom and top of the cylinders. For the uniform external pressure, V-shaped buckle lines are occurred. The models with CFRP were more resistive to the buckling. The CFRP coating increased strikingly, the buckling resistance of the cylinders.

3.6. Comparing the theoretical and experimental buckling loads

Buckling loads were found as 11.6, 11.6, and 11.72 kPa according to similar theories like; Jawad's Theory, Venstel and Krauther’s Theory, and Ross’ Theory, respectively. The experimental buckling loads are presented in Table 5. The comparisons of experimental initial buckling loads of every model with theoretical loads are shown in Fig. 9. Theoretical loads are smaller than the experimental ones. The buckling loads according to these theories are not including the effect of corrosion, and they should be multiplied with certain coefficients.
3.7. Energy Absorption Capacity of Models

Areas under the buckling load-strain curves are presented in Fig. 10. This area represents the ductility of the cylinders as they can absorb more energy. The model M1-F-A10-CN had the largest area, when all models are compared. By coating the cylinders with CFRP buckling load increases significantly, and it also increases the ductile behavior of cylinders. Ductility is an important feature for shell design because it allows shells to carry more loads by increasing their deformability. Deformability is also related to ductility. As the energy absorption capacity of shells increases, deformability and load carrying capacity also increases. With more ductility, shells can keep carrying loads by being able to change their shape more.

4. Conclusion

The corrosion can be a big problem for the thin walled storage members. Especially, the storage of liquids, which decrease the pH value by time, will result corroded thin-walled steel shells. Thus, as a purpose of this work, the corrosion of the models are intensively investigated. The corroded thin-walled cylindrical steel shells are experimentally tested by using 12 thin walled cylindrical shells, corroded ten and non-corroded two models, and subjected to external pressure. The key findings and observations of this study are presented as follows:

- All models are resisted after the initial buckling and then, they have shown the post-buckling behavior. The comparisons of overall and collapse buckling with initial buckling are observed within the range of 67%-79%, and 55%-60%, respectively, for fully filled models with 10% HCl. Relevant observations for 5% HCL are observed within the range of 58%-71%, and 46%, respectively.
- The comparison of half-filled models evaluated the overall and collapse buckling with initial buckling between 58%-70%, and 43%-58%, respectively, for the 10% HCL ones. Relevant observations for 5% HCL are observed within the range of 55%-57%, and 55%-57%, respectively. The CFRP coating significantly increased the initial buckling capacity of the models.
✓ The models lost weight due to corrosion’s thickness loss effect. For the models, which are fully filled with 10% HCl solutions, the weight loss was about 4% and for the half-filled ones lost was about 1% of their weight. Furthermore, fully filled 5% HCl solution models were lost about 3% of their weight, and half-filled ones were lost about 1% of their weight. Thickness loss caused the buckling load to decrease in all models.

✓ Filling the cylinders with more solution causes buckling capacity to decrease. The models filled with more HCl solution are presented lower buckling capacities.

✓ The acid ratio of the solution affects the damage caused by corrosion. As the acid ratio increases, initial buckling capacity of thin walled cylindrical shells decreases.

✓ When the experimental results are compared, it can be seen that the theoretical results can be used to evaluate the loads of the models with certain coefficients, however, the theories are not determined for the purpose.

✓ By coating the cylinders with CFRP buckling load increases significantly, and it also increases the ductility of cylinders.

ACKNOWLEDGMENT

The research is part of the Ataturk University Projects No: FHD-2019-7272 and FHD-2019-7344. The authors would like to thank to Ataturk University for funding the project.

REFERENCES

7. Çelik, Ö. “Paslanmaz Çeliklere Uygulanan Düşük Sicaklık Nitrürleme İşleminin Mekanik Ve Korozyon Özelliklerine Etkisi”, Istanbul Technical University, Turkey (2010).

Biographies

**Abdulkadir Cüneyt AYDIN** is a professor at the department of Civil Engineering, Atatürk University, Turkey. He is a member of Engineering Faculty Research Commission and also, he’s head of the Department of Civil Engineering Structural Engineering Division. His research focuses are steel constructions, thin-walled structures, structure strengthening, construction materials and reinforced concrete structures. He’s a well known researcher with his published articles and conference papers. He’s also the chief-editor or editorial board member of many international
Mahyar Maali is an associate professor at the department of Civil Engineering, Erzurum Technical University, Turkey. He studied civil engineering in Islamic Azad University, Maragheh, Iran and he took his M.Sc. at the same university. Then, he studied for his PhD in the department of Civil Engineering, Ataturk University, Turkey. His research interests are mostly about steel structures.

Mahmut Buğra BİLEN is a research assistant at at the department of Civil Engineering, Erzurum Technical University, Turkey. He studied Civil Engineering in Ataturk University, Turkey and he’s currently studying for his master’s degree at the same university. His researches interests are including thin-walled steel structures.

Captions

Fig. 1. Experimental Setup

Fig. 2. Filling cylinders with HCl solution

Fig. 3. Overall view of the system

Fig. 4. Models before and after buckling tests

Fig. 5. Buckling load-displacement curves of all specimens.

Fig. 6. Buckling load- strain curves of all specimens.

Fig. 7. Locations of the buckling phases

Fig. 8. Initial, Overall and Collapse Buckling Loads of the Models

Fig. 9. Comparison of initial and theoretical buckling loads

Fig. 10. Areas under pressure-displacement curves for all models

Table 1. Model Properties

Table 2. Properties of epoxies

Table 3. Properties of CFRP Fabrics used in experiments

Table 4. The properties measurement system

Table 5: Buckling Loads, Experimental Waves and Approximate Waves
Table 6: Increase and decrease of the buckling loads of the models compared to initial

Fig. 1. Experimental Setup

Fig. 2. Filling cylinders with HCl solution
Fig. 3. Overall view of the system

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M1-F-A10-CN

M2-F-A10-CF

M3-F-A5-CN

M4-F-A5-CF

M5-H-A10-CH

M6-H-A10-CF

Buckling Load (kPa) vs. Strain (µm/m) x 10^-6

Vertical Strain Gauge vs. Horizontal Strain Gauge
Fig. 6. Buckling load-strain curves of all specimens.
**Fig. 7.** Locations of the buckling phases

**Fig. 8.** Initial, Overall and Collapse Buckling Loads of the Models
Fig. 9. Comparison of initial and theoretical buckling loads

Fig. 10. Areas under pressure-displacement curves for all models
### Table 1. Model Properties

<table>
<thead>
<tr>
<th>Model</th>
<th>Fulness</th>
<th>HCl Solution (%)</th>
<th>CFRP Height (mm)</th>
<th>Weight of the model (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Non-corroded Corroded</td>
</tr>
<tr>
<td>Perfect Model</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Perfect Model with whole surface CFRP</td>
<td>-</td>
<td>800</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>M1-F-A10-CN</td>
<td>Full</td>
<td>10%</td>
<td>-</td>
<td>3100 2980</td>
</tr>
<tr>
<td>M2-F-A10-CF</td>
<td>Full</td>
<td>10%</td>
<td>800</td>
<td>3080 2980</td>
</tr>
<tr>
<td>M3-F-A5-CN</td>
<td>Full</td>
<td>5%</td>
<td>-</td>
<td>3080 3000</td>
</tr>
<tr>
<td>M4-F-A5-CF</td>
<td>Full</td>
<td>5%</td>
<td>800</td>
<td>3100 3020</td>
</tr>
<tr>
<td>M5-H-A10-CH</td>
<td>Half</td>
<td>10%</td>
<td>400</td>
<td>3080 3060</td>
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</table>
Table 2. Properties of epoxies

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (kg/l)</th>
<th>Bending strength (N/mm²)</th>
<th>Compression Strength (N/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Epoxy resin adhesive</td>
<td>1.02</td>
<td>&gt;50</td>
<td>&gt;60</td>
</tr>
<tr>
<td>Epoxy resin primer</td>
<td>1.08</td>
<td>&gt;20</td>
<td>-</td>
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</table>

Table 3. Properties of CFRP Fabrics used in experiments

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
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<tbody>
<tr>
<td>Modulus of Elasticity</td>
<td>230 000 N/mm²</td>
</tr>
<tr>
<td>Ultimate Tensile Strength</td>
<td>4900 N/mm²</td>
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<tr>
<td>Thickness</td>
<td>0.111 mm</td>
</tr>
<tr>
<td>Weight</td>
<td>230 g/m²</td>
</tr>
<tr>
<td>Ultimate Strain</td>
<td>2.1%</td>
</tr>
<tr>
<td>Width</td>
<td>500 mm</td>
</tr>
</tbody>
</table>
Table 4. The properties measurement system

<table>
<thead>
<tr>
<th>Models</th>
<th>Position of the device from ground (mm)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>For the LVDT's</td>
<td>For the strain gauges</td>
<td></td>
</tr>
<tr>
<td>Perfect Model</td>
<td>480</td>
<td>600</td>
<td></td>
</tr>
<tr>
<td>Perfect Model with whole surface CFRP</td>
<td>460</td>
<td>580</td>
<td></td>
</tr>
<tr>
<td>M1-F-A10-CN</td>
<td>500</td>
<td>620</td>
<td></td>
</tr>
<tr>
<td>M2-F-A10-CF</td>
<td>500</td>
<td>570</td>
<td></td>
</tr>
<tr>
<td>M3-F-A5-CN</td>
<td>470</td>
<td>580</td>
<td></td>
</tr>
<tr>
<td>M4-F-A5-CF</td>
<td>480</td>
<td>590</td>
<td></td>
</tr>
<tr>
<td>M5-H-A10-CH</td>
<td>470</td>
<td>610</td>
<td></td>
</tr>
<tr>
<td>M6-H-A10-CF</td>
<td>460</td>
<td>550</td>
<td></td>
</tr>
<tr>
<td>M7-H-A10-C100</td>
<td>480</td>
<td>550</td>
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</table>
## Table 4. The properties measurement system

<table>
<thead>
<tr>
<th>Models</th>
<th>Position of the device from ground (mm)</th>
<th>For the LVDT's</th>
<th>For the strain gauges</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perfect Model</td>
<td>480</td>
<td>600</td>
<td></td>
</tr>
<tr>
<td>Perfect Model with whole surface CFRP</td>
<td>460</td>
<td>580</td>
<td></td>
</tr>
<tr>
<td>M1-F-A10-CN</td>
<td>500</td>
<td>620</td>
<td></td>
</tr>
<tr>
<td>M2-F-A10-CF</td>
<td>500</td>
<td>570</td>
<td></td>
</tr>
<tr>
<td>M3-F-A5-CN</td>
<td>470</td>
<td>580</td>
<td></td>
</tr>
<tr>
<td>M4-F-A5-CF</td>
<td>480</td>
<td>590</td>
<td></td>
</tr>
<tr>
<td>M5-H-A10-CH</td>
<td>470</td>
<td>610</td>
<td></td>
</tr>
<tr>
<td>M6-H-A10-CF</td>
<td>460</td>
<td>550</td>
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</table>
Table 5: Buckling Loads, Experimental Waves and Approximate Waves

<table>
<thead>
<tr>
<th>Specimens</th>
<th>Initial Buckling (kPa)</th>
<th>Overall Buckling (kPa)</th>
<th>Collapse Buckling (kPa)</th>
<th>Experimental Waves</th>
<th>Approximate Waves [20,37]</th>
</tr>
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<tbody>
<tr>
<td>Not Corroded Specimens</td>
<td></td>
<td></td>
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<tr>
<td>Perfect Model</td>
<td>40.85</td>
<td>95.63</td>
<td>93.05</td>
<td>5</td>
<td>6-7</td>
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<tr>
<td>Perfect Model with CFRP</td>
<td>120.19</td>
<td>165.68</td>
<td>115.46</td>
<td>4</td>
<td>6-7</td>
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<tr>
<td>Corroded Specimens</td>
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<tr>
<td>M1-F-A10-CN</td>
<td>32.00</td>
<td>96.07</td>
<td>70.63</td>
<td>5</td>
<td>6-7</td>
</tr>
<tr>
<td>M2-F-A10-CF</td>
<td>43.35</td>
<td>207.11</td>
<td>108.09</td>
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<td>6-7</td>
</tr>
<tr>
<td>Specimens</td>
<td>Overall – Initial</td>
<td>Collapse – Initial</td>
<td></td>
<td></td>
<td></td>
</tr>
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<td></td>
</tr>
<tr>
<td></td>
<td>Overall (%)</td>
<td>Collapse (%)</td>
<td></td>
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<tr>
<td><strong>Not Corroded Specimens</strong></td>
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<tr>
<td>Perfect Model</td>
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<td>56,1</td>
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<td>Perfect Model with CFRP</td>
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<td>-4,1</td>
<td></td>
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<tr>
<td><strong>Corroded Specimens</strong></td>
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<tr>
<td>M1-F-A10-CN</td>
<td>66,69</td>
<td>54,69</td>
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<tr>
<td>M2-F-A10-CF</td>
<td>79,07</td>
<td>59,89</td>
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<tr>
<td>M3-F-A5-CN</td>
<td>57,74</td>
<td>46,14</td>
<td></td>
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</tr>
<tr>
<td>M4-F-A5-CF</td>
<td>70,62</td>
<td>45,95</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 6: Increase and decrease of the buckling loads of the models compared to initial buckling.
<table>
<thead>
<tr>
<th>M5-H-A10-CH</th>
<th>66,33</th>
<th>43,16</th>
</tr>
</thead>
<tbody>
<tr>
<td>M6-H-A10-CF</td>
<td>70,05</td>
<td>57,5</td>
</tr>
<tr>
<td>M7-H-A10-C100</td>
<td>58,41</td>
<td>50,3</td>
</tr>
<tr>
<td>M8-H-A5-C100</td>
<td>55,4</td>
<td>46,75</td>
</tr>
<tr>
<td>M9-H-A5-CH</td>
<td>55,18</td>
<td>45,5</td>
</tr>
<tr>
<td>M10-H-A5-CF</td>
<td>56,48</td>
<td>37,36</td>
</tr>
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