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| **Keywords** |  | **Abstract** |
| *Theoretical and experimental, Cylindrical shell,* *CFRP strips,* *Longitudinal dent number, Hydrostatic pressure.* |  | Tanks, silos, and most large steel-shell structures consist of smaller pieces connected together during the manufacturing process. This causes several types of malformations on the shell walls. Furthermore, thin-walled members can be easily deformed in wall surfaces owing to the thickness of the structure. Fourteen thin-walled cylindrical shell specimens in two groups with different dent depths and various longitudinal dent numbers subject to hydrostatic pressure were tested in the present work. The models were designed to demonstrate how repairing dents by using carbon-fibre-reinforced polymer can recover lost capacity. The results of testing under different theories and codes were compared. This study shows the decreasing effects of the longitudinal dent number on the buckling capacity of the shells. Using carbon-fiber-reinforced polymer strips resulted in softening or stiffening behaviour in the models. Furthermore, to obtain the initial and overall buckling according to theoretical formulas, coefficients were predicted to obtain the initial, overall, and collapse buckling without an experiment for the models that were beyond the scope of the theories. |

**1.Introduction**

For a decade, cylindrical geometry has been considered as an important thin-walled structure type for shells. The member structure plays the main role in the deformations and disturbances of the wall surfaces. The manufacturing process for thin-walled cylindrical shells is critical for the designed member. During the manufacturing process, the panels, which are used for tanks and silos, exhibit geometrical defects. The thin-walled shells, a classical structural analysis problem, are a continually increasing concern for modern industries. Thus, it is important to examine the problem of instability in this type of structure.

Many steel structures such as high-water tanks, water and oil reservoirs, marine structures, and pressure vessels, including shell elements, are widely under stress. Furthermore, shell elements are subject to instability owing to the loads applied. The theoretical buckling resistance (theoretical) is based on a two-branch linear elastic analysis that is suitable for conventional cylinder shells.

There have been many research studies regarding thin-walled structures, including many geometric properties and types of loads [1]. Teng and Hu (2007) [2] examined the benefits of the fiber reinforced polymer (FRP) confinement of hollow steel tubes. Moreover, axial compression tests on FRP-confined steel tubes were described. Batikha et al. (2009) [3] investigated a novel method of strengthening cylindrical shells against elephant-foot buckling, in which a small amount of FRP composite used at a critical location can effectively eliminate the problem and increase the buckling strength. However, the elephant-foot-type buckling phenomenon is a result of axial load, especially for thin-walled short cylindrical shells, and is outside the scope of this work. There have been many studies, both experimental and theoretical, regarding the calculation of buckling loads for thin-walled shells [1–19]. As an example, Vakili and Showkati [16] studied elephant-foot-type buckling and the retrofitting of cylindrical shells using FRP.

Maali et al. (2012) [4] discussed 14 laboratory specimens in two groups: shallow conical caps (SCC) and deep conical caps (DCC). Models were loaded under uniform hydrostatic pressure. The samples were modified to include either one- or two-line imperfections with amplitudes of thickness; 1t, 2t, and 3t in depth.

Fatemi et al. (2013) [5] investigated imperfect cylindrical shells under uniform external pressure. Nilufari et al. (2014) [6] discussed 12 laboratory specimens in three groups, loaded under uniform hydrostatic pressure. The samples were modified to include circumferential imperfections at the junctions between the curved edges of the panels of the cylindrical and conical shells with amplitudes of 2t, 4t, and 8t in depth.

Most recently, the effect of longitudinally stiffened cylindrical shells under external pressure was investigated, and researchers showed that the buckling capacity increased for the tested models [7–9]. Additionally, Ghanbari Ghazijahani et al. (2014) [10] studied damaged cylindrical shells under compression. This study presented an experimental program in which the buckling and failure response of damaged shell specimens were analysed. Ghanbari Ghazijahani et al. (2014) [11] conducted experiments on dented cylindrical shells under peripheral pressure. They reported on an experimental program concerning the buckling and post-buckling response of thin cylindrical shells with local dent imperfections under uniform external pressure. The results of this study can be used in practical structures with similar geometrical features.

Ghanbari Ghazijahani et al. (2015) [12] focused on recovering the fatigue life for larger cutouts by reinforcement with carbon fibre reinforced polymer (CFRP). Fatigue life was not only fully recovered with the CFRP reinforcement but was also dramatically increased relative to the unreinforced intact specimen. In addition, Ghanbari Ghazijahani et al. (2015) [13] studied a new approach for strengthening in which vertical corrugations were introduced to 11 cylindrical shell specimens under uniform external pressure. The results showed a considerable increase in the buckling capacity of such structures. Ghanbari Ghazijahani et al. (2015) [14] studied the effect of large local imperfections, known as dents, on the plastic buckling capacity of short steel tubes under axial compression. A total of 11 tests on such short columns conducted. Ghanbari Ghazijahani et al. (2015) [15] discussed the structural behaviour of an innovative composite column through an experimental study. The new composite was composed of steel cylindrical hollow sections (CHSs), solid timber infill, and CFRP confinements.

The abovementioned literature review may be concluded as follows. The cylindrical shell is a main structural element and is considered to be a basic need in modern industry. The structures of shells are prone to buckling phenomena owing to their particular shape. The insignificant thickness of the other dimensions and the emergence of compressive stresses owing to loading are factors that cause the buckling phenomenon. In this research, dents are introduced at different depths of t and 2t, and with various longitudinal dent numbers (d2, d4, and d6), into cylindrical tanks. The models are designed to show how the repair of dents using CFRP can recover lost capacity as well.

The models are divided to two groups: the without-CFRP group and the with-CFRP group. Each group is compared to the individual models of the group itself, and then both groups are compared together. All initial and overall buckling and collapse are compared using theoretical formulas. Finally, the buckling waves (using theory) and the method of reversal are described. The purpose of the present work is to investigate the effect of dents and/or CFRP on the buckling behaviour of cylinders which are not in the range of theoretical formulas. Thus, it will be possible to obtain the initial and overall buckling loads according to theoretical formulas, without experiments, by using some coefficients.

1. **Testing process**

**2.1. Test specimens and properties**

In this research, 14 laboratory specimens in two groups with verified dent numbers (d2, d4, and d6) and with dents at different depths of t and 2t are examined. The first group of specimens (seven specimens), labelled ‘without CFRP’, and the second group, ‘with CFRP’, were loaded under hydrostatic pressure. Each group contained a perfect model and a perfect model with an entire surface of CFRP, with the remaining specimens having a dent with amplitudes of t and 2t (t = thickness of the cylindrical shell). A perfect model and a perfect model with entire-surface CFRP were used for control in each group. The details of the CFRP and epoxy are presented in Table 1, and the details of the specimens are presented in Table 2 and Fig. 1. The CFRP strip was calculated with the formula 3bd × (Ld + 2bd), where 3bd is the width of the CFRP strip, and Ld + 2bd is the length of the CFRP strip (Ld = dent length, and bd = dent width).

Table 1. Tensile Properties of CFRP and epoxy used

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Name and Supplier | Type | ρ (g/cm3) | E (GPa) | σ (MPa) | ε (%) |
| BASF, MasterBrace, 300/50 CBS | Thermoplastic | 1.77 | 227 | 3800 | 1.67 |
| BASF, MasterBrace, SAT 4500 | Low viscosity epoxy  | 0.983 | 3.034 | 55.2 | 3.5 |

Table 2. Initial geometries of test models

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Group | Specimen | Model | Ld | hd | bd | FD | di |
|  | t-2t-d2 | M1 | hc/2 | t | 2t | - | 2 |
|  | 2t-4t-d2 | M2 | hc/2 | 2t | 4t | - | 2 |
| Without | t-2t-d4 | M3 | hc/2 | t | 2t | - | 4 |
| CFRP | 2t-4t-d4 | M4 | hc/2 | 2t | 4t | - | 4 |
|  | t-2t-d6 | M5 | hc/2 | t | 2t | - | 6 |
|  | 2t-4t-d6 | M6 | hc/2 | 2t | 4t | - | 6 |
|  | Perfect model | M7 | - | - | - | - | - |
|  | CFRP-t-2t-d2 | M8 | hc/2 | t | 2t | 3bd × (ld + 2bd) | 2 |
|  | CFRP-2t-4t-d2 | M9 | hc/2 | 2t | 4t | 3bd × (ld + 2bd) | 2 |
| With | CFRP-t-2t-d4 | M10 | hc/2 | t | 2t | 3bd × (ld + 2bd) | 4 |
| CFRP | CFRP-2t-4t-d4 | M11 | hc/2 | 2t | 4t | 3bd × (ld + 2bd) | 4 |
|  | CFRP-t-2t-d6 | M12 | hc/2 | t | 2t | 3bd × (ld + 2bd) | 6 |
|  | CFRP-2t-4t-d6 | M13 | hc/2 | 2t | 4t | 3bd × (ld + 2bd) | 6 |
|  | Perfect model with entire-surface CFRP | M14 | - | - | - | Entire-surface CFRP | - |

Specimen: hd – bd – di; hd: Dent depth; bd: Dent width; di: dent number (d2, d4, and d6 as two, four, and six dents, respectively); Ld: Dent length; hc: Height of cylinder (1250 mm for all models); t: Thickness of cylinder (t = 1 mm for all models); FD: Fibre dimensions (width × height); R: Radius (500 mm)



Figure 1. Details of test model

* 1. **Testing system and manufactured specimen**

The test machine consists of two plates: upper and bottom plates with dimensions of 1500 × 1500 mm and a plate thickness of 30 mm. The plates were first cut into 1500 × 1500-mm sizes by a CNC cutting device and then ring-cut with a CNC cutting machine. Soldering was applied to minimise the error rate and improve the weld performance via the seam fusing method [4–6, 20–22]. To decrease the initial distortion and residual stress, the edges of the cylinder were joined through soldering. The steel plates were cut in the exact dimensions of the models and rolled into cylinders by a rolling machine.

Fig. 2 shows the test machine used in this research. In one of the plates on the upper part, there are two holes in the middle of the passage of the vacuum hose from the first hole. The load cell is inserted into the second hole, and four sets of studs on the four sides of the plate lift the plate using a welding crane. On the sides of the plates, three holes of the bolt are intended to be six in total, until the configuration shown in Fig. 2 is achieved. The reason for these six bolts is the installation of a top plate assembly, which, when tested with the crane, prevents these bolts from entering the axial load into the cylinder.

After the test machine was manufactured, it was time to build laboratory samples. Three tensile coupon tests were performed to obtain the material properties. The average yield and failure stresses were found to be 198.8 MPa and 342.4 MPa, respectively. Young’s modulus was calculated to be 210 MPa, and Poisson’s ratio was obtained as 0.29. To make samples, sheets with a thickness of 1 mm were prepared. Ten sheets were cut to 1250 mm in height and 3140 mm in length with scissors. Then, a cylindrical roller was used to create rolled specimens. During the welding, it was considered that the lowest porosity and inadequacy of welding on the laboratory models were not achieved, and the models were prepared without imperfections in welding. In addition, during rolling, we were careful not to cause any imperfections.

The edges of the models were welded through metal inert gas welding by using 0.8-mm electrodes for a 1-mm weld thickness. After the creation of the laboratory models, it was necessary to create inadequacies. To create disadvantages in the models, stainless steel shapes (SPKR) were made in the form of cutting and the wire cut method. Fig. 2 shows the dent piece for the experimental tests. First, a dent length was indicated at the centre of the height of the model with a ruler and a marker, and then a four-base was laid inside the model.

A static load pump was employed with a maximum load of 900 kN, stroke of 300 mm, and constant speed of 0.016 mm/s. The pump was used to create dents in the models [23–30]. In Fig. 2, the dent implementation in the models is shown. All dents were manufactured to be inward and equidistant from each end for all of the models. Furthermore, the dents were manufactured with equal angles (3600/dent number). For the group with CFRP models that were to be used, two-component epoxy-coated adhesive was stuck onto the specified parts. Table 2 lists the data for the experimental models.

To install the laboratory models, the following was accomplished. Beginning at the bottom of the laboratory model, after fitting the model on the bottom plate of the silicone silencer model, the edge of the model was filled to the plate inside and outside the cylinder to prevent air from escaping from the inside of the cylinder. After that, to fit the other side of the cylinder, the bolts around the device were opened, and the upper plate was slowly raised and guided by a crane to the cylinder. Prior to guiding the top plate, the bolts were adjusted to the height of the cylinder to prevent a sudden collision of the plate with the cylindrical model.

Finally, after inserting the top plate, the bolt shown in Fig. 2 was closed to prevent gravity loading on the cylindrical model. Alternately, the crane transported the top plate during the test to maintain a gravity-load-avoidance sample. After the plate around the cylinder was filled with silicon glue, silicon was added to an argon boil in order to prevent air from escaping.

After performing the above steps, four metal support rings, two on the bottom and two on the top of the cylinder, were installed so that all laboratory models with a simple support were closed only in the radial direction.

**Nomenclature**

X : The length of the specimen in horizontal direction

Y : The length of the specimen in vertical direction

**Declaration of Conflict of Interests**

The author(s) declare(s) that there is no conflict of interest. They have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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