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An experimental study on externally pressurized stiffened and thickened cylindrical shells

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A B S T R A C T

It has long been identified that stiffening of steel shells is one of the most effective ways of enhancing the capacity of these structures. Stiffeners largely in the form of welded elements have been employed to strengthen shell structures in which the stiffeners generally cover the whole length of the structure. In this research the effect of partial and full length stiffening of shells was studied in which the stiffeners were attached without welding to avoid the adverse effect of the residual stresses. Furthermore, local thickening of the shells by the same stiffening strips was investigated and the results were evaluated against the plain specimen. The effect of strengthening provided by local thickening was slightly less but comparable to that provided by the stiffeners.

1. Introduction

Cylindrical shells are present in a vast range of structural elements, which are seen in a great many different industrial applications. Such structures sometimes resist external pressure, particularly in the offshore industry. In some cases, in contrast, internal evacuation pressure takes place due to discharge of liquid inside these structures.

A great deal of research has been conducted in regard to thin shells under external pressure. In some cases, modeled structures were directly subjected to external pressure imposed from outside the surface of these structures whereas in some cases a vacuum is applied such that the atmospheric pressure plays the role of peripheral pressure. Since 1996, Showkati and his research colleagues have conducted many studies in which a uniform external pressure was imposed through an internal vacuum. Some of these investigations are outlined herein: the effect of boundary condition on shell structures was studied in Ref. [1], in which different buckling modes were exhaustively discussed. Buckling and post-buckling of imperfect thin shells [2,3], and the effect of thickness variation on the buckling response of such structures under vacuum [4] were also explored. In addition, the effect of load combination in the presence of the vacuum in long cylindrical shells [5] and the effect of various types of geometric imperfections for the shells with similar D/t ratios were thoroughly investigated [6–12].

The effect of stiffeners in thin structures under uniform vacuum was studied in two respective studies [13,14]. In Ref. [14], the effect of stiffeners was evaluated against thickening of the steel specimens. The capacity increase was determined for each strengthening method. The effect of rings or ring-beams on the buckling behavior of tanks and silos were studied by Chen and Rotter [15]. The effective length of shells with stiffeners was calculated theoretically in this research.

It should be mentioned that in most cases welding was utilized to connect the stiffening elements. However, Barkey et al. performed some tests on conical shell specimens in which epoxy adhesive was employed to connect the stiffeners to the surface of the shells [16]. In fact, this connection method helped the structures have uniform material properties in comparison with the welded or soldered connections, in which a lot of residual stress can affect the buckling behavior of such structures.

In this study the authors used the same method of connection using epoxy in the present thin shells, which eventually resulted in a highly satisfactory connection both for longitudinal stiffeners (known as stringers) and thickeners. On the other hand, to the best of the authors' knowledge, no other researchers have employed an end plate attached to one end of the specimens to impose axial stresses to the body of such structures subjected to a vacuum. It is of interest that this geometry leads to a different collapse mode in these structures which has not been reported yet. Note that

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stiffened shells with an end plate are quite widespread in many applications, in which the end plate takes the role of a cap in such cylindrical shell structures.

2. Details of the test rig

2.1. Apparatus and specimens

Figs. 1 and 2 illustrate the main features of the test apparatus and specimens used in this set of experiments. Two grooved end plates were made in order to apply the boundary conditions in these specimens. These plates were installed on an MTS machine such that the distance between the plates was easily adjustable in the axial direction. The end edges of the specimens were covered by the grooves such that a rotational restriction was applied to the boundary regions. Accurately fabricated mild-steel specimens and stiffeners were used in these tests (see Table 1). A structural epoxy adhesive "Spabond 345" was employed to connect the stiffeners. The area to be stiffened was carefully degreased and cleaned prior to the connection of the stiffeners to reach a perfect connection (see Figs. 3–5).

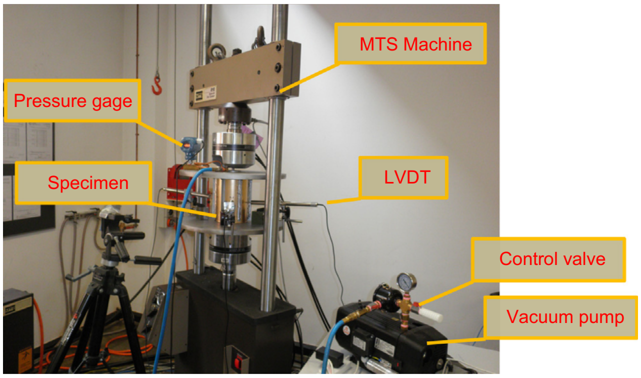

Fig. 1. Main features of the test rig.

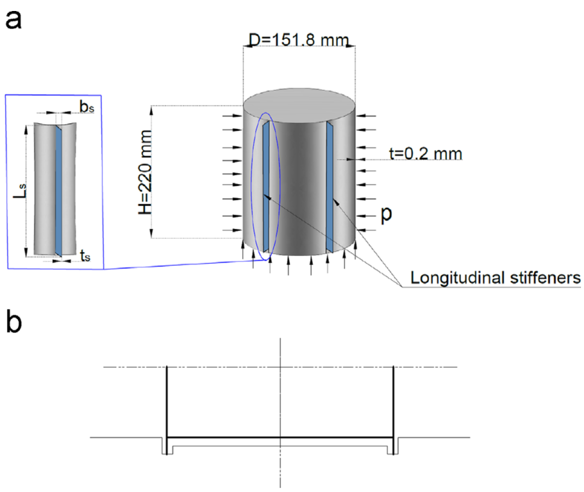

Fig. 2. (a) Schematic illustration of the specimens and stiffeners and (b) boundary conditions.

2.2. Loading

A vacuum pump was utilized to apply the loading. A control release valve was used to control the rate of the loading to ensure a uniform pressure with a monotonic and low rate of increase. A digital pressure gauge measured and reported the pressure throughout the tests. This gauge was connected to the pressure chamber by means of a flexible copper hose through a hole in the top plate to reach the chamber. The inlet hose to the pressure pump was connected to the pressure chamber by the same means.

2.3. Measurments

Four LVDTs were used to measure the radial displacement of four points on the specimens. These devices were placed at mid-height of each specimen at each quarter of the circumference in a symmetrical manner between stiffeners. CEA-06-240UZ-120 strain gauges (Micro-Measurements, Vishay Precision Group, Inc. USA) were attached midway between the stiffeners to record the micro-strain of the specimens.

3. Results and discussions

3.1. Test observations

3.1.1. Partially stiffened shells

Initial buckling in the form of lobed buckling midway between the stringers was observed in this set of tests. The top and bottom portions of the surface were not stiffened so the buckling propagated to those zones. For ECS.2 specimen the circumferential unstiffened area between the stringers was large so V-shaped yield lines appeared midway between the stringers. These became zigzagged at the post-buckling stages of loading (see Fig. 7). Axial shortening was quite obvious in this type of specimens as the top and bottom unstiffened regions were fairly crumpled at the collapse stage.

Table 1
Specimens and stiffeners geometric specifications.

Geometry	Specimen	Strengthening type	Strengthening	n	L_s (mm)	t_s (mm)	b_s (mm)
D/t = 758.85 t = 0.2 (mm) H/D = 1.45	ECS.1	–	–	–	–	–	–
	ECS.2	Stiffener	Partial	4	100	0.5	16
	ECS.3	Stiffener	Partial	6	100	0.5	16
	ECS.4	Stiffener	Partial	8	100	0.5	16
	ECS.5	Stiffener	Partial	10	100	0.5	16
	ECS.6	Stiffener	Full	6	198	0.5	16
	ECS.7	Stiffener	Full	8	198	0.5	16
	ECS.8	Thickener	Full	6	198	0.5	16
	ECS.9	Thickener	Full	8	198	0.5	16