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An experimental study on buckling and post-buckling behaviour of cylindrical panels with clamped and simply supported ends

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The effects of the length, sector angle and boundary conditions on the buckling load and post-buckling behaviour of cylindrical panels have been studied experimentally by applying a compressive axial load on the panels using a servo-hydraulic machine.

Keywords: Buckling, Post-buckling, Cylindrical panels, Experimental test

The shell structures are important in various engineering fields. The buckling load is usually the most criterion in designing of a long thin shell. Investigation of this subject is usually based on a numerical method like the finite elements, the analytical methods for special cases and the experimental tests. An analytical solution for the buckling load of isotropic and orthotropic panels has been presented by Timoshenko[1] and Lekhnitskii[2]. Magnucki[3] solved the Donnell's equation for buckling of panels with three edges simply supported and one edge free subjected to axial load using the Galerkin method. Patel[4] discussed on static and dynamic stability of panels with the edge harmonic loading. Jiang[5] studied the buckling of panels subjected to compressive stress using the differential quadrature element method. The most experimental works, relates to the buckling of columns and cylinders. Young[6] presented an experimental investigation of concrete-filled cold-formed high strength stainless steel tube columns subjected to uniform axial compression.Young studied the effects of the tube shape, plate thickness and concrete strength. The test results were compared with American and Australian standards. Zhu[7,8] studied experimentally the failure modes and strengths of aluminum alloy with and without transverse weld subjected to pure axial compression between fixed ends. The observed failure modes include yielding and buckling for different lengths. The test results were compared with some standards for aluminum structures. Liu[9] described a test procedure on cold-formed stainless steel square hollow sections subjected to pure axial compression. Liu concluded that design rules in Australian standard are slightly more reliable than the design rules in the American and European specifications for performed tests. Zhang[10] presented experimental and numerical investigations on the performance of repaired thin-skinned, blade-stiffened composite panels in the post-buckling range. The results showed that under the present repair scheme, the strength of the panel can be recovered satisfactorily. Further, the repair scheme was seen capable of restoring the general load path in the panels as well as the general post-buckling behaviour. Lanzi[11] reported the results of an experimental investigation on stringer-stiffened panels made of carbon fabric reinforced plastic. The axial compression tests were performed up to collapse. Experimental data demonstrated the strength capabilities of the identified structures to operate in post-buckling, allowing further weight savings.

In this paper, the effects of the length, sector angle and different boundary conditions on instability of metal cylindrical panels have been studied experimentally. Also, the behaviour of the panels in post-buckling path has been shown.

Experimental Study

Some specimens with different lengths and sector angles have been prepared. All the specimens have been manufactured from one tube branch and so they have the same radius and thickness. Figure 1 shows schematic of a panel and the dimensions of panel are given in Table 1. The bucking test is performed using

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a servo-hydraulic machine (INSTRON 8802). This universal test machine includes a hydraulic actuator for applying axial load on panels and two load cells with capacities 25 kN and 250 kN for different applications. The test results can be transmitted to a computer.

Mechanical properties

The mechanical properties of the metal panels have been obtained using the tensile test. The dimensions of tensile test specimens which are cut from the original tube have been chosen according to ASTM E8 standard. Figure 2 shows the stress-strain diagram for this material. The Young's modulus and the yield stress which are given in Table 1 have been determined from Fig. 2.

Table 1— Geometrical and mechanical properties of panels

Diameter	*D*=60 mm
Thickness	*t*=0.9 mm
Sector angle	θ=90°, 120°, 180°, 355°, Complete
Length	*L*=100,150,250 mm
Yield stress	σ_y=240 MPa
Elasticity modulus	E=150 (GPa)

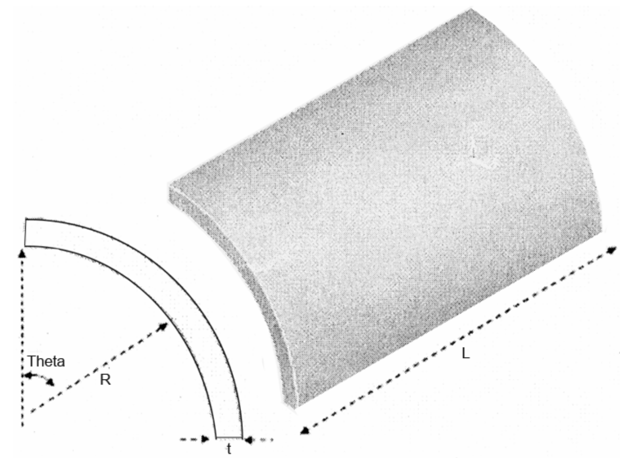

Fig. 1— Schematic of panels

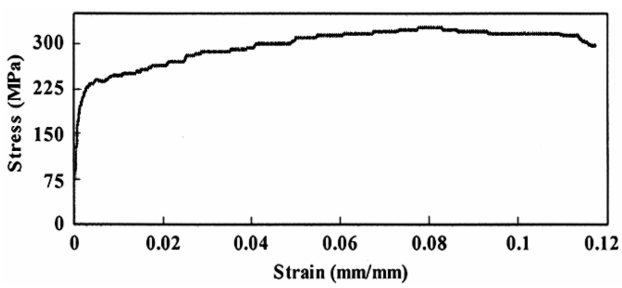

Fig. 2— Stress-strain diagram

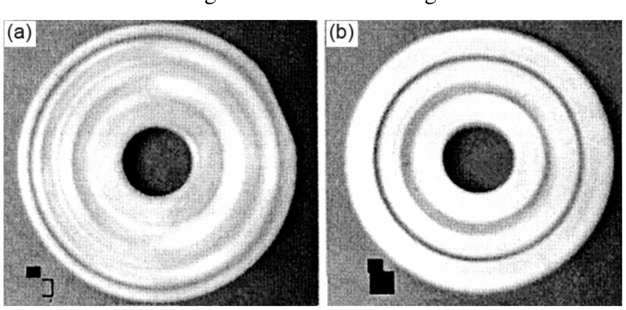

Fig. 3— (a) Simply supported fixture and (b) Clamped supported fixture

Boundary conditions

Two types of fixtures were designed to simulate the simply supported and clamped boundary conditions for the arc ends. Figure 3a shows a fixture for simply supported conditions. It does not have any resistance to rotation. A fixture for clamped boundary conditions has been shown in Fig. 3b. It has a narrow width and a deep slot so the zero slope condition at the end is reasonable.

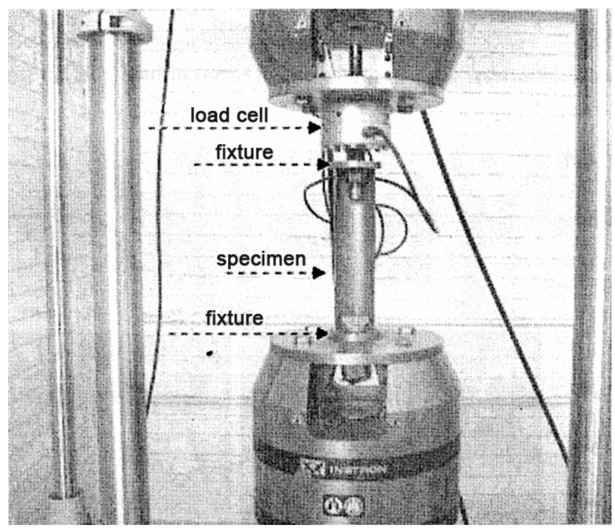

Fig. 4— Experimental test setup

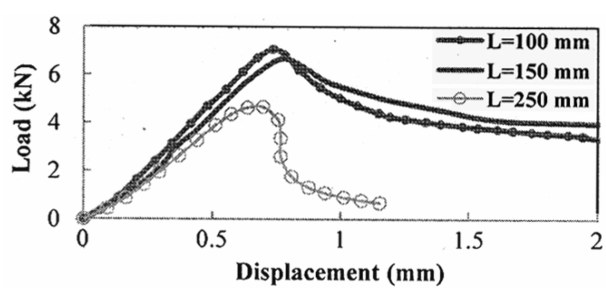

Fig. 5— Load-displacement diagram (θ = 90°, simple supports)

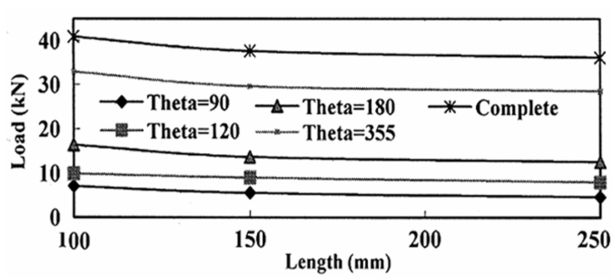

Fig. 6— Buckling load in terms of the length (for different sector angles)

Buckling Test

For the buckling test, an axial load was applied on the panels and by measuring the axial displacement, the load-displacement diagram was determined. These tests were performed for different panels with clamped and simply supported boundary condition. In all tests (except for a complete cylinder), the straight edges are free and the simple or clamped supports were applied on arc edges of panels. Figure 4 shows the test set-up.

Length effect

For investigation of the length effect, the buckling test was performed on some panels with the same angle and different lengths. The load-displacement for each panel was drawn. The peak values stand for the buckling load. For example, Fig. 5 is the load-displacement diagrams for different lengths with θ=90°. Figure 6 shows the variation of the buckling load in terms of the length for different sector angles. The "Complete" in Fig. 6 stands for a cylinder (θ=360°). Deformations of tested panels have been shown in Fig. 7. The experimental tests show that by decreasing the panel length the buckling load increases slightly.

Sector angle effect

Some experimental tests were performed on panels with L=100 mm and θ=90°, 120°,180°, 355° and 360°. The load-displacement diagrams for panels with different sector angle are shown in Fig. 8. θ=355° corresponds to a narrow cutting on the original tube as shown in Fig. 9. Figure 10 shows the variations of the buckling load in terms of θ for different lengths and Fig. 11 shows the buckling stress which can be defined easily as the ratio of the load to cross-section.

Boundary conditions effect

By changing the boundary conditions from simple to clamped, the degrees of freedom of supports reduce and the buckling load will increase. Figures 12 and13 show the load-displacement diagrams for panels (θ=90°) with different boundary conditions and the buckling loads are given in Table 2.

Results and Discussion

The buckling load decreases slightly with increase in length (Fig. 6). This reduction is more for shorter lengths. Also by increasing the sector angle of a panel, the buckling load increases. It is possible to approximate the buckling load as $P = k\,\frac{\theta^n}{L^m}$ here k,m,n are constants and they depend on the geometrical and mechanical properties of panels. In Fig. 7, the deformed shape of the tested panels has been shown. For a short panel, it is snap-through like. For a long panel it deforms like the Euler column and for a cylinder it has a symmetric deformation. This symmetry can be approved the uniformity of the applied load. According to Fig. 8, the existence of a narrow cutting (θ=355°) can reduce the buckling load significantly. It may be due to reduction of the structure stiffness. Also the buckling load capacity of a complete cylinder is more than that of this panel. Figure 9 shows the deformed shape of panel for this case. The variations of the buckling load with respect to the sector angle is nearly linear expect for a cylinder

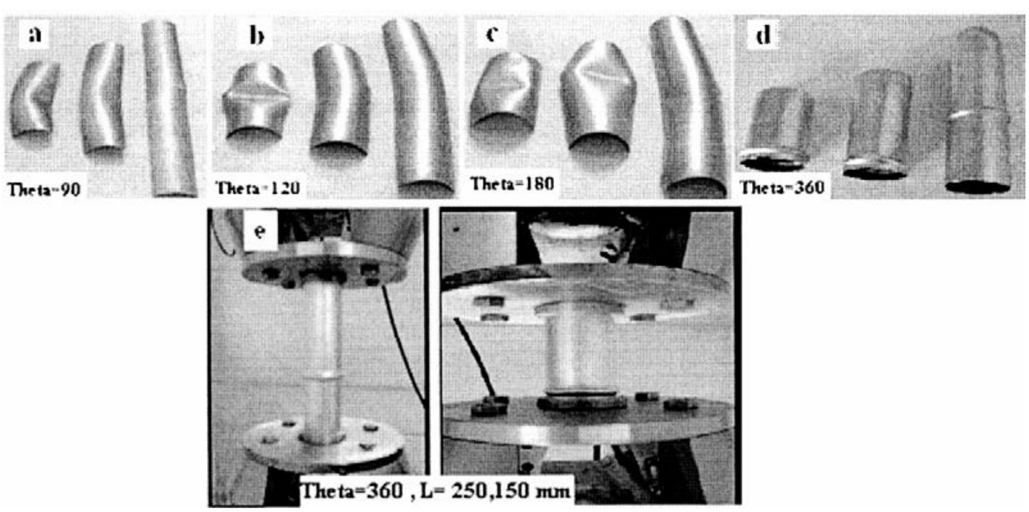

Fig. 7 Buckling mode shapes of panels with the same sector angles and different lengths (L=100,150,250 mm), (a) θ=90°, (b) θ=120°, (c) θ=180°, (d,e) θ=360°

(Figs 10 and 11). The yielding occurs before buckling in cylinder with L=100 mm, so its results are not reported in Figs 10 and 11. The buckling stress is constant approximately for θ>90° or the buckling stress is not sensitive to the sector angle for tested specimens. For clamped boundary conditions, the buckling load is more than the simple support (Figs12 and 13, Table 2). According to Figs 12 and 13, there is a delay of the buckling load by using simply supported boundary condition because the support permits the rotation in addition of axial displacement but in the clamped boundary conditions, there is no rotation or the structure is more restricted. In the other word, clamping the boundaries will increase the stiffness of the structure. The behaviour of the panel in post-buckling path may not be predicted or by changing the length (Fig. 5), sector angle (Fig. 8) and boundary conditions (Figs 12 and 13), the behaviour of the panel will change. To check the

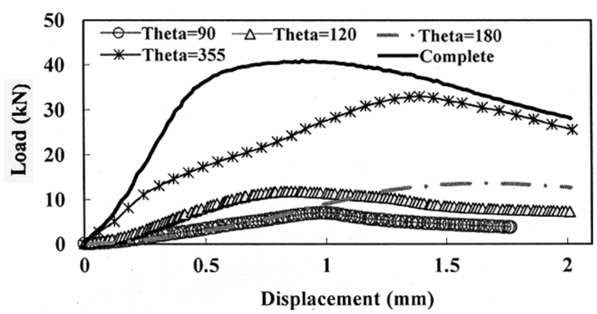

Fig. 8— Load-displacement diagram (L=100 mm, simple supports)

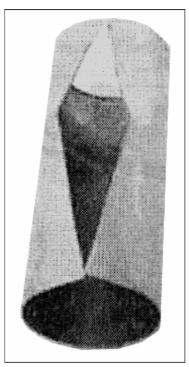

Fig. 9— Panel deformation (L=100 mm, θ=355°)

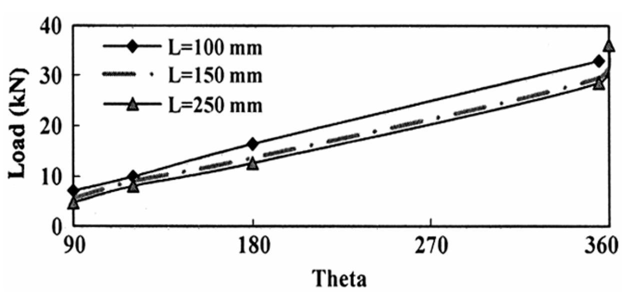

Fig. 10— Variations of buckling load in terms of sector angle for different lengths (simple supports)

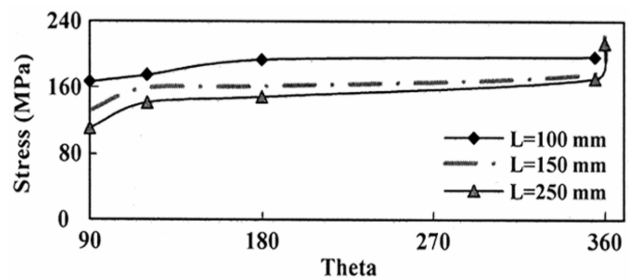

Fig. 11— Variations of buckling stress in terms of sector angle for different lengths (simple supports)

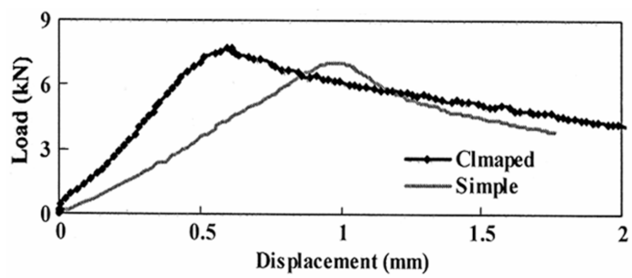

Fig. 12— Load-displacement diagram for clamped and simple supports (L=100 mm, θ=90°)

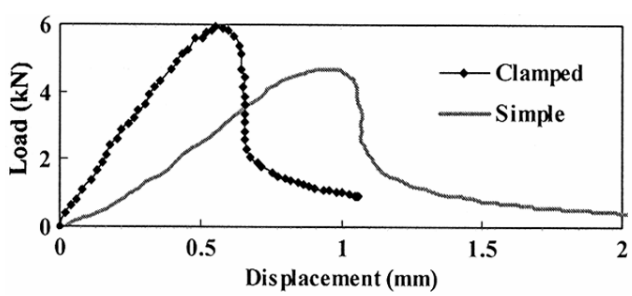

Fig. 13— Load-displacement diagram for clamped and simple supports (L=250 mm, θ=90°)

Table 2— Buckling loads (kN) for panels with clamped and simple supports

	θ = 90°		θ = 120°		θ = 180°		θ = 355°		θ = 360°	
	Simple	Clamped	Simple	Clamped	Simple	Clamped	Simple	Clamped	Simple	Clamped
L=100 mm	7.07	7.72	12.26	13.08	15.02	16.37	32.98	33.35	-	-
L=150 mm	5.59	6.08	11.72	12.52	13.69	14.86	29.65	32.93	37.69	-
L=250 mm	4.68	5.95	8.94	9.75	12.59	13.07	28.58	29.55	36.22	37.93

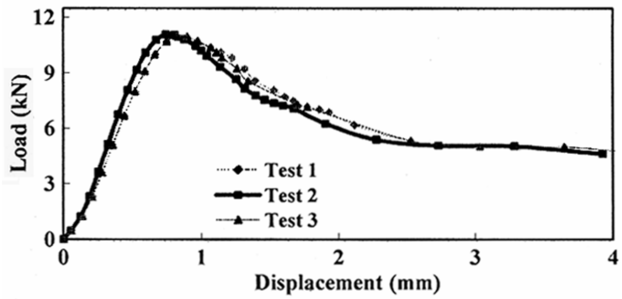

Fig. 14— Load-displacement diagram – test repeatability (L=150 mm, θ=120°)

repeatability of test, three tests have been performed for a panel with L=150 mm, θ=120°. The load-displacement diagrams have been shown in Fig. 14.

Conclusions

The following conclusions may be drawn from this study:

(i) By increasing the length of the panels, the bucking load decreases slightly. It is more important for short panels.

(ii) For θ>90°, the buckling load increases by increasing the sector angle. Approximately, for tested panels, the buckling stress is not sensitive to the sector angle.

(iii) Clamped boundary conditions can increase the bucking load but the post-buckling path does not change significantly.

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