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Composite Cylinders Subjected to External Pressure

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Summary

Nine tests on cylinders with a composite, steel-concrete-steel, wall subjected to external pressure are described. The results show the advantage of this form of construction.

1. Composite Construction

The unpublished research reported in this paper was commissioned by Tecnomare SPA of Italy as part of their study to develop vessels to resist high external pressure for hydrocarbon production in deep water. It was carried out by the University of Manchester, England, and consisted of testing nine cylinders with steel-concrete-steel walls with a hemispherical dome at one end. Such vessels are relatively insensitive to initial imperfections and fail, after the steel skins have yielded, by strength breakdown of the filler material. Previously published reports describe the theory and show it is a faithful guide to the actual structural behaviour and strength.

2. Tests

The objectives of the tests were:

1. To compare the experimental pre-collapse behaviour and failure pressure with theoretical predictions.
2. To examine the cylinder/hemisphere interaction.
3. To study the effect of a penetration through the cylinder wall.
4. To measure the change in radial deformation with time under sustained pressure and the effect of sustained pressure on the ultimate strength.

All nine shells tested were cylinders, with an outside diameter (D_o) of 495 mm and steel skin thickness (t_o=t_i) of 2.00 mm (f_y = 297 N/mm^2; except TEC 6 where, for the inside skin, t_i = 1.91 mm, f_y = 260 N/mm^2), with a hemispherical dome as closure at one end (the steel in the skins of the dome was thinner 1.25 mm to 1.4 mm and of lower strength). The strength of the concrete filler varied, cube and cylinder strength is given for each cylinder in Table 1. The cylindrical portion was 1000 mm (approx. 2D_o) except for TEC 6 where it was 683 mm. TEC 5, 6, 7 & 8 had penetrations, formed of steel tubes 108 mm outside diameter, through the cylinder wall. In TEC 9 the pressure was sustained for 38 days at 6 N/mm^2, causing yield of the inside skin. The test failure pressure (p_{fx}) is compared with the simple limit theory failure pressure (p_f) in Table 1.

Shell	Wall thick. h_{av} mm	cube f_{cu} N/mm^2	cylinder f'_c N/mm^2	Test p_{fx} N/mm^2	Theory p_f N/mm^2	p_{fx} / p_f
TEC 1	23.1	49.7	42.2	7.6	8.28	0.92
TEC 2	23.2	49.4	45.4	8.6	8.29	1.04
TEC 3	22.0	47.0	41.1	7.5	7.93	0.95
TEC 4	20.3	48.0	43.3	7.2	7.68	0.94
TEC 5	23.0	50.2	40.8	8.6	8.29	1.04
TEC 6	22.8	52.3	42.5	9.6	7.90	1.22
TEC 7	20.6	46.8	43.8	7.8	7.68	1.02
TEC 8	23.1	52.0	44.9	8.6	8.42	1.02
TEC 9	22.9	56.8	46.6	9.1	8.65	1.05
				Average (excluding TEC 6)		1.00

Table 1. Test results compared with theory

The failures occurred with an inward facing lobe, about 600 mm long and 220 mm wide, in the cylinder portion of the shell and were not affected by the dome or penetrations or the sustained pressure. The higher strength achieved by TEC 6 is attributed to its shorter length ($L/D_o = 1.38$), with the restraint provided by the stiffer dome and closed end enhancing its strength.

Theoretically failure is assumed to occur when the maximum principal stress in the concrete σ_1 (which will be the circumferential stress near the inside skin) reaches: $\sigma_1 = \sigma_{uniax} + 3\,\sigma_3$ where σ_{uniax} is the uniaxial strength of the concrete (taken as 0.75 f_{cu} to compare with tests, though 0.67 f_{cu}/γ_m should be used in design) and σ_3 is the minimum principal stress (the radial stress in the concrete at the interface with the inside skin).

The simple limit state failure pressure is given by:

$$p_f = 2\,[\,t_o f_{yo} + t_i f_{yi} + (\,h_{av} - t_o - t_i\,)\,(\,0.75\,f_{cu} + 6\,t_i\,f_{yi} / (D_o - 2\,h_{av} + 2\,t_i\,)\,]\,/\,D_o$$

Table 1 shows that **this theory is a reasonable predictor of ultimate strength**. The detailed results show that **the elastic/plastic theory was a good predictor of pressure/deformation behaviour and of ultimate strength**. These results are particularly satisfying in view of the unexpectedly high yield stress of the steel. This had the effect of bringing the steel yield pressure close to the failure pressure thus causing stresses in the concrete filler to be approximately 70% of the cube strength when the steel skin first started to yield. **The domes**, which had a similar total wall thickness as the cylinder, were stronger than the cylinders even though the strength of the steel skins in the domes was less than half the strength of the skins in the cylinder. There were no problems at the **cylinder/dome intersection**; the failure zone was in the cylinder, except for TEC 3 where the failure lobe encroached into the dome. **Creep** of the concrete filler during the sustained pressure test on TEC 9 caused the initial deformation to increase by 25% after one day and by 70% after 38 days under a pressure that was 70% of the predicted failure pressure; the ultimate strength was not affected by the cylinder being subjected to sustained pressure. **Penetrations** through the composite shell wall, with a diameter up to 22% of the main cylinder diameter, gave no cause for concern either at the design working pressure or at failure. In no case did the penetration initiate failure or reduce the shell's strength.

A more detailed description of this work and references to other research on composite cylinders under external pressure is available at the poster presentation.