INELASTIC BEHAVIOUR, FAILURE MODES AND ULTIMATE LOAD DESIGN OF PRESTRESSED CONCRETE PRESSURE VESSELS

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SUMMARY

A research programme concerning the behaviour in the inelastic range to rupture on six model vessels is now completed.

The geometry of the models is scaled 1:3.6 to the Scandinavian PCPV-model (reference pressure 84 kp/cm^2). Geometrical data: external height 180 cm, external diameter 120 cm.

The first and second parts of the test programme, containing models No. 1 to No. 4, were presented in SMIRT-1-Paper H 5/7 and SMIRT-2-Paper H 2/4. The aim of the first parts of the test programme was to study the inelastic behaviour up to failure on pneumatically loaded vessels.

The final series, containing two models, is a part of the Scandinavian verification programme. One of the models has a penetrated bottom slab and one has a top-construction with removable lid.

The last model (M 6) was made and tested in cooperation with the Danish Atomic Energy Commission Research Establishment, Risø. Models No. 5 and No. 6 were subjected to water pressure.

Model	Max. pressure	Failure	Characteristics	
			Bonded reinforcement	Geometry
No. 1	270 kp/cm^2	Liner-leakage (corner)	Yes	Symmetric
No. 2	267 kp/cm^2	Explosion (corner region)	No	Symmetric
No. 3	276 kp/cm^2	Liner-leakage (corner)	Yes	Symmetric
No. 4	257 kp/cm^2	Explosion (wall)	No	Symmetric
No. 5	288 kp/cm^2	Liner-leakage (corner)	Yes	Penetrated bottom slab
No. 6	297 kp/cm^2	Leakage (lid-membrane)	Yes	Removable lid

Diagrams of total deflections up to failure are presented together with corresponding strains measured on liner and bonded reinforcement, and are compared with computed values.

Calculations of the pressure/deformation relation for the plastic range up to failure are presented, together with final conclusions of the test series.

1. Testprogram

A study of the inelastic behaviour to rupture of six PCRV-model vessels have been the main purpose of the now completed testprogram. The two first sub-project, containing model M1 - M4, are earlier presented, but will, as to the totality, shortly be recapitulated, see Figure 1.

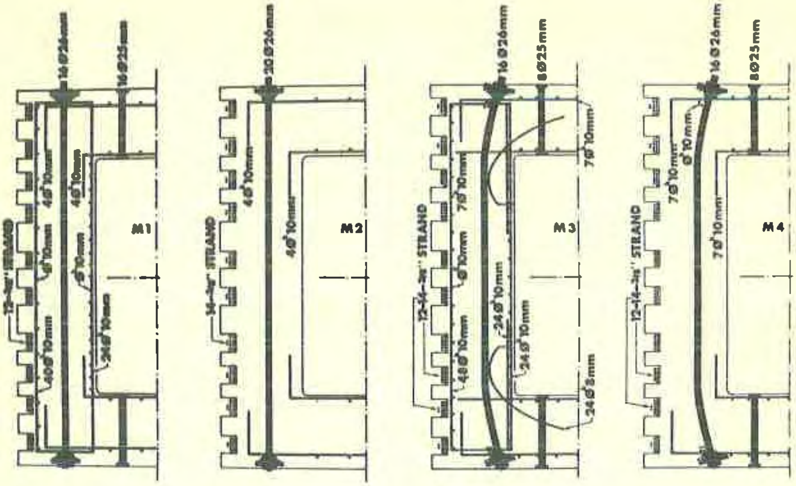

Figure 1. Cross-sections showing total reinforcement

The major differences between the models were that M2 and M4 had no bonded reinforcement in the wall, and that the vertical prestressing cables (System Dywidag) in M3 and M4 were curved in the liner-corner region. In M2 the number of Dywidag-cables (St 85/105) was increased from 16 to 20 to compensate for the absence of the bonded reinforcement in the wall, but the total nominal prestressing force was not increased. The axial cable forces were for model M1 = 30,5 Mp, M2 = 24,5 Mp, M3 = 32,5 Mp and M4 = 32,5 Mp. In the circumferential direction there were 10 rings, consisting of 3/8" prestressing strands (St 170/190). The nominal prestressing forces in this direction were for model M1 = 73 Mp per ring (12 - 3/8"), M2 = 73 Mp per ring (14 - 3/8") and models M3 and M4 = 66 Mp per ring (12 - 3/8") for the 6 rings in the midregion of the model and 78 Mp per ring (14 - 3/8") in the endregions.

All bonded reinforcement consisted of deformed bars (St 40/60). The liner, which was without anchors, was made of mild steel. The models were made of concrete with an average cube strength of 575 kp/cm^2.

The final sub-project was carried out as a part of the Scandinavian verification program and consists of model M5 and M6.

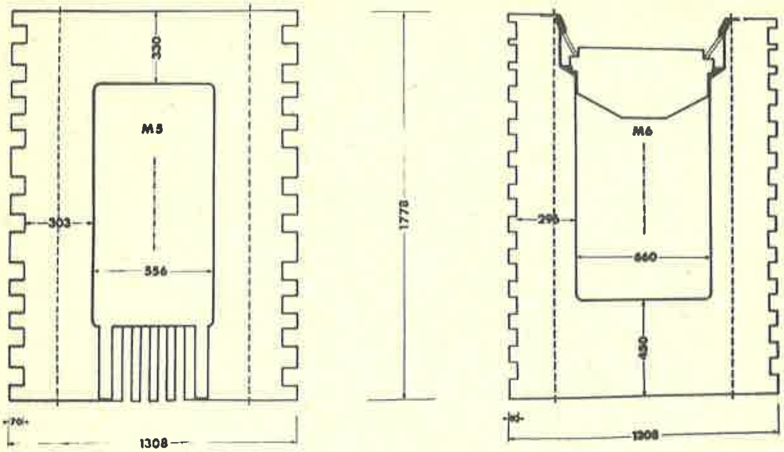

Figure 2. Geometry of model M5 and M6

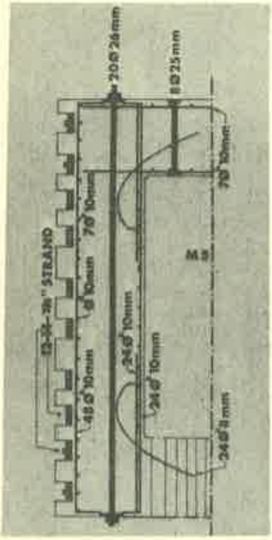

Figure 3. Total reinforcement of model M5.

Model M5 has penetrated bottom slab, and 20 straight Dywidag-cables with a nominal axial force of 33.0 Mp per cable. The nominal prestressing forces in circumferential direction are equal to that of model M3 and **M4**. The amount of bonded reinforcement is equal to M3, see figure 3.

The liner was for model M5 modified according to the simplified penetrating pattern shown in Figure 4. Full internal pressure acts on the tubes (8 pump-channels"), which are situated on the exterior circumference. In addition to the interior liner it was used an exterior liner welded to the tubes and the Dywidag-supporting ring.

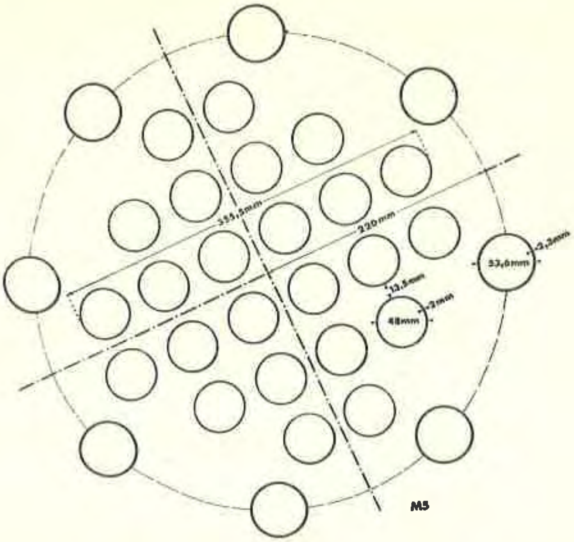

Figure 4. Penetration pattern - M5

Model M6 is a teamwork between the Danish Atomic Energy Commission Research Establishment (AEK), Risø, and the Cement and Concrete Research Institute (FCB), University of Trondheim, Norway. The liner and the removable lid was manufactured at AEK. Production and testing of the model was carried out by a joint team from AEK and FCB.

The vertical prestress in axial direction is equal to that of M5, i.e. 20 straight Dywidag-cables with a nominal axial force of 33.0 Mp per cable. In the circumferential directions there were 12 rings with a nominal prestressing force of 63.1 Mp for the upper ring, 30.7 Mp for the next one and 68.0 Mp per ring for the remaining 10 rings. Total reinforcement for M6 is shown in Figure 5.

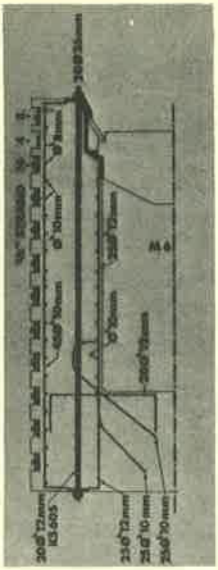

Figure 5. Total reinforcement of model M6

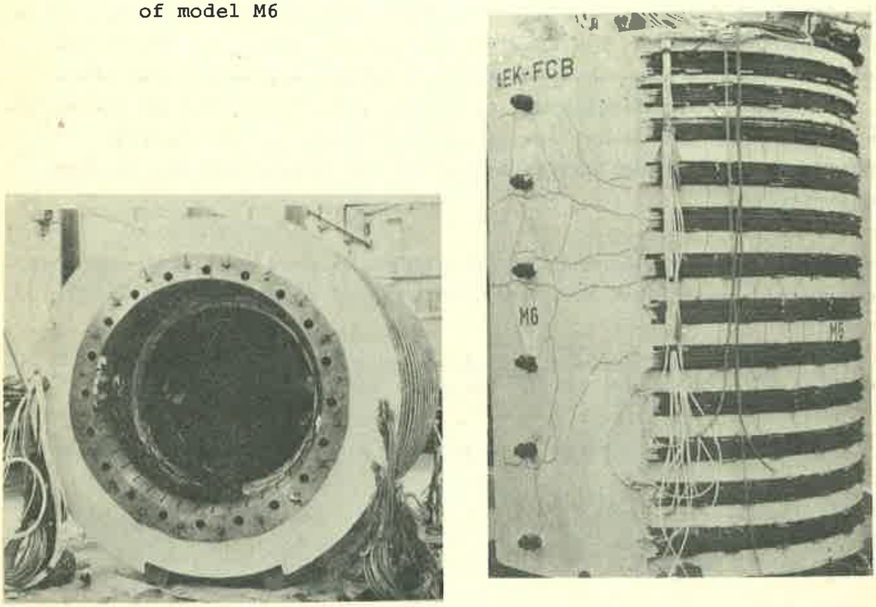

Figure 6. Photos of model M6 (right: visible cracks at 297 kp/cm^2)

2. Significant test-results.

Model M5 and M6 were instrumented as the earlier models, with a total amount of tranducers of about 200. The test procedure of model M5 was equal to that of the models M1 - M4, while M6 was tested directly to failure. In this final sub-project the models were subjected to waterpressure.

The purpose of M5 was to study the mode of failure in the penetrated bottom slab. The test had to be terminated due to an extensive leakage in the liner at an internal pressure of 288 kp/cm^2. No structural failure took place. In mid-height of the vessel the concrete was extensively cracked. No cracks were observed neither in the top slab nor in the bottom slab.

The purpose of M6 was to study the mode of failure of the upper part of the vessel. The test had also in this case to be terminated, this time due to leakage past the toroid seal of the lid at 297 kp/cm^2 (about 3.5 x design pressure). After repair of the vessel, a new test was carried out. At this time the test was terminated at 315 kp/cm^2 due to a new leakage in the toroid seal.

The behaviour of model M5 and M6 showed the same progressive development that was observed during the testing of the models M1 to M4. Within the range of rupture there was yielding in the axial cables, the bonded reinforcement, the liner, the circumferential prestressing and for M6 also in the top flange. The development of strain and deflections in the vessels is almost identical for diametrically opposite parts of the models. This underlines the symmetrical behaviour of the models and the uniform crack distribution.

Measurements in the top and the bottom slab of M5 show small deformations. The tubes in the penetrated zone had all measured strains below yielding.

Figure 7 is a comparison between the strain development of bonded reinforcement with 45 angel to the vertical in the upper and lower corner regions.

Figure 8 shows total deflections at different pressure levels for model M6.

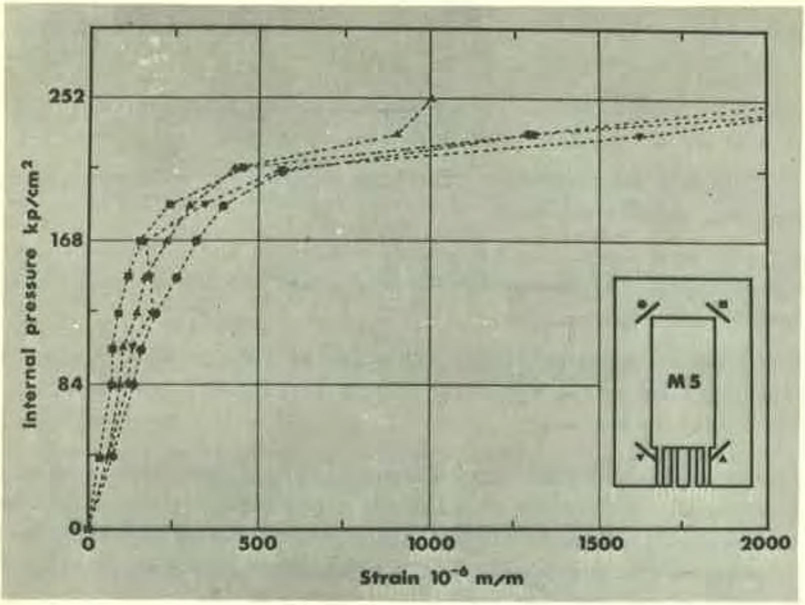

Figure 7. Measured strain on sloping reinforcement in the corner regions.

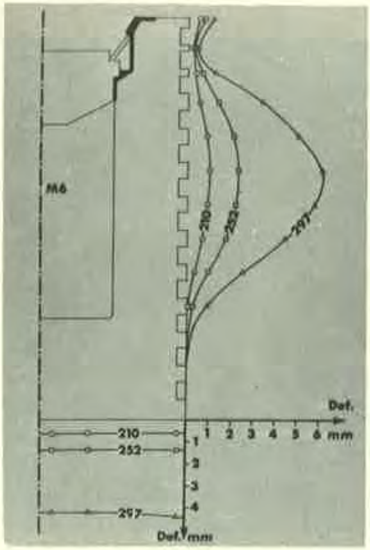

Figure 8. Measured total deflections at 210-252 and 297 kp/cm^2 internal pressure.

3. Failure analysis

These failure tests confirm an analysis of failure based on the following assumptions:

a) The cylindrical wall consists of a number of rigid elements (lamellae) held together in the longitudinal direction by hinges.

b) Strain differences in the radial direction through the wall are ignored after the concrete has cracked.

c) The strain differences in the tangential direction in the prestressed ring reinforcement, the bonded reinforcement and the liner are functions of the radial deflection alone.

d) The bottom slab is uncracked up to the point of failure and consequently the deformations in the end slabs have a negligiable influence on the deformations in the wall.

The wall is assumed to be divided into elements in the longitudinal direction as shown in Figure 9. Within the plastic range possible configurations are depending on the amount of reinforcement and where this reinforcement is situated. Corresponding forces, acting in an unsymmetrical vessel without bonded reinforcement are shown in Figure 9.

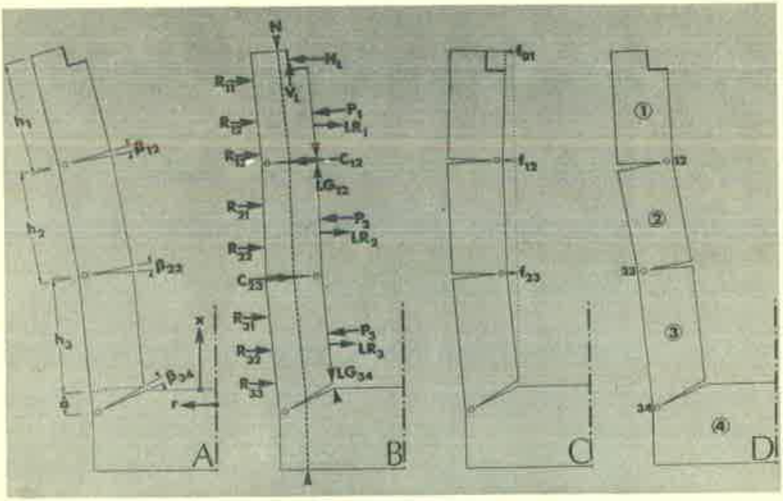

Figure 9. Lamellae-configurations for an unsymmetrical vessel with lid. (3 elements).

The compression force in the "hinges" is given by the prestressing force in the longitudinal direction and the internal pressure. The strain in the bonded reinforcement depends on the deformation conditions in each local section, whereas the strain in the cables depends on the total deformation condition of the model. The strain in the cables is uniform over the whole cable length if the friction forces are ignored.

The assumed height of the compression zone is of little numerical importance because of the low compression force. A rectangular stress distribution in the compression zone, with a stress equal to 0.63 x cube strength, has been assumed in the calculations. If the liner is situated in the compression zone it will contribute to the yield force of the liner steel, and in this case the yield force is often great enough to keep the balance without additional force from the concrete.

With a fixed value of the internal pressure force and moment equilibrium can be satisfied through an appropriate variation of f. The strains in the reinforcement at the start of the test and the stress-strain relation are input information in this calculation. The increase in strain in the cables is geometrically determined by following the element-configuration.
The longitudinal strain in the liner and bonded reinforcement crossing a crack is assumed equal to the yield strain.

The failure model has been created for an unsymmetrical vessel with the cylindrical wall consisting of 3 or 4 rigid elements. This gives for a symmetrical vessel 6 respectively 8 elements. Comparison between the measured and computed values of the radial and axial (along a generatrice) deflections are shown in the figures 10 to 13.

4. Conclusions

The models without bonded reinforcement in the cylindrical wall got an explosive failure. The models with such reinforcement failed, due to liner-leakage after great plastic deflections of the wall.

Use of bonded reinforcement contributes to a distribution of cracks and therefore increases the safety against explosive failure, but it is no garantie against this type of failure. If the ductility of the liner is great enough, the vessel will explode when the prestressing reinforcement reaches its ultimate strain. Calculation of the pressure-deflection relation of the cylindrical wall for the plastic range up to failure corresponds fairly to the test results. This calculation uses a kinematic chain having several links.

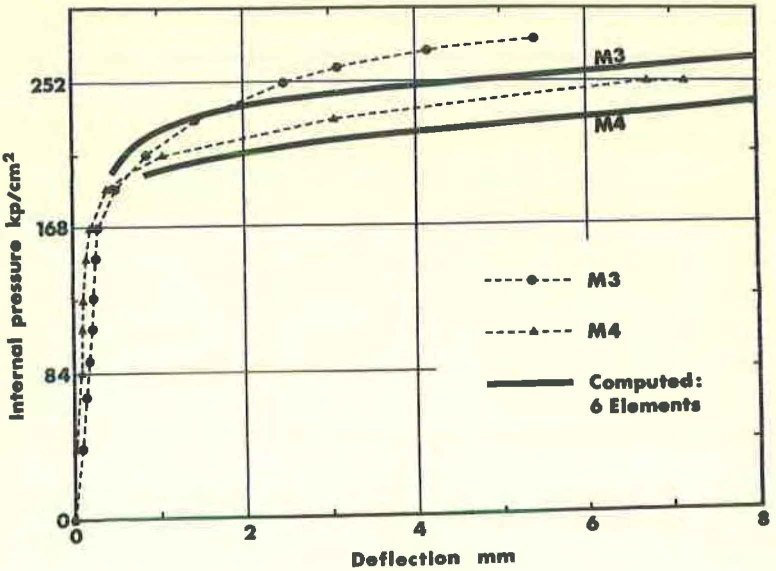

Figure 10. Measured and computed deflections at mid-height.

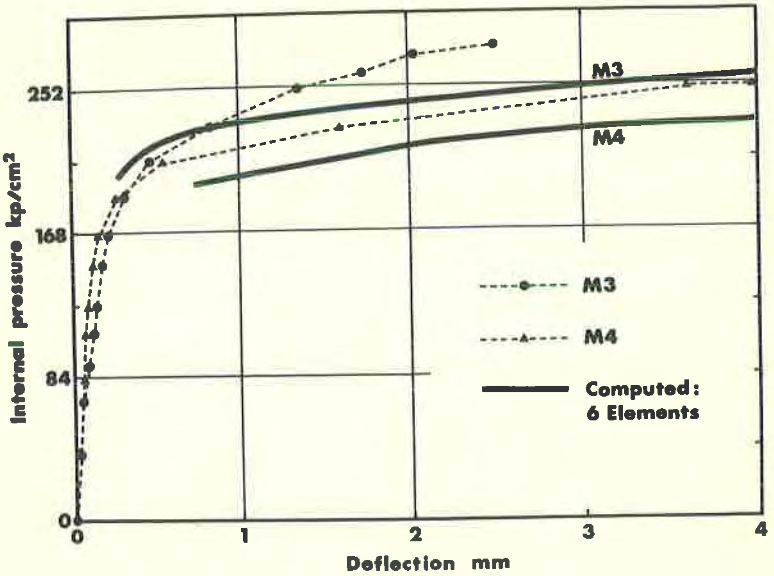

Figure 11. Measured and computed axial deflections.

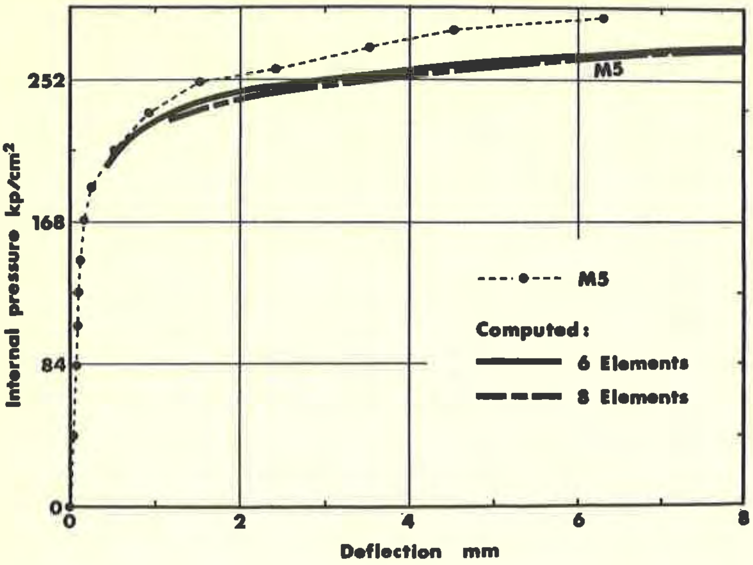

Figure 12. Measured and computed deflections at mid-height.

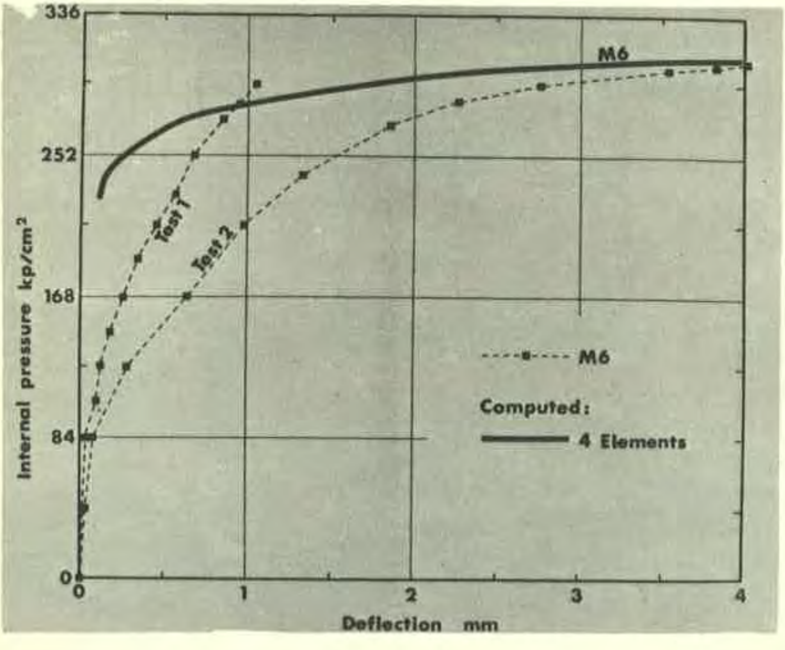

Figure 13. Measured and computed radial deflections at top of the vessel.