RESEARCH INTO THE STRUCTURAL INTEGRITY OF LNG TANKS

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In 1985 British Gas decommissioned an LNG tank at Ambergate, Derbyshire. Demolition was delayed and experimental research performed to extend previous studies into the structural integrity of LNG tanks. Six major experiments were carried out which included a hydrostatic test and a novel partial vacuum experiment. Results have added significantly to technical knowledge and have provided evidence of sound design and construction.

INTRODUCTION

British Gas operates six peak shaving LNG facilities, the largest capable of storing 180,000 cubic metres of LNG in four above ground double wall tanks.

British Gas has always recognised the importance of safety and invests substantially to ensure that its facilities are designed and operated to the appropriate national and international standards. The Company has also maintained a policy of supporting research to identify and mitigate the possible hazards presented by facilities such as LNG storage.

The British Gas Engineering Research Station (ERS) has been responsible for investigating the structural behaviour of these tanks under both normal operating and abnormal conditions. Many areas of research have been pursued including stress and fatigue analysis of welded junctions, loading caused by in-tank insulation and tank structural buckling.

The theoretical methods which have been developed have often been of a novel nature and therefore required experimental validation. The design of laboratory experiments to provide this confirmation can be difficult because factors such as the large diameter to thickness ratio and the non-linear behaviour of the insulation materials cannot easily be scaled.

In 1985 however, it was decided that the LNG tank at Ambergate, Derbyshire was surplus to operational requirements and would be demolished. This presented an excellent opportunity to perform a series of tests on the tank which would validate theoretical techniques at a realistic scale. Demolition was therefore delayed for 12 months to allow a comprehensive experimental programme to be undertaken by ERS.

AMBERGATE TANK DESIGN

Fig 1 shows a cross-section of the 11,000 cubic metre Ambergate LNG tank. Built in the late 1960's, the tank was of conventional design with a liquid and pressure containing aluminium alloy inner tank surrounded by a mild steel outer tank. Holding down bolts on the inner tank resisted the upthrust from the internal pressure within the inner tank. The interspace insulation consisted of Perlite with a resilient glass fibre blanket adjacent to the inner tank. Nitrogen gas was used to maintain an inert atmosphere in the interspace. The base insulation was load bearing Foamglas blocks.

EXPERIMENTAL PROGRAMME

Previous research had indicated the type of experiment which would significantly increase understanding of tank structural integrity, however various constraints had to be considered including timescale, cost and environmental restrictions.

A large number of experiments were undertaken and it would be impossible to give details of all of them within this paper. For this reason, two of the major tests have been selected and are presented in detail. The remainder of the experiments are briefly described and some of the more important conclusions given.

Experiments Presented In Detail

Hydrostatic and Pressurisation Experiment. Operational tank loading was simulated by filling the inner tank with water to the hydrostatic test level and strains measured at critical locations. Results were compared with theoretical predictions. After filling with water the inner tank was pressure tested and strains measured at critical locations.

Buckling Experiment. The inner tank was subjected to a partial vacuum and its response monitored to validate theoretical methods to predict elastic buckling

Other Experiments

Tank Warm Up. The warming up was monitored to establish the behaviour of the tank and to compare displacement, temperature and strain response with predicted values.

Tank Inspection. An inspection was carried out to allow the condition of the inner tank to be compared with design and construction standards.

Tank Geometry Measurement. General tank geometry, including out of roundness and floor plate flatness was measured and compared with design.

Nozzle Loading Experiment. An experiment was carried out to measure the stiffness of the outlet nozzle/ tank wall connection for various levels of liquid head. In addition the stress distribution around the nozzle was measured.

Dynamic Loading. Time varying loads from a mechanical shaker and instrumented impacts were applied with the dynamic response of both inner and outer tanks measured. This was to provide information about response to blast and seismic loads.

Examination of Samples. Following demolition of the tank, selected samples of tank material and welded areas were retained and subjected to detailed mechanical and metallographic testing. This was to establish the construction quality of the tank and indicate whether any deterioration had occurred following service.

HYDROSTATIC AND PRESSURISATION EXPERIMENT

Filling and emptying an LNG tank causes changes in the hydrostatic pressure inside the inner tank. Pressure cycling of this nature could eventually give rise to fatigue damage resulting in the extreme case in plate or weld failure with consequent leakage.

A number of regions on the inner tank could be significantly affected by these pressure cycles, such as the shell to base weld, the bottom outlet nozzle in bottom outlet tanks and the floor plates. If the floor plates are flat then they should be unstressed by hydrostatic pressure, however it is not uncommon to find bulges and buckles in the floor which when flattened could give rise to high stresses.

Of the three areas mentioned, it was thought that the shell to base junction was the most critical. Previous work had in fact shown that the fatigue life of large tanks would be based on the performance of this detail. An accurate prediction of the stresses at this joint was therefore essential.

The normal assumption to regard the tank shell as fully fixed at the bottom was considered too pessimistic. An analysis was therefore developed which incorporated a solution to the edge bending of circular cylindrical shells with a solution to the non-linear bending of circular flat plates and a trial and error technique to solve the combined non-linear simultaneous equations. Holding down bolts, which resist the upthrust due to internal pressure, could also be included. This analysis was used to predict the behaviour of the shell to base junction and compare it with experiment.

To experimentally investigate the distribution of stress at the critical locations, a hydrostatic test was carried out with strains measured in these areas. Twenty strain gauges measuring strain in axial and circumferential directions were attached to the shell to base junction at three locations round the tank. In the area of the welded outlet nozzle sixty gauges were distributed around the nozzle and on the adjacent tank wall and floor. Three of the tank floor bulges which had been previously inspected and measured were strain gauged to obtain information about stresses developed in the floor as it was progressively flattened.

The strain gauges and other monitoring transducers were connected to a Solartron Orion data logger which was controlled by a BBC microcomputer. Software had been prepared to allow on-line monitoring of any transducer and data could be recorded on disc as required. In addition processing of previously recorded data could be carried out as the test was continuing. Plots of a wide variety of measured or calculated parameters e.g. measured strain or principal stress could be immediately obtained to provide a picture of tank response and allow decisions to be made as the test progressed.

The tank was filled via the LNG inlet line and several days elapsed before the required water depth was reached. Strains were recorded for a wide range of liquid levels during filling and emptying.

Fig 2 shows the measured variation in base plate strain close to the shell to base junction as the water depth was increased. The strain increases rapidly at the start but becomes linear after 700 mm water depth. The reason for the sudden change in strain at the beginning is the flattening of the distorted floor plates near the junction. This causes high bending stresses to be generated. Also shown on this figure are the theoretical predictions assuming (i) a rigid fixing at the base and (ii) using the theory described above. Clearly the rigid assumption is overly pessimistic but the developed theory is in excellent agreement with the linear portion of the experimental results.

Strain measured at the crown of a floor bulge is shown in Fig 3. Again high strain changes take place on initial filling after which strain remains constant. These results indicate that distortions have flattened out with the floor in contact with the foundation.

Strains at the outlet nozzle were similar to the nominal strains present on the tank wall. Increases in strain generated by the presence of a structural discontinuity were offset by the increased thickness of the nozzle reinforcement.

The evidence indicates that where fatigue may be a problem, tanks with flat bases constructed from thin *plate should not be completely emptied*, but a heel of at least 1 metre of LNG should remain to stabilise any plate distortions. This will avoid the large variations in strain caused by small changes in liquid level at low liquid depths.

With the tank filled to the test level with water the remaining air space was pressurised to its test value of 12.4 kN/m2. Strains were measured and compared with theoretical predictions. Most strains showed good agreement, however larger than expected strains were recorded at certain shell to base locations, Fig 4. This was found to be associated with a small number of inner tank holding down bolts which had become slack and were not able to resist upthrust until a substantial upward movement had occurred at the bottom junction. The slackness of the bolts had resulted from settlement of the base insulation system. The evidence indicates that tanks which require holding down bolts to resist internal pressure should have the facility for inspection and retightening.

PARTIAL VACUUM EXPERIMENT

Elastic buckling is a phenomenon which occurs when slender structures are subjected to compressive loads. A familiar example is the simple Euler strut. In Euler buckling, instead of the maximum allowable load being limited by material strength, the controlling parameter is structural stiffness. LNG tanks, which have large diameter to thickness ratios can behave in this manner when subjected to compressive stresses. These could arise from several possible loads.

If an LNG tank were decommissioned, the warming of the inner tank could result in appreciable radial expansion. The insulation system is designed to accommodate this displacement, however, if for some reason the resilience of the insulation has been lost, then expansion against a rigid boundary, (e.g. compacted Perlite) could cause high compressive stresses and hence buckling. A buckling response could also occur if a high vacuum was developed inside a pressure containing inner or outer tank.

A further possible case results when a tank is affected by a blast wave following a large external explosion. Loading may be transferred through the insulation to the inner tank.

The prediction of buckling under these loadings is difficult for double walled LNG tanks. British Gas together with the Department of Engineering Science, University of Oxford have performed research to predict tank buckling under static and time varying loads. Methods have been developed based on mathematical relationships and complex non-linear computer codes such as ABAQUS (Hibbitt et al (1)). Validation has been carried out using small scale precision models and results have provided confidence in the application of these methods.

It was realised that an experiment which created a partial vacuum and induced buckling in a full size LNG tank could provide a unique opportunity to validate the techniques and allow them to be used with confidence over a range of potential buckling conditions. To investigate the feasibility of the experiment, a theoretical buckling analysis of the Ambergate tank was carried out.

The first buckling response to occur in tank walls under vacuum is termed "local buckling". Circumferential waves are produced in the unsupported side wall areas between stiffening rings with significant radial displacement developed. If the vacuum is increased, local buckling develops into "global buckling" when stiffening rings deform and considerable plasticity is developed.

The analysis revealed that the first buckling response would be local buckling on the inner tank wall between the second and third stiffening rings 6.7 metres from the floor. The vacuum to cause this buckling was calculated to be between 6.2 and 8.0 kN/m2, seven times the permitted design vacuum. Buckling of the tank wall in a global mode, and roof buckling were predicted to occur at much higher levels of vacuum.

The analytical methods are capable of estimating the vacuum pressure and vertical position for first buckling on the wall. However the circumferential location is impossible to predict as it is a function of local geometric deviation. Displacements for a large area of wall must be measured in order to identify a buckling response. The design of a system to measure extensive displacements and allow on-line monitoring was crucial if a vacuum experiment were to be performed.

Two systems were developed - an optical system using a Moire fringe technique, and a mechanical system based on conventional displacement transducers.

The optical system was developed by the British National Physical Laboratory. Vertically lined paper was pasted on the inner tank wall between the second and third stiffening rings 6.7 metres from the floor. An area extending over 40% of the circumference was viewed by three fixed point cameras attached to a stiffening ring. Photographic slides were made of the papered wall at the datum positions to be used as a reference grid for each camera position. Then during the experiment the wall was viewed through each reference grid via remotely operated video cameras. As the wall displaced , fringe patterns were developed presenting an immediate picture of the buckled shape and allowing measurements of displacement to be performed.

Fig 5 shows a diagrammatic representation of the tank wall with actual fringe patterns superimposed. Each fringe provides a contour from which displacement can be calculated. The human figure is included only to give an indication of dimension.

The second system used displacement transducers positioned around the tank wall between the third and fourth stiffening rings above the optical system. Video signal cables and transducer leads for both systems were taken out of the tank through a gland in the outlet line to video monitors and microcomputer logging units.

The partial vacuum was achieved by removing air from the tank using compressed air driven venturi air movers. To prevent the floor from being pulled upwards during the test, the tank was filled with water to a height of 3.5 metres.

Fig 6 shows a typical displacement plot. Elastic buckling usually occurred abruptly - for the position shown, the displacement jumped to 42 mm at a vacuum of 7.0 kN/m2. Displacement continued to increase linearly as vacuum increased. On unloading, the response was similar, however reverse buckling occurred at a lower level. This is expected since the theory of elastic buckling of curved plates predicts different instability positions for loading and unloading. The response of the tank was wholly elastic with the walls returning to the datum position on unloading.

Buckling did not occur at the same time at all circumferential locations. The effects of local deviations meant that the pattern developed as the vacuum increased.

Following the successful completion of the test, the interspace insulation was removed and the experiment repeated. As the insulation imposes a compressive pressure on the inner tank, the vacuum required to initiate buckling for this experiment was expected to exceed the previous value by an amount equivalent to the insulation pressure. A difference was found which averaged 0.8 kN/m2. Table 1 gives a comparison between predicted and experimental values for local wall buckling in the optically measured region.

The methods used to predict buckling assume that the whole of the wall circumference elastically buckles at the same vacuum whereas, as noted, this does not occur in practice. The differential pressure at which 80% of the buckles had formed compares well with the predicted pressure. The number of buckles eventually formed around the circumference is also in good agreement.

The net pressure exerted by the insulation inferred from the final experiment was less than one half the predicted value. This had been derived from known compression data for the insulation system and application of Janssen's formula (Janssen (2)). Further small scale experimental studies suggest that the fibre glass blanket was more compliant than had been assumed.

At the end of the final experiment a major failure of the inner tank roof occurred. The vacuum pressure was one third of that calculated for roof buckling. Extensive analysis showed that a critical buckling response had not been considered in the methods used. Further research has resulted in new methods for predicting the behaviour of roofs under vacuum loading. This work is reported elsewhere (Schleyer et al (3)).

Table 1 : COMPARISON OF BUCKLING RESULTS

	Predicted Result		Experimental Result
	Analytical Method	Finite Diff. Method	
Local Buckling Pressure kN/m2	6.2	8.0	7.0*
Number of Buckles	35	34	33

* equivalent to 80% buckle formation.

RESULTS FROM OTHER EXPERIMENTS

Ambergate

Much useful information was gained from the other experiments in the programme. Monitoring of the tank during warm up proved that the insulation system was successful in accommodating expansions without significant radial pressures being developed. Information from the partial vacuum experiment showed that the pressure generated by the interspace insulation is certainly no greater than predicted using the normal design equations.

Inspection of the tank, geometry measurement and examination of samples showed that the tank had been well constructed within standard. No significant deterioration had occurred over the years and this has provided good evidence to confirm the soundness of this type of design.

From the nozzle loading experiments it was found that established techniques underestimated the nozzle stiffness for this tank. The stiffness of the junction and stresses resulting from externally applied loading were predicted accurately using a finite element representation of the nozzle.

Natural frequencies were determined for the tank from the dynamic loading experiments, and the behaviour of the interspace insulation to transmit loading, and attenuate low frequency vibration was identified.

Additional Research

Predictions for buckling pressures had been made on the basis of existing knowledge about the characteristics of the insulation in the tank interspace. The insulation is capable of applying load to the tank in two ways. Firstly, during normal service, the Perlite material applies a horizontal pressure to the inner and outer tank. Secondly, as the inner tank warms up, the glass fibre blanket and Perlite insulation system is compressed producing an additional horizontal pressure.

These phenomena were investigated separately. To understand the pressures developed as a result of Perlite loading, a rectangular section static rig 8m high was constructed which was capable of modelling gravity loading at an appropriate scale (Fig 7). The loads developed on the containment walls derived from Perlite self weight were measured using purpose built pressure transducers. In addition, the transmission of externally applied loads through the Perlite was examined by application of dead weight to the top of the Perlite column.

Experimental results were compared with predictions made using Janssen's equation whose critical parameters are K, the ratio of horizontal to vertical stress and M, the friction coefficient between Perlite and the containment surface. Shear box tests were performed to derive values for K and M for Perlite. Best fit values were then derived assuming that the observed pressures in the rig could be determined by application of Janssen's equation. Table 2 gives the comparison between results

Table 2 : COMPARISON OF PERLITE PARAMETERS

Parameter	Shear box	Large scale derivation
K	0.4	0.4
M	0.47	0.4

Sensitivity analyses demonstrated that the difference in the result for friction coefficient did not result in significantly different values for horizontal pressure.

A second experiment examined the stiffness characteristics of the insulation system. A rig was developed which allowed a half scale representation of the insulation system to be compressed. Load/displacement relationships were determined for various Perlite and glass fibre blanket combinations present in LNG tanks and then compared with stiffness curves derived from individual small scale tests on the materials. Fig 8 shows a comparison for one system confirming that compression of the insulation can be accurately predicted from simple small scale experiments.

OVERALL CONCLUSIONS

The programme of experiments on the Ambergate tank generated a considerable amount of important information about the behaviour of double walled LNG storage tanks.

The design and execution of the experiments produced a wide range of problems. These problems were overcome using the expertise at ERS gained from many years experience in undertaking full scale experiments in the field.

The hydrostatic and partial vacuum experiments provided contrasts in approach. The hydrostatic experiment was straightforward in concept because tanks are normally subjected to this test following construction - thus it was not expected to generate insurmountable problems in execution. It was performed using conventional strain gauges and its success depended on the expertise involved in instrumentation and data collection. At the other end of the scale was the novel partial vacuum experiment *which exposed the tank to a load condition beyond its* normal test level. Measurement and data collection depended on systems untried in this application and this was one of several experiments in which methods for implementation of loading and measurement of response had to be purpose designed and constructed.

The use of up to date methods for data collection and processing was a significant factor in the success of the programme. The microcomputer linked to a data logger provided great scope for on line data processing and review. Software development carried out in advance at ERS allowed the full potential of the system to be realised at site. Immediate access to information about the experiment allowed careful control to be exercised and assisted decision making at crucial stages. Without this facility it is doubtful whether the partial evacuation experiment could have been contemplated.

In general the experimental results confirmed the various theoretical approaches which have been developed by ERS. Techniques have been confirmed for the calculation of strain in tank wall, shell to base and shell to roof junctions. Predictive methods for tank wall buckling have also been shown to be correct. Further research has confirmed the methods used for deriving insulation *loading and response*.

Two important findings will be of interest to operators. Tanks with floors constructed of thin plate are prone to distortion and high cyclic strains can be developed if a tank is fully emptied. This could markedly reduce fatigue life if performed regularly. At least 1 m of LNG should be retained to prevent uplift if fatigue is thought to pose a problem.

Settlement in the foamed glass insulation system can result in holding down bolts becoming slack. Pressurisation of the tank results in lifting at the shell to base junction with resulting high strain. If possible, holding down bolts should be periodically inspected and retightened to avoid this potential problem. New designs which incorporate inner tank holding down bolts should always have the facility for retightening.

FINAL REMARKS

The Ambergate experimental programme has provided extensive important information about the structural behaviour of LNG tanks which confirms their general integrity and safety over a long period of operation. Theoretical techniques to predict the behaviour of LNG tanks under a wide variety of loads have been developed and validated by ERS. These techniques can now be used with confidence in future design studies, structural analysis investigations and hazard assessments.

ACKNOWLEDGEMENTS

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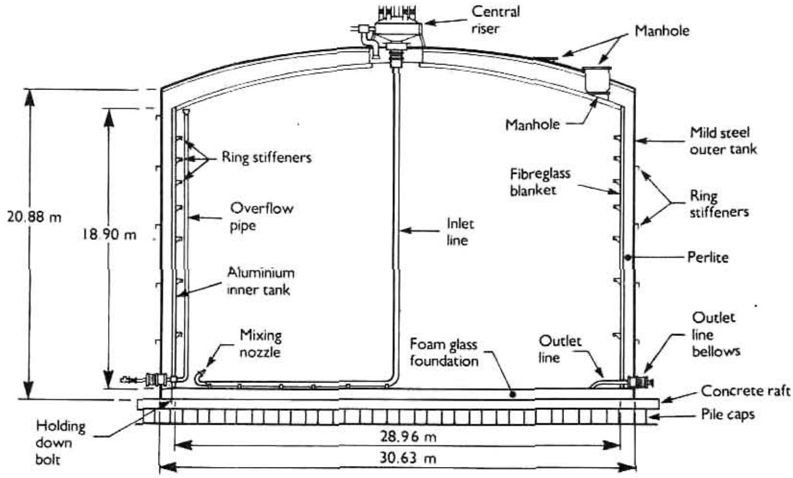

Figure 1 : Section Through Tank

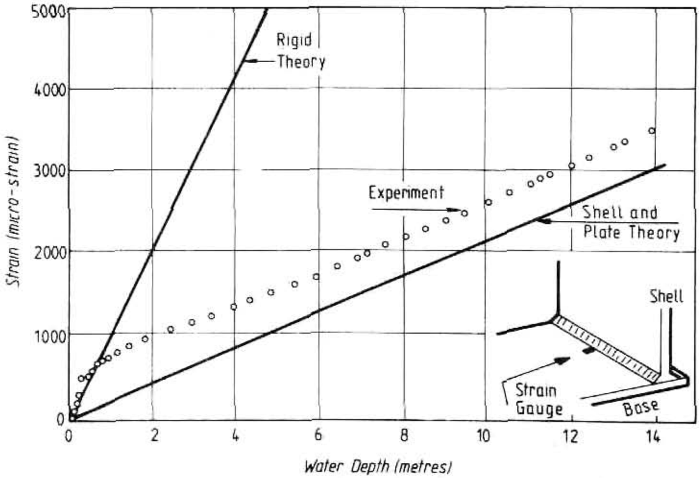

Figure 2 : Strain at the Shell to Base Junction - Water Fill

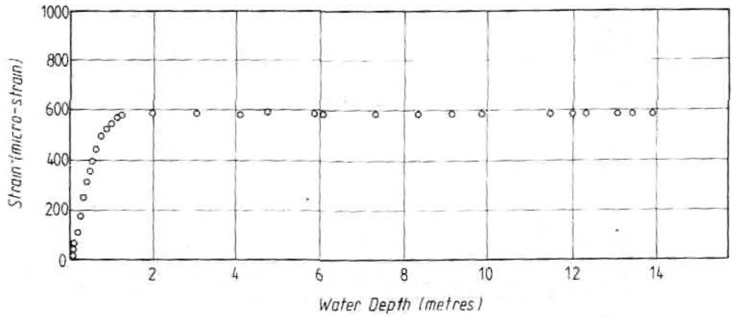

Figure 3 : Strain on Crown of Floor Bulge

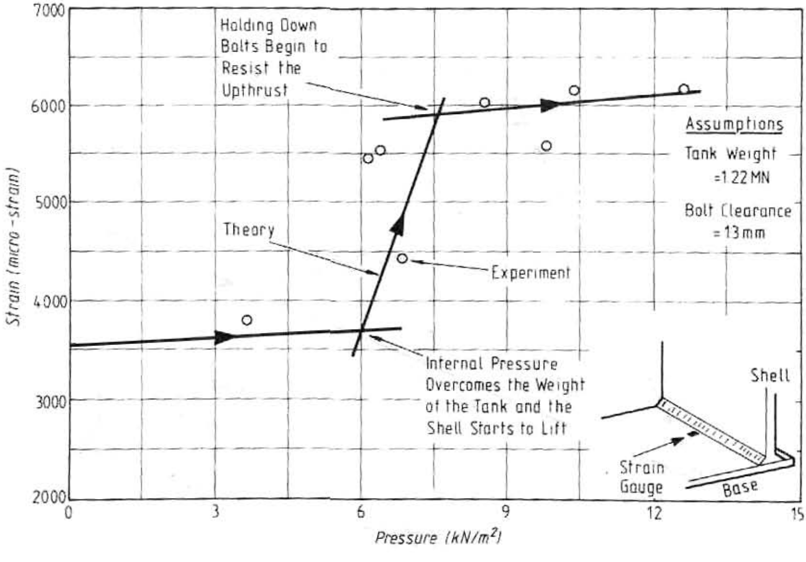

Figure 4 : Strain at the Shell to Base Junction - Internal Pressure

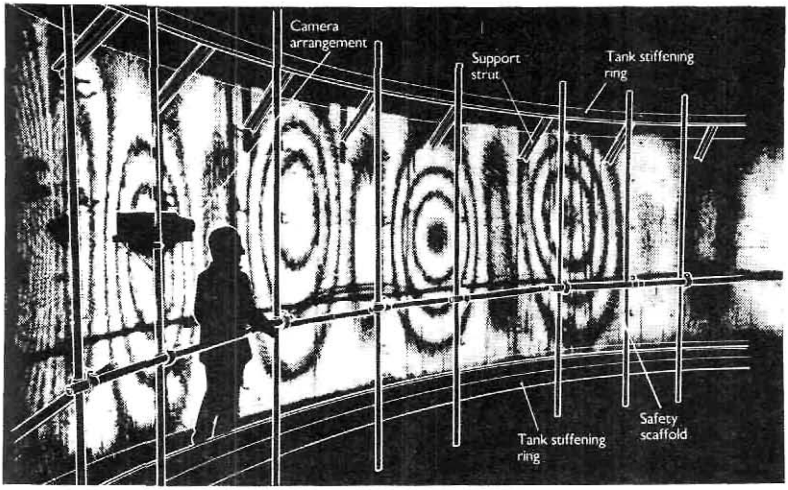

Figure 5 : Contours on the Tank Wall

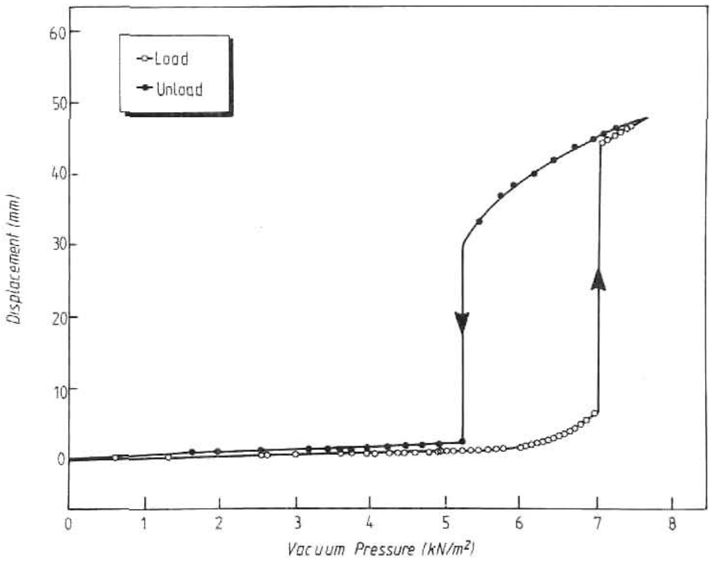

Figure 6 : Typical Buckling Displacement Plot

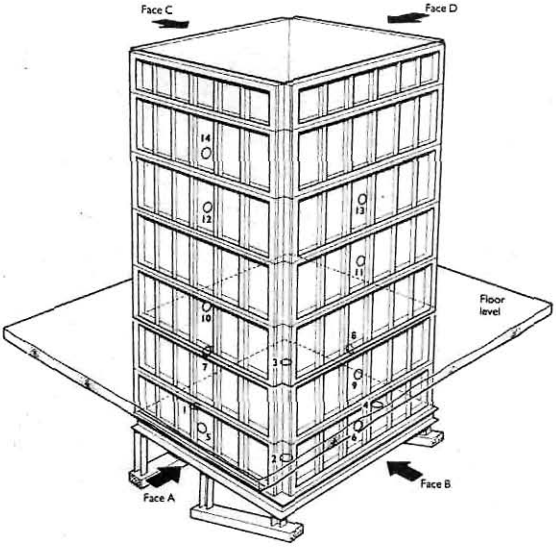

Figure 7 : Perlite Rig Showing Pressure Cell Locations

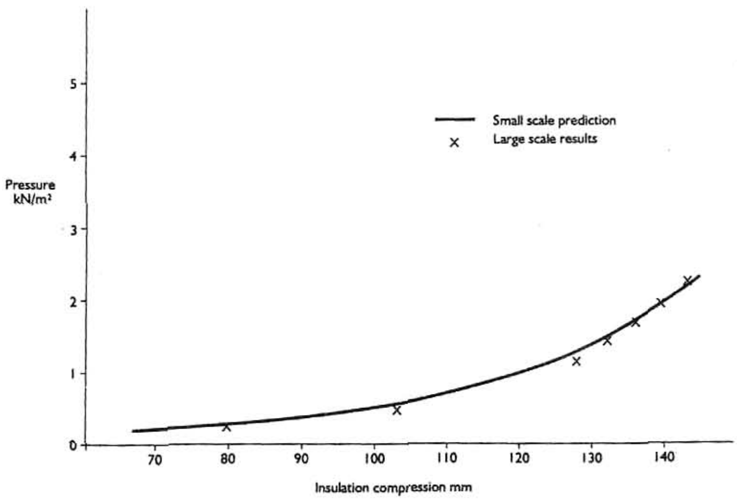

Figure 8 : Insulation Compression Characteristics