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Experiments on model shell roofs

Modellversuche mit Schalendächern

Ensaios em modelo reduzido de coberturas delgadas

Essais sur modèles de toitures en voile mince

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In a symposium on Concrete Shell Roofs held in London in 1952, Dr. J. J. McNamee stated, «It is somewhat remarkable that shell roof theories have profilerated so rapidly with practically no assistance from experimental results».

The series of experiments described in this paper was started in the laboratories of University College, Dundee in 1949, but in an under--staffed provincial University progress was slow. Since moving to Glasgow in 1952 the writer has been unable to carry on with the experimental work and has therefore decided to publish the work which was carried out at Dundee. Unfortunately no definite conclusions were obtained nor could any «labour saving» design formula be obtained from the results.

The experiments are however as far as can be ascertained the most comprehensive yet carried out on a series of shells and it is hoped that they will be of use to the large number of engineers who are now interested in shell structures.

There have been however, a number of other miscellaneous experiments on shell roofs. For example Baker[1] describes experiments carried out on a single concrete shell roof. He gives the values for the longitudinal and transverse stress distribution across the shell, but does not describe how this stress has been obtained. The values of the transverse bending moment — the main difficulty in shell roofs — are not given.

Morice[2] describes some experiments on a continuous shell but only gives values for the deflexions and not the stresses.

Both these experimenters have only used one shell, made of concrete in each case. Just as it is impossible to determine the strength of a batch of concrete from tests on one cube so the Author feels that the above experimenters must test at least one further shell of each type before their results can be relied upon.

Selvanayagem[5] describes some experiments on model shells made from steel plate. In the graphs showing his results however, he only compares the experimental fibre stresses on *one* side of the shell with the theoretical values. Since the fibre stress is a combination of that due to direct stress and bending stress the values on both sides must be given to ensure an adequate check.

The experiments described in this paper were carried out to determine the distribution of longitudinal stress — generally referred to as Nx — and transverse bending — generally known as $M\phi$. These two functions will vary at all points in the span but it was eventually decided to measure their values at one section only; since in general the maximum values occur at mid span it was decided to concentrate on this section. The span of the shells was kept constant but the thickness, radius of curvature and oher features were varied.

The choice of material from which to make shells was not easy. Concrete is the material generally used in practice but has the disadvantage that its physical properties, e. g. modulus of elasticity, vary so much that one cannot say with any degree of certainty what they are at the time of test. The technique of using electric resistance gauges on concrete, and for small models they are the best type to use, is far from perfect and for these main reasons it was decided not to use it.

Thin steel plate was actually used for the models. This has the advantage of constant elastic properties, no creep and no moisture content to affect the gauges. The difficulty in its use was that the thin sections required in order to give measurable stresses under the loads which could be applied gave a model which was very much thinner relative to the other dimensions than the average reinforced concrete roof.

The paper is divided into five main parts: —

Part I — Experimental method
Part II — Effect of vertical loading
Part III — Effect of inclined loading
Part IV — Effect of stiffening ribs
Part V — Ultimate load carrying capacity.

Part I – ***Experimental Method.***

A tinned steel plate was used for the shells. The tinned plate had the advantage that ribs etc. could be soldered on to the shell.

The shells tested had a span of 36 inches and width of 18 inches. The edge beams were $2\,^1/_2$ inches deep. The radius, thickness, and flange width varied with each shell. The leading dimensions of the shell are as shown in Fig. 1. and the complete range of shells tested is given in Table 1.

TABLE 1

Details of Shells

Shell No.	Type	Radius (R)	Thickness (t)	Flange Width	Half Central Angle θ radians
1	AF AO BF BO CF CO	12″	0.022″ » 0.048″ » 0.066″ »	¾″ — ¾″ — ¾″ —	0.848
2	AF AO BF BO	15″	0.022″ » 0.048″ »	½″ — ½″ —	0.6425
3	AF AO BF BO	10″	0.022″ » 0.048″ »	¾″ — ¾″ —	1.120

The shells were bent to shape in a crimping machine. The cross section was checked at frequent intervals with templates to ensure that the bending was accurate. The shell was closed by soldering the end pieces in position after the bending had been done.

The simple shell shown in Fig. 1. would tend to bow out horizontally under load, This would occur in practice in the case of a single shell but many shells erected form part of a series and with equal loads on each shell horizontal deflexion will not take place. Two methods were tried to prevent horizontal movement of the sides of the shell. The first consisted of the insertion of 1″ × 1/8″ horizontal tie bars as shown in Fig. 2-A and the second used 1″ deep ribs, of the same thickness as the shell as shown in Fig. 2-B. In each case four ribs or ties were used, spaced at equal intervals. The ties did not prove effective but the ribs had a considerable effect on the stresses in the shell. This was considered

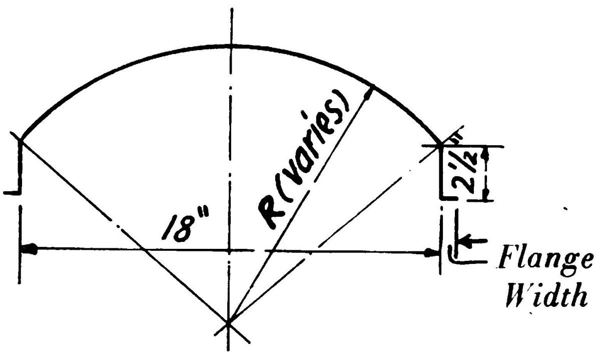


FIG. 1

worthy of special investigation and Part IV describes experiments carried out on shell 3-B when the positions and details of the rib were varied. In general however all the shells listed in Table 1. were tested (a) as single shells and (b) shells reinforced with ribs.

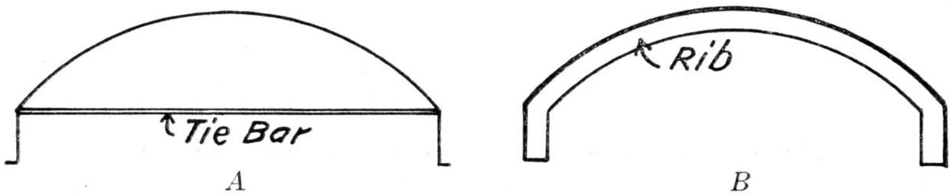


FIG. 2

Method of Loading.

Preliminary experiments showed that the effect of a uniformly distributed load could not be obtained by using point loads on a grid approximately 4 in. square nor was it obtained by erecting a sand box on the top of the shell and applying a load through the sand. The method adopted was to place an inflated air bag on the top of the shell and apply dead weights to a saddle resting on top of the bag. The bag had framed ends which enabled it to fit the shell closelly.

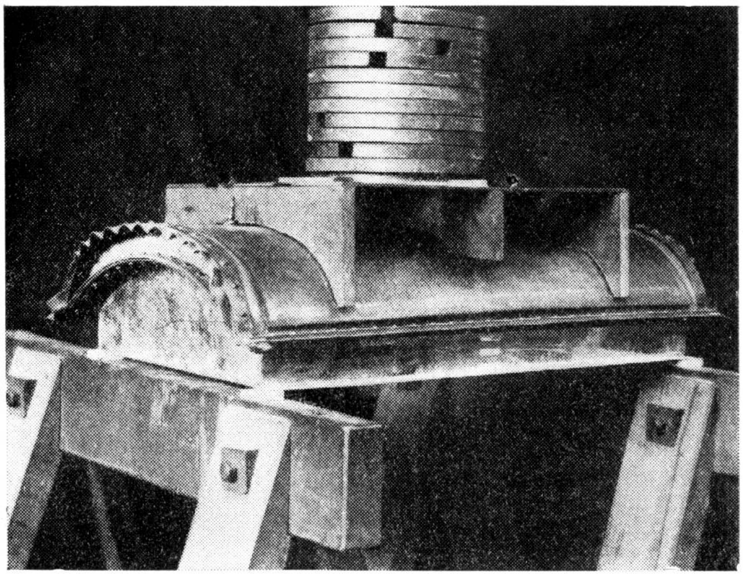


FIG. 3. Arrangement for Vertical Loading

The load was applied vertically and obliquely the latter representing the effects of wind pressure. Since it would have been difficult to apply the load obliquely the method adopted was to place the shell and its supports on a slope and load vertically.

The set-up is shown photographically in Figs. 3 and 4.

Strain Measurement.

The strains under load were measured by electrical resistance strain gauges of $^1/_4$ in. gauge length. The standard Wheatstone bridge circuit was adopted and the deflexion method used for measurement.

The gauges were placed in pairs as shown in Fig. 5., six pairs of gauges being placed across a half section for measuring $M\phi$ and seven for Nx. In order to allow for any lack of symmetry in loading each experiment was repeated but with the shell reversed end-for-end and the average reading from the two experiments taken for each pair of gauges.

Since some of the gauges were in contact with the rubber air bag and others were exposed direct to the atmosphere, two compensating gauges at least had to be used to represent these two conditions. After the first shell had been tested the procedure adopted was to use the gauges on a tested shell as compensators for those on the shell under test.

The metal used was very thin and it was thought advisable to calibrate the gauges and Wheatstone bridge circuit by direct test rather than calculate the strains in the ordinary way. Accordingly pairs of gauges were attached to sheet metal of the same thickness as used in the manufacture of the shells and tested in pure bending and direct tension to determine the number of galvonometer divisions corresponding to given moments and direct loads.

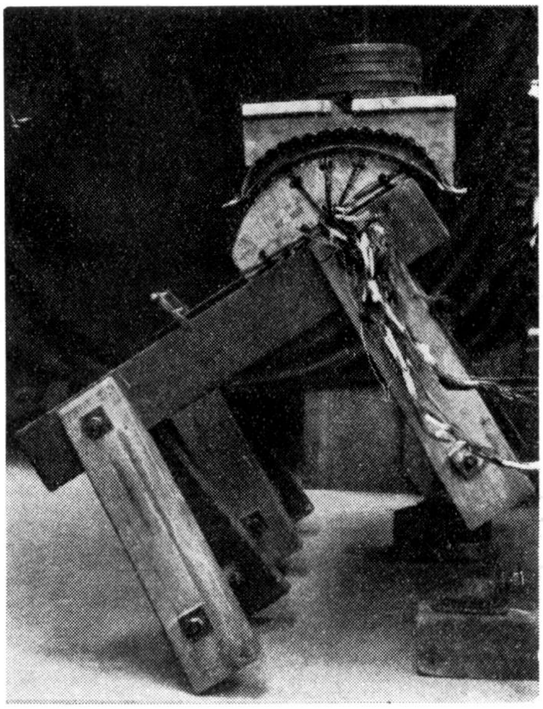
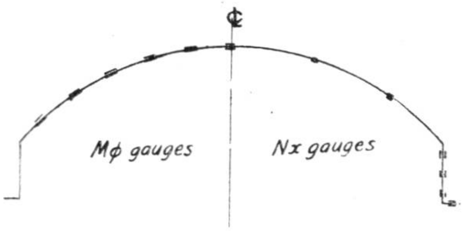


FIG. 4. Arrangement for Inclined Loading



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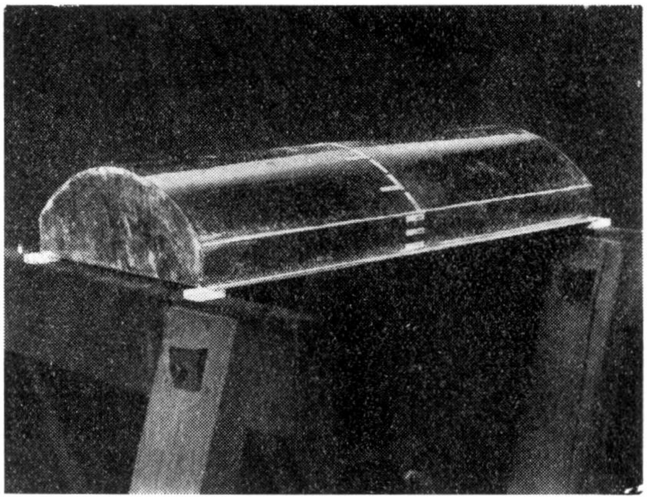


FIG. 5. Position of Gauges

B

Part II – *Vertical Loading.*

The results of the vertical loading tests are shown graphically in Fig. 6. These give the distribution of direct stress and bending moment at the mid span section. The values given are for a uniformly distributed pressure of 1 lb./sq. in. In actual fact loads of this intensity were never applied to the shell as in many cases failure would have taken place.

It was felt however that to reduce the various experiments to a common load would make comparison easier. Each graph shows the experimental values for shells with and without ribs, the former in general being shown as points whilst in the latter case the best curve fitting the points has been drawn in.

In each case the experimental results have been compared with the «beam theory» as developed by the author[4] and in addition the theoretical

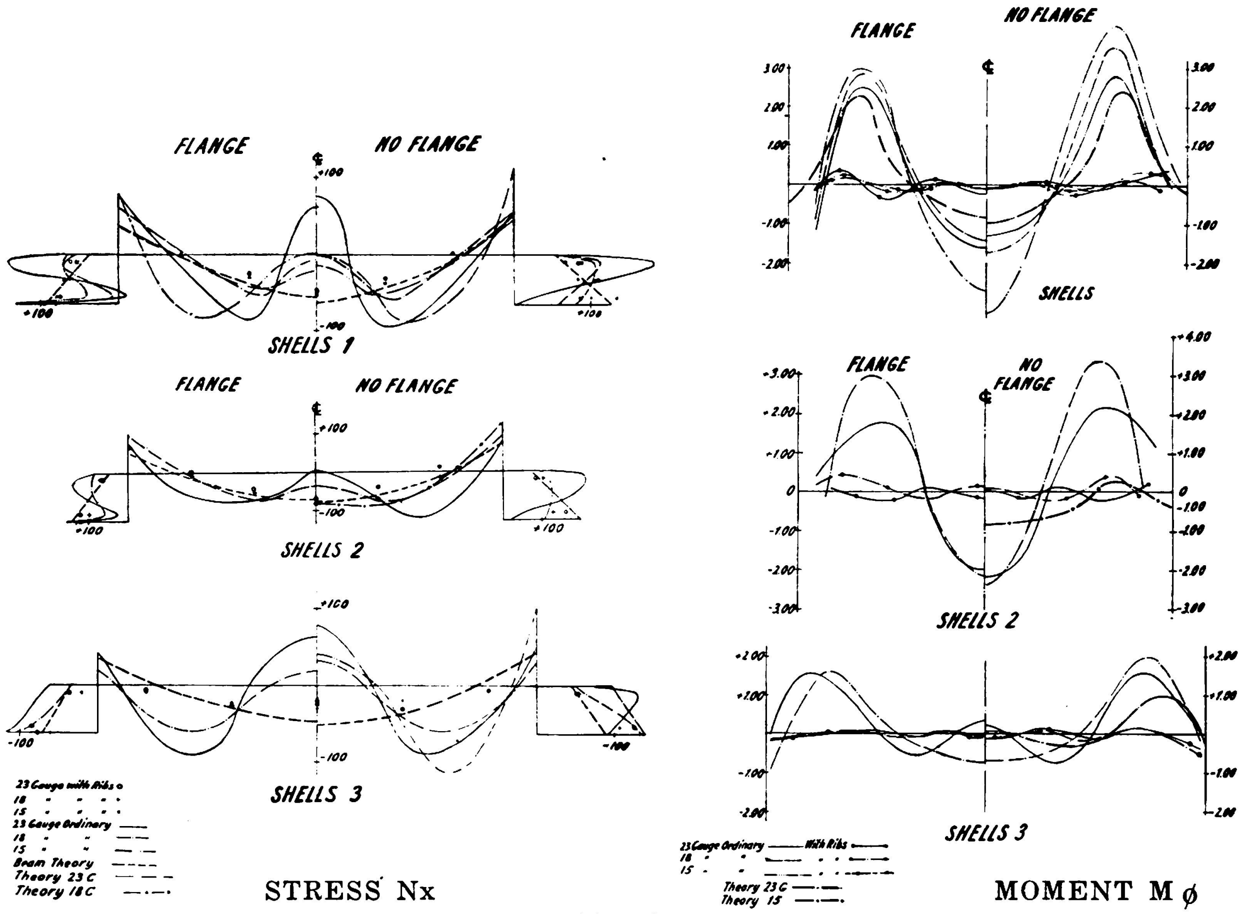


Fig. 6

stresses have been calculated on the elastic theory by the following method:— Gibson & Cooper[5] for shells 1-B; Schorer's method neglecting twisting of edge beams for shells 2 and Jenkins[6] for shells 3-A.

This comparison unfortunately gives no accurate check with any particular theory but does reveal the following facts: —

1. The beam theory only predicts the longitudinal stresses when the shells used in the experiment have stiffening ribs. Without the ribs there is no comparison whatsoever between the experimental values and those obtained from the beam theory. The latter fails completely to predict the tension at the crown which was a feature of the experiments on the 23 gauge material.

2. The experimental distribution of longitudinal stress in the shell is of the same form as that given by the elastic theory for shell 1-B, but

the maximum value of the latter is about 50 % greater than the experimental. The same comparison is seen in shell 3-A but theory here is only about 30 % greater.

The tensile stress at the crown however is almost 100 % greater in this case where as in shell 1-B there was quite good agreement between theory and experiment at the crown.

The tension at the crown is an interesting feature of the experiments. The beam theory certainly does not predict it and it says much for the elastic theory that it does show that tension should occur at the crown. The tension increases with an increase in the radius of curvature of the shell.

The maximum compression, as is expected, increases as the radius of curvature decreases.

3. Instead of the maximum stress in the edge beams occurring at the lowest fibre it tends to be uniform throughout the depth and in the case of the thinnest shells to have a greater value at the top than at the bottom. This is probably due to two facts (a) the slight fixity resulting from friction at the supports because the shell was not supported on roller bearers and (b) the horizontal bowing previously mentioned would have its maximum effect at the top of the edge beam; these are relatively very much thinner than are likely to be met in practice and theory does not deal with the larger deformations arising in the experiments.

4. The transverse moment, $M\phi$, is very much lower (roughly only 10 %) in the case of the ribbed shells than in the case of the shells without ribs.

5. The experimental values whilst of the same general shape as those calculated on the elastic theory are of much greater magnitude, the maximum from the experiments being about 50 % greater than the theoretical.

The presence of the flange on the stiffening beam has a greater effect on the bending moment $M\phi$ than on the direct stress Nx. The moments when the flange is removed are, in some cases, as much as 30 % greater. The elastic theory predicts that the removal of the flange will increase the moment by about 15 %.

In general the moments are smaller with thinner shells and tend to reduce in value as the radius of curvature of the shells increases.

6. In shell 2-B where the twisting of the edge beam was neglected the direct stresses Nx, agree reasonably with the experimental values but the moments $M\phi$ are vastly different. With thin edge beams of the type used in the experiments there is a definite danger in neglecting twist.

Part III – ***Inclined Loading.***

The air bag loading used in the experiments gave a uniform radial pressure. When this was applied to one half of the shell only the inclination of the resultant to the vertical would vary with the radius of curvature of the shell. The angle of inclination of the resultant to the vertical is given in Table 2. for the different types of shell. This angle gave the slope at which the supports had to be inclined in order that the load could be applied vertically.

TABLE 2.

Inclination of Resultant Load

Shell No.	1	2	3
Inclination of Resultant to Vertical	25°	18½°	32°

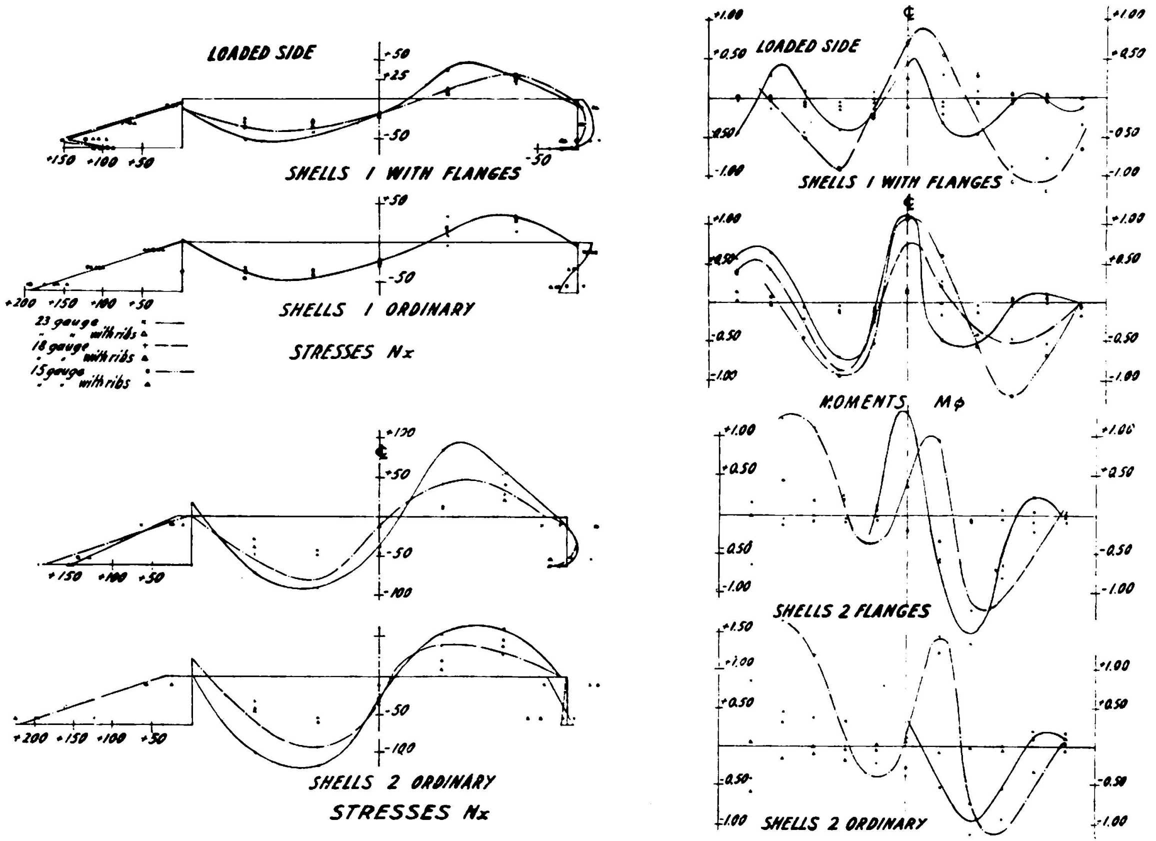
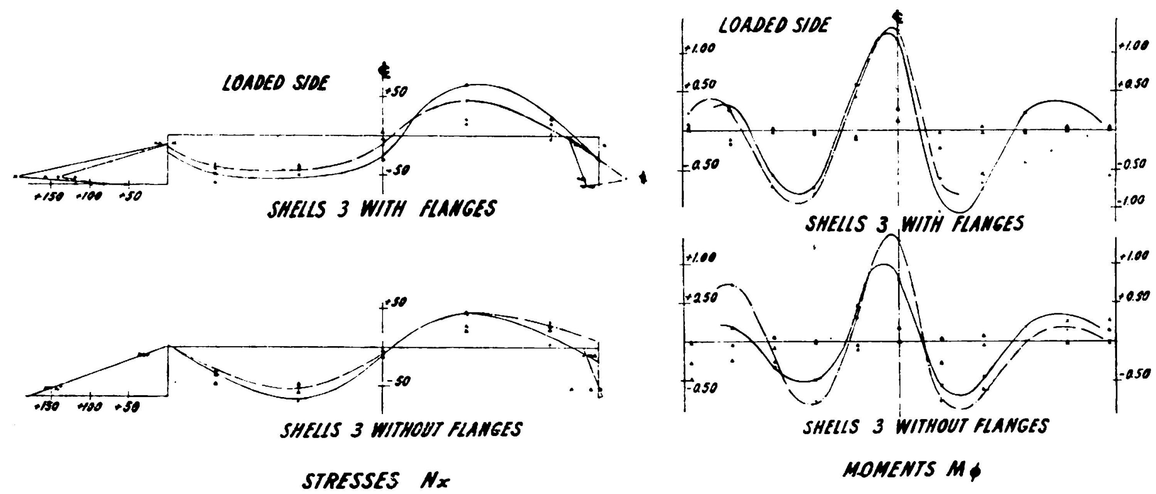


FIG. 7.



INCLINED LOADING

The results of the experiments are shown in Fig. 7. The values given are for a unit load applied on one half of the shell, i. e. the total load is one half of that used in the experiments described in Part II.

The general effect of this loading is to produce a tension in the edge beam on the loaded side followed by compression in the shell itself extending into the unloaded portion, the remainder of the shell is in tension whilst the edge beam on the unloaded side has a very small stress in it.

These general characteristics are in accordance with those obtained when the stresses in the shell are calculated for this type of loading by the elastic theory.

The beam theory might be applied to this type of loading by considering the inclined shell as a beam with the load applied at an angle to the principal axes as shown in Fig. 8. Under these assumptions the maximum tension would occur at «a» on the unloaded edge beam whilst the edge beam «b» on the loaded side would have a low stress. This is the opposite to the state of affairs predicted by the elastic theory and to the experimental results.

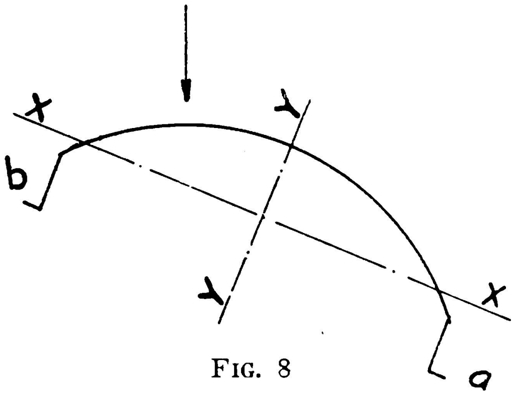


FIG. 8

The results of the ribbed shells differ from the vertical loading tests on these shells in respect to the longitudinal stress. Here the ribs appear to have little effect in shells 1 and 3, although for the flatter shells 2 the effect of the ribs is noticeable. The effect of the ribs on the bending moment is however quite appreciable and similar to that described in Part II.

Part IV – ***Effect of variation in Ribs.***

The effect of the ribs on the stresses in the shell was twofold; they reduced considerably the transverse bending stresses and also produced a longitudinal stress distribution similar to the beam theory. The ribs used in the Parts II and III experiments were of the same thickness as the shell, were 1″ deep and attached to both edge beam and shell and placed at 5 equal intervals along it, i. e. they were approximately at 7″ centres. It could be said generally that the ribs were an advantage and the question naturally arose whether such advantage could be gained by using less ribbing. Accordingly shell 3-B was tested with the following variations in ribs: —

A. 1″ deep on shell and edge beam as used in other experiments.
B. 1″ deep on shell only.
C. $^1/_2$″ deep on shell only.
D. $^1/_2$″ deep on shell only and centre ribs spaced at 21″ centres.
E. No ribs.

The results of the tests using vertical loading are given in Table 2. The results of some experiments on shells 1-A and 1-C showed similar characteristics to those given in this table. It appears that the ribs can be reduced to half their size without causing any appreciable increase in the magnitude of the transverse moment or alteration in the distribution of longitudinal stress.

Measurements were also made of the stresses in the ribs. It is not possible to make a generalised statement on them. They varied with each series of shells. For the shells in series 3 they were compressive

TABLE 3

Effect of Variation in Ribs

Force Nx

Ribs \ Gauge No.	7	8	9	10	11
A. 1″ deep on shell & beams at 7″ crs.	—22.4	—29.9	—6.4	+52.0	+126.1
B. 1″ deep shell only	—23.2	—30.2	—0.4	+50.9	+126.0
C. ½″ deep shell only...	—11.1	—31.4	—20.7	+51.0	+152.0
D. ½″ deep shell only at 21″ crs.	—5.8	—24.1	—33.7	+61.6	+150.0
E. No Ribs	+32.5	—41.5	—38.9	+65.0	+143.7

Moment $M\phi$

Ribs \ Gauge No.	1	2	3	4	5	6
A	—0.119	+0.082	—0.130	+0.011	—0.038	—0.551
B	—0.129	0.0	—0.050	0.0	—0.036	—0.019
C	—0.144	—0.015	—0.040	+0.021	+0.078	—0.245
D	—0.029	—0.021	—0.326	0.0	+0.704	Not given
E	—0.621	—0.684	—0.252	+1.035	+1.900	—0.116

and approximately 100 lb./in. width for a unit load applied to the shell. Their magnitude did not however vary appreciably with variation in rib type. It would therefore appear that type C is more economical than type A since it uses less material without any corresponding increase in stress.

Part V – ***Collapse Loads carried by Shell.***

To conclude the series of experiments it was decided to apply vertical loading through the air bag until collapse occurred. It was found that whilst the load at which the first buckling of the shell took place could be applied in most cases the actual collapse load was not generally measurable. A stage was reached when the shell became very badly deformed but nevertheless was carrying a load of about twice the intensity required to produce the initial buckling.

Details of the shells tested together with the intensity of loading required to produce the first buckling are given in Table 4.

The method of failure was generally the same. The first buckle took place near mid span in that portion of the shell which the Part II experiments had shown to be in compression.

TABLE 4

Details of Collapse Loads

Shell Series	Type	Thickness in.	Pressure at 1st buckle lb./sq. in.	Maximum Load carried lb./sq. in.
1	AO	0.022	0.73	—
	BO with ribs	0.048	13.2	—
2	AO	0.022	0.715	1.25
	BO	0.048	4.50	5.20
3	AO	0.022	0.863	—
	BO	0.048	6.20	—

Contours of the deflected form of shells 1-A, 2-A and 3-A after test are shown in Figs. 9, 10, and 11. It would appear from Fig. 10. that in the case of shell 2-A the initial buckling took place at the crown of the shell. This was not in fact so. The first buckle occurred approximately at the point where the force Nx has its maximum compressive value. Indentations however quickly spread across the shell and the contours given in Fig. 10 are those existing at collapse load. It is seen from Fig. 6. that a noticeable difference between shell 2-A

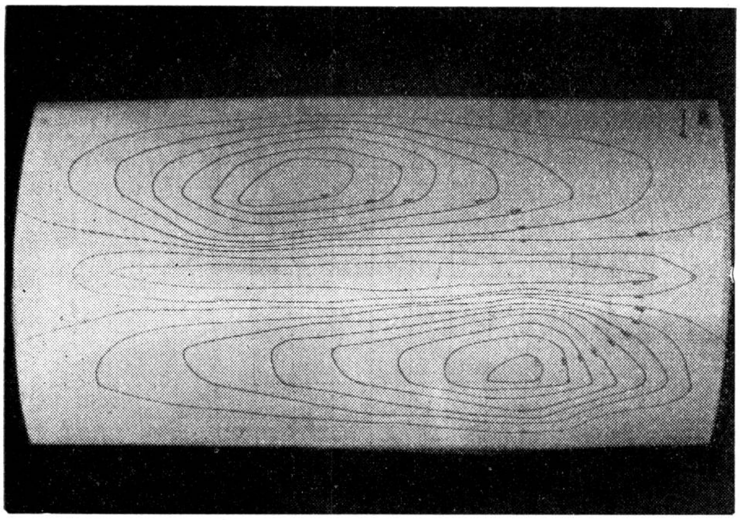


Fig. 9

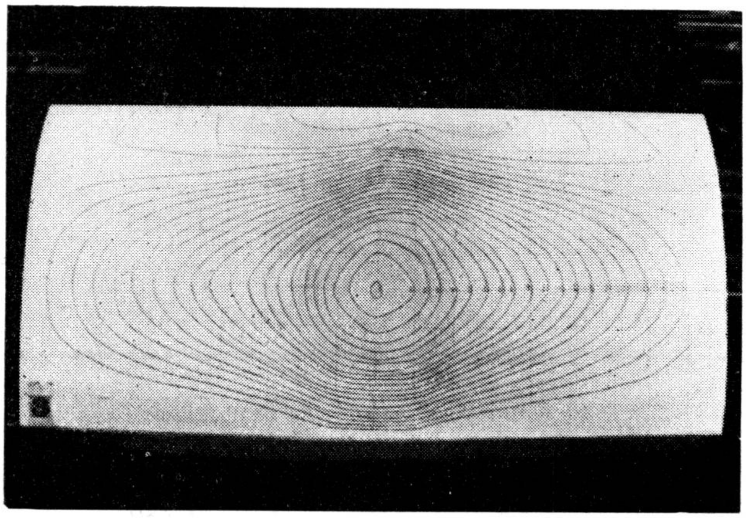


Fig. 10

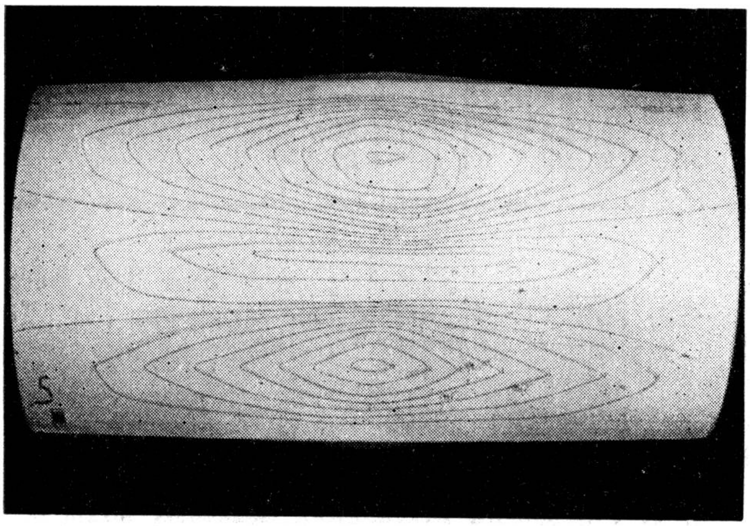


Fig. 11

and shells 1-A and 3-A is that in the former little or no tension is developed at the crown whereas in the latter two cases it is appreciable.

Fig. 6. gives the force Nx in the various shells in lb./in. width for a pressure of 1 lb./sq. in. If the maximum compressive force shown in Fig. 6. is multiplied by the intensity of load required to produce the first buckle the result is as follows: —

Shell	Compressive force at first buckle	Compressive Stress lb./sq. in.
1 AO	67.8 lb./in. width	3080
2 AO	78.0 » » »	3550
3 AO	75.0 » » »	3410
2 BO	360.0 » » »	7500
3 BO	373.0 » » »	7760

The agreement between all the shells of 0.022 in. thickness is interesting. A buckling stress of the order of 3500 lb./sq. in. from such a thin section implies a very small effective length if ordinary strut formulae are considered. The ratio of stress at first buckle for shells 2 A0 and 2 B0 it is noted, is approximately equal to the ratio of the shell thicknesses.

In conclusion, the writer would like to express his thanks to the late Mr. R. J. Linton, the senior technician in the Engineering laboratories of University College, Dundee, who performed the experimental work described in this paper, and to Dr. J. E. Gibson for his help with the theoretical study.

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SUMMARY

The paper describes tests carried out in the Engineering Laboratories of the University of St. Andrews on model shell roofs. These roofs were made from tinned steel plate varying in thickness from 0.022 — — 0.066 in. They were cylindrical and had a span of 36″, a width of

18″ and had varying radii of curvature and edge beams. The primary object was to obtain values of $M\phi$ and Nx.

The paper is divided into five main sections. The first deals with the experimental method, the second and third deal with tests under vertical and inclined loading respectively, the fourth investigates the effect of stiffening ribs whilst the fifth describes the tests to determine the maximum load carrying capacity of the shells.

The load was applied to the shells through an air bag and the stresses under load were measured by strain gauges.

The vertical and inclined loading tests showed stress distribution similar to those expected from the elastic theory although the magnitudes differed by as much as 50 %. The simple beam theory certainly did not hold for such thin shells.

This theory did however agree with the experiments in the case of shells with stiffening ribs. Such shells also had much lower values, only about one-tenth, of $M\phi$ than predicted by the elastic theory. The ribbed shell seemed from the experiments to give the most economical type.

Ultimate load tests showed that failure was initially due to buckling at the point of maximum compression. The maximum load was about 50 % greater than that which produces the first buckle. Very consistent values were obtained for the load/ unit width required to produce the first buckle. The shells with stiffening ribs were very much stronger than the plain shell.

ZUSAMMENFASSUNG

Die beschriebenen Untersuchnungen wurden an der St. Andrews Universität mit Modell-Schalendächern aus vezinntem Stahlbelch durchgeführt, dessen Dicke zwischen 0.022 und 0.066 in. lag. Die Spannweite der Zylinderschale betrug 36″ und im Querschmitt 18″; sowohl für Krümmungsradius wie Randträger wurden verschiedene Werte gewählt. Der Hauptzweck lag darin, Werte für $M\phi$ und N_x zu erhalten.

Der erste der fünf Hauptabschnitte der Arbeit behandelt die Prüfmethode, der zweite und dritte die Prüfungen unter vertikaler und geneigter Belastung, der vierte die Wirkung von Verstärkungsrippen, während der fünfte die Versuche zur Bestimmung der Schalen- Tragfähigkeit beschreibt.

Die Lastübertragung auf die Schale erfolgte über Luftkissen und die Beanspruchungen wurden mit Dehnungsmess-Streifen gemessen.

Die Untersuchungen mit lotrechten und schiefen Belastungen zeigten ähnliche Spannungsverteilungen wie sie nach der Elastizitätstheorie zu erwarten waren, wenn sich auch die Werte bis zu 50 % unterschieden. Hingegen war die Theorie mit einfachen Balken für solch dünne Schalen ungeeignet.

Sobald aber die Schalen mit Rippen ausgesteift wurden, ergab diese Theorie gute Uebereinstimmung mit den Versuchsergebnissen. Solche Schalen zeigten auch viel kleinere $M\phi$-Werte, etwa ein Zehntel, als nach der Elastizitätstheorie vorauszusehen war. Auf Grund der Versuche scheint diese gerippte Schale den wirtschaftlichsten Typ darzustellen.

Die Bruchlastprüfungen erwiesen, dass dem Bruch das Beulen im Punkt des grössten Druckes zu Grunde liegt. Die grösste Last war aber um 50 % grösser als jene, die das erste Ausbeulen verursachte. Gut übereinstimmende Werte für die zum ersten Ausbeulen notwendige Last pro Einheit der Spannweite liessen sich bestimmen. Die Schalen mit Versteifungsrippen erwiesen sich als viel stärker im Vergleich mit glatten Schalen.

RESUMO

O autor descreve ensaios sobre modelos de coberturas delgadas efectuados no Laboratório de Engenharia da Universidade de St. Andrews. Os modelos foram executados em chapa de aço estanhada com espessuras variáveis de 0.022″ a 0.066″. Tratava-se de coberturas cilíndricas com 36″ de vão e 18″ de largura, de raios de curvatura variáveis e tendo vigas laterais de suporte. O principal objectivo destes ensaios era a obtenção dos valores $M\phi$ e N_x.

A contribuição divide-se em cinco partes principais. A primeira descreve o método experimental, a segunda e a terceira tratam respectivamente dos ensaios sob cargas verticais e inclinadas, na quarta examina-se o efeito de nervuras e na quinta, enfim, descrevem-se os ensaios efectuados para a determinação da capacidadde de carga máxima das coberturas.

A carga era aplicada por meio de um saco de ar e as tensões eram determinadas por flexómetros.

Os ensaios mostraram que a distribuição das tensões era semelhante à indicada pela teoria da elasticidade, se bem que os valores diferissem em certos casos de 50 %. A teoria das vigas simples não se podia aplicar a estas coberturas por serem muito delgadas.

A referida teoria estava no entanto de acordo com os resultados dos ensaios sobre coberturas com nervuras. Estas coberturas também acusavam valores de $M\phi$ muito mais baixos, de cerca de um décimo dos valores obtidos pela teoria da elasticidade. As coberturas com nervuras pareciam, pelos ensaios, serem as mais económicas.

Os ensaios à rotura mostraram que esta era devida à encurvadura no ponto de compressão máxima. A carga máxima era de cerca de 50 %. superior à que causava o encurvamento inicial. Obtiveram-se valores coerentes para a carga por unidade de largura, correspondente ao encurvamento inicial. As coberturas com nervuras eram muito mais resistentes do que a cobertura simples.

RÉSUMÉ

L'auteur décrit une série d'essais effectués sur des modèles de voiles minces aux Laboratoires de Génie Civil de l'Université de St. Andrews. Ces voiles étaient en tôle d'acier étamée d'épaisseur variable de 0.022″ a 0.066″. Ils étaient de forme cylindrique, à rayon de courbure et poutres de bordure variables, et avaient une portée de 36″ et une largeur de 18″. L'objectif principal de ces essais était l'obtention des valeurs de $M\phi$ et N_x.

Le mémoire se divise en cinq parties principales. La première décrit le processus opératoire, la seconde et la troisième traitent des essais sous

charges verticales et inclinées, la quatrième s'occupe de l'effet de nervures de raidissement tandis que la cinquième décrit les essais entrepris pour déterminer la capacité de charge maximum des voiles.

La charge était appliquée au moyen d'un sac empli d'air et les contraintes étaient mesurées par des flexomètres.

Les essais sous charges verticales et inclinées permirent de déceler une distribution de contraintes semblable à celle découlant de la théorie de l'élasticité bien que les valeurs correspondantes diffèrent en certains cas de 50 %. La théorie de la poutre simple ne s'appliquait certainement pas à des voiles aussi minces.

Cette théorie était toutefois en accord avec les essais de voiles nervurés. Ces voiles présentaient pour $M\phi$ des valeurs bien inférieures, environ un dixième de celles données par la théorie de l'élasticité. Les voiles nervurés paraissaient d'après les essais, être les plus économiques.

Les essais à la rupture montrèrent que celle-ci avait lieu par flambage au point de compression maximum. La charge maximum était de 50 % supérieure à celle qui produisait le début du flambage. On a obtenu des valeurs cohérents pour le rapport charge unité de largeur correspondant au début du flambage. Les voiles nervurés étaient beaucoup plus résistants que les voiles simples.