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Corrugated Concrete Shell Structures. New Developments

Schalenkonstruktionen in Beton mit gewellter Oberfläche. Neue Entwicklungen

Constructions de toits plissés en béton armé. Nouveaux Développements

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1. Introduction

Reference is made here to a Paper of the same title by the same author published in the "Preliminary Publications" of the Third Congress of I.A.B.S.E., Liege, 1948. Group IVc 2, pages 545—551.

Concrete shell structures suffer from the disadvantages that the cost of scaffolding and formwork is high and that they require considerable skill in erection. The impact of war has led to the development of simplified forms of shell roofs which form the subject of the previous Paper and has produced, among others, corrugated shell types constructed on steel ribs with flexible covering.

This corrugated shell structure of reinforced cement mortar is of parabolic cross section. A structure of, say, 60 ft. span and 30 ft. height has a 1:3 cement sand mortar shell of approximately $2^1/_2$ in. thickness, built up on hessian draped over temporary supporting frames at 6′ 0″ centres, so as to produce transverse corrugations of 6′ 0″ pitch and an amplitude varying from approximately 16 in. at the crown to approximately 6 in. at the springing.

The mortar is laid by hand in three coats, the first to stretch and stiffen the hessian, so as to act as formwork for the remainder of the shell, the second to encase the reinforcement and the third as a finishing coat.

2. Developments

a) Multi-span structures

To cover large floor areas a number of these corrugated shell roofs were constructed side by side. All internal springings are carried on elevated lintols and rows of columns, while the external vaults spring from continuous strip foundation at floor level. Fig. 1 shews a typical multi-span roof of seven barrels, five internal and two external. It is a jute factory at Umtali, Northern Rhodesia, and the roof covers approx. 100,000 sq. ft. The columns are at 40 ft. by 42 ft. spacings. The lintols from which the corrugated barrels spring are reinforced concrete truss girders which were precast on the site. The building was erected by Messrs. Vandenbergh, Black & Co. in record time with almost entirely indigenous labour.

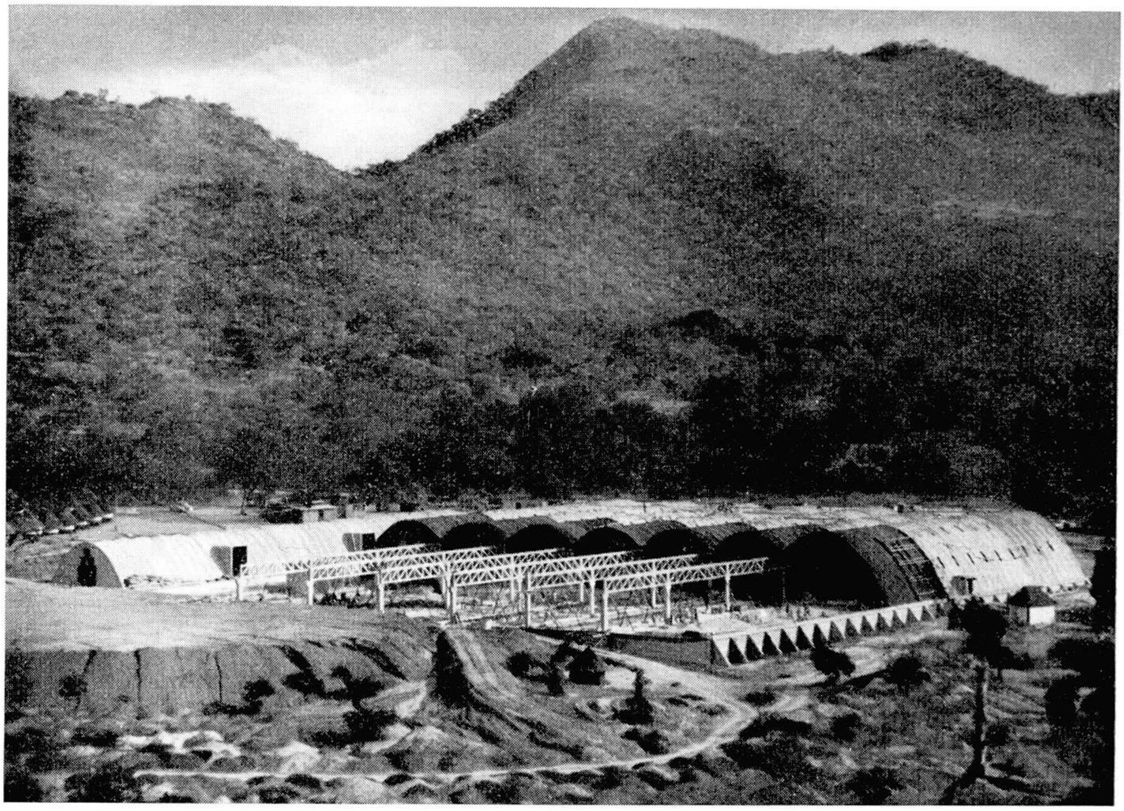

Fig. 1. Multi-span. Jute factory at Umtali, Northern Rhodesia

b) Open-sided shells

In many types of buildings it is essential that a large part of the frontage remains open to give access to every part of the covered floor. This applies specially to garages and agricultural implement sheds. To provide buildings for these purposes, open-sided shell roofs have been designed and constructed. Fig. 2 shews such a roof, 60 ft. × 100 ft. in plan, where one side of the arch is open over its full length of 100 ft. This building was erected in Tipperary, Eire, and is used as a garage. It consists of a three-quarter arch of corrugated shell roof and a front canopy over the open side. The canopy is a reinforced concrete structure and works as a lintol of 100 ft. span taking the horizontal thrust of the vaulted roof. There are two couples of slender columns under the central part of the canopy to carry part of the dead weight of the structure and reduce vertical bending moments in the canopy structure.

c) Elevated shells on buttresses

Fig. 3 shows one of these roofs carried on buttressed walls to increase the enclosed volume. This building of 60 ft. span serves for the storage of bagged grain. It was erected by the Roberts Construction Co. in South Africa.

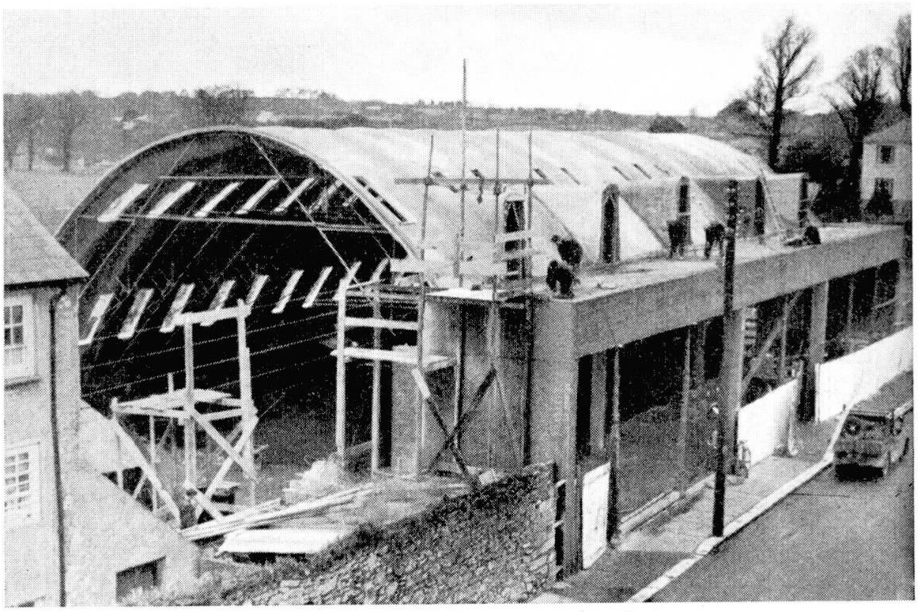

Fig. 2. Open-sided. Garage at Tipperary, Eire

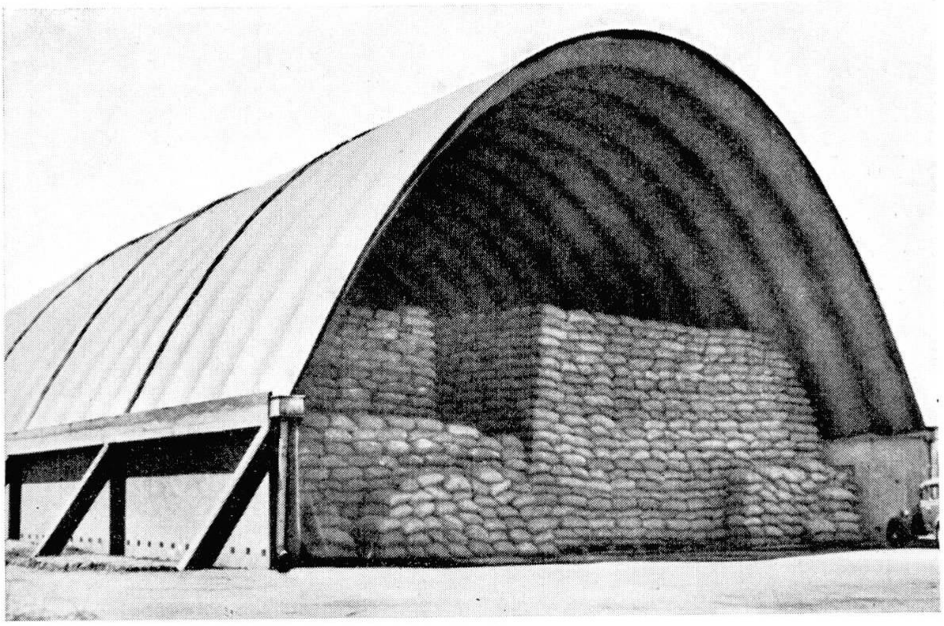

Fig. 3. Elevated supports. Grain store South Africa

d) Domed structures

Due to the considerable height of shell roofs of larger spans, the end walls become quite substantial structures and in short buildings the proportion of their costs to those of the shell proper may become unduly high. The method of corrugated shell construction has therefore also been applied to the ends of the buildings. Fig. 4 shows a 60 ft. span shell roof with domed ends erected to house machinery at the Field Test Unit of the Ministry of Works, at Barnet, near London.

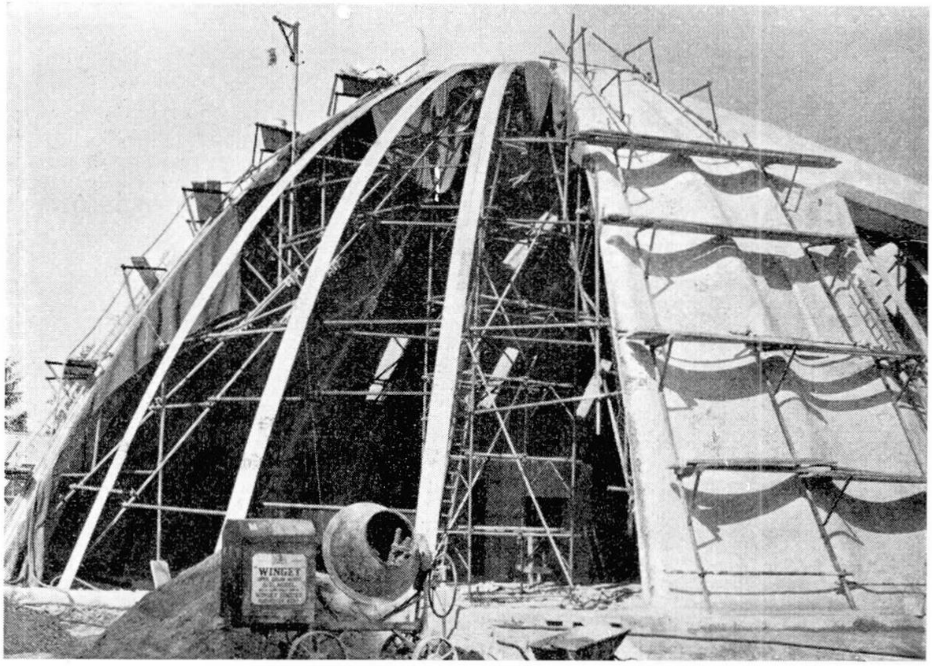

Fig. 4. Domed end. Machinery shed near London

Domed ends are erected with the same falsework which is used for the straight vault. The arch-ribs are erected in radial positions converging towards the centre of the dome and they are supported on a few half-circular rings which link up with the stringers of the falsework of the straight barrel. The hessian tent covering this spherical umbrella of falsework is usually made up on the site.

It has been found that the cost of such domed ends is appreciably lower than that of endwalls in traditional materials such as bricks or blocks. Apart from that, the covered floor area is increased and the stability of the building is improved.

Up to the present, such domed structures have been constructed only as ends to corrugated shell roofs. It is, however, intended to adapt this method of construction also to large domes and parts of domes with marginal arches.

3. Design

The method of design is very similar to that of ordinary arch structures with the one difference: that the dead weight of the structure is extremely low and the moment of inertia of the cross section extremely high due to the corrugated shape of the thin shell. Because of these two interdependent properties the total compressive stresses in structures of large span still remain far below the permissible working stresses of low-quality concrete.

Important progress was made in the development of corrugated multi-span shells when it was discovered that these shells had also considerable load carrying capacities in the longitudinal direction similar to plain (Zeiss-Dywidag) shells. The theoretical analysis was confirmed by results obtained from loading tests on models that these shells are self-supporting not only in the direction of the arch, but also in the longitudinal direction, if certain precautions are taken to prevent the alteration in depth of the corrugations under load.

In the design of larger spans care must be taken in controlling the deformations of the corrugations due to bending. The load tests on models revealed that under positive bending moments the corrugations have an outspoken tendency of deepening, and under negative bending moments they tend to flatten. These tendencies may be explained in the following way: a positive bending moment will cause compression in the crests and tension in the valleys. Due to the curvature of the arch, both stresses have components perpendicular to the surface of the arch. The components point outwards in the crests, and inwards in the valleys, with the effect that these alternating stresses tend to increase the depth of the corrugations. Similarly, negative bending moments will cause alternating stresses which tend to decrease the depth of the corrugations. Both tendencies can be controlled by the provision of continuous longitudinal members between the waves which are to work as struts in the region of positive bending moments and as ties in the region of negative moments.

In multi-span roofs where the columns are spaced at considerable intervals in the longitudinal direction, the shells act as deep continuous girders of high moment of inertia. The compressive stresses produced by dead weight and superloads along the crown portion of the shell are of relatively low value, but still high enough that the danger of a concertina action in the corrugations near the crown is not excluded. To prevent this deformation, a ridge member is built in at the crown consisting of a concrete strut which spans from crest to crest. Its connection with the crests should be well rounded out so as to ensure the co-operation of the strut with the shell. The duties of the ridge member are twofold: first, when compression is produced in the crown part of the shell, it should become an essential part of the compression zone and form a counterpart to the reinforcing steel which is laid longitudinally along the springings of the roof shell. Secondly, due to its relative stiffness, it prevents the previously described deformation of the corrugation.

The general system of the load carrying capacity in plain shells is characterised by the fact that the internal reactions produced by external loads consist of three groups of forces in the shell membrane: longitudinal axial forces, forces tangential to the curve, and shear forces. The part of the shell between the crown and the springings acts as web of the shell beam and resists shear stresses due to bending. In contrast to the plain shell the shear in corrugated shell structures is led upwards and downwards through the corrugations. The outward and inward components of the stresses on each side of the corrugations cancel each other, and the effective remaining stress should be equivalent to the shear developed in the plain shell.

4. Loading tests

With the erection of corrugated shell roofs of larger spans it became important that stability tests should be carried out on such large spans. An opportunity for it arose when the Field Test Unit of the Ministry of Works erected a 60 ft. span roof for their own use to house machinery on their test grounds near Barnet. Two 6 ft. bays at one end of the building which were separated from the remainder of the building by a complete joint, were subjected to a number of loading tests to ascertain the behaviour of the structure

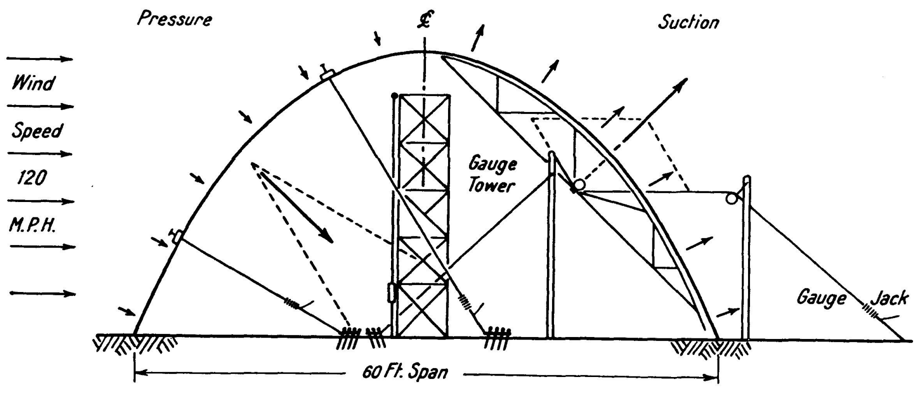

Fig. 5. Diagram showing arrangement of test straining devices

and its deformation under wind pressure equivalent to those defined in the Code of Practice, C.P. 3, Chapter V, for wind velocities of 60 and 85 m.p.h. See Fig. 5. Four groups of tests were completed: three for 60 m.p.h. wind velocity, and one for 85 m.p.h. The three loading conditions for 60 m.p.h. were: (1) with no internal pressure, (2) with internal suction, and (3) with internal pressure. As a result of the deflection measurements by more than 30 gauges it was found that group (3) represented the most severe loading condition of all. In this, the external suction and the internal wind pressure are applied to the same side of the shell structure. The final group of tests (4) was for loads corresponding to a wind force of 85 m. p. h. and for a loading condition identical with (3) to test the building for the worst possible case. Stiffness and strength tests were made, in each group, with the application of 150 and 200 percent of the specified loads, resp. No cracks were observed due to loading. The maximum deflection measured, corresponding to a wind load of 120 m. p. h., was 0.40 in. and its recovery 73 percent.

Summary

Since the last Report on corrugated concrete shells at the Third Congress, considerable progress has been made in their design and construction due to the fact that the load carrying capacity of corrugated shells in the longitudinal direction had been proved. Such shells have now been used for the construction of multi-span, open-sided, and domed structures. Loading tests under wind velocities of 120 m. p. h. proved their stability.

Zusammenfassung

Seit dem letzten Bericht über Schalenkonstruktionen in Beton mit gewellter Oberfläche am Dritten Kongreß wurden beträchtliche Fortschritte in dieser Bauart dadurch erzielt, daß die Tragfähigkeit dieser gewellten Schalenkonstruktionen in der Achsrichtung nachgewiesen wurde. Eine Anzahl solcher Schalendächer wurden als Durchlaufkonstruktionen errichtet, andere als Schalen mit hochgelagerten Widerlagern, und wieder andere als Schalenkuppeln. Belastungsversuche unter 200 km. p. h. Winddruck haben ihre Standfestigkeit nachgewiesen.

Résumé

Depuis le dernier rapport présenté au Troisième Congrès sur les couvertures minces en béton ondulé, de notables progrès ont été enregistrés dans ce domaine; on a pu en particulier vérifier la capacité de charge des couvertures minces ondulées, dans la direction longitudinale. Cette disposition a été utilisée pour la réalisation d'un certain nombre de couvertures continues à plusieurs portées, de couvertures à appuis relevés, ouvertes sur les côtés et de voûtes minces. La stabilité de ces couvertures a été confirmée par des essais sous vent de 200 km/h.

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