Cylindrical shell structures

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Cylindrical Shell Structures.

Zylindrisches Schalengewölbe.

Les voiles cylindriques.

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During the last few years the construction of shell roofs has been influenced by the following two factors:

1) Recognition of the plastic properties of concrete.
2) Endeavours to eliminate tension zones from the concrete of tensile members as far as possible.

Ever since shell roofs were first introducet it has been sought so to improve the underlying theory that the design (of what are often very bold constructions) might be placed on the safest possible basis. As Prof. *Dischinger* has indicated in his paper, it has been found possible to describe the conditions of stress very completely, but an important pre-condition for this continues to be the assumption of an elastic material with characteristics corresponding to those assumed in the calculations.

In this respect reliance has been placed mainly on the official regulations which prescribe a value of $E = 210000$ kg/cm^2 as a basis for the calculation. On this value being checked by means of measurements when the shuttering was struck it was found that the deflections actually observed were smaller than those calculated, and from this circumstance it was deduced that a higher modulus of elasticity might be assumed, and with it a greater degree of safety against buckling than had been taken in the calculation.

The fact is however, that in course of time the deformations considerably increase and may often reach several times their original values. This increase in the deformation does not always follow immediately upon the construction, but more usually it occurs in the warmer seasons of the year when the concrete is exposed to the sun's rays and is caused to dry out; in winter time, on the other hand, only a small amount of movement can usually be observed. Despite the drop in the modulus for deformation as regards dead loading, an increase in the stiffness against temporary loading is observed, so that the actual modulus of elasticity has in fact become greater. If the dead load were to be removed this deformation would vanish only in accordance with the actual modulus of elasticity and the greater part of it would remain; it follows, therefore, that the initial state must have undergone a change.

This phenomenon is important in shell construction, because if the span is notably large and the thickness is small in proportion to the curvature, a limiting condition may be reached in which the initial shape undergoes considerable alteration through bending, this being true of shell construction in much the same way as of slabs subject to large deflections. Once a certain ratio between the curvature and the thickness (governed, among other factors, by the magnitude of the bending stresses) is exceeded, the shell requires to be stiffened by ribs, just as T-beams are used instead of flat slabs.

The bending stresses in a cylindrical shell can be reduced by the well known expedient of adopting an increased curvature, made up of sectors of circles, in the neighbourhood of the springing. This gives small radii of curvature near the springing where bending stresses mainly occur but where they exert no important effect, while at the same time the crown portions, where the radius of curvature is a maximum, are free from bending.

According to its conditions of loading, the shell may be stiffened by cross ribs in the direction of the arch or in the case of still flatter curvatures by both transverse and longitudinal ribs. The spacing of these ribs will depend on the danger of buckling in the intermediate portion of the shell, which tends to buckle into short waves. Since the camber of the shell is very small in proportion to the length of such a buckling wave, this arch effect is neglected, and buckling is calculated as for a flat slab which is stressed in its own plane and fixed along the edges. The depth of the rib is so chosen that dangerous bending deformations due to creep are eliminated, and that an adequate guarantee against buckling of the ribbed shell between the frames is assured.

On these principles very large arched roofs have been built over aircraft hangars, covering up to 60 m free span, for the girders with an arch span of 45 m and very flat curvature. Such a structure is shown in Fig. 1 in the characteristic one-sided form which offers the simplest possible solution to the problem in question: The two-storeyed building for workshops and offices was required to be open on the side of the aerodrome, and to have as flat a roof as possible, while allowing a free doorway opening of 50 m. Contrary to the usual arrangement the axis of the arch is placed parallel to the doorway so that the shell girder with its large moment of inertia spans across the door opening; at the back it is carried down to the level of the out-buildings and is supported on a row of pivoting columns, the auxiliary buildings at the back not receiving any horizontal thrust from the arch. In the end walls and in the central frame a heavy horizontal thrust from the arch is taken up, and to provide for this the edge of the arch along the end walls is strengthened to form a tension boom and is carried on the columns of the wall framing. The central girder is designed as a two-hinged frame with a pre-stressed tie in the floor, its loading is equal to the width of the door in one panel, or in the present case 50 m; it is designed as a twin frame to allow of possible dilatation. The shell is stiffened by thin ribs at 3.60 m centres which also serve the purpose of transferring point loads from the crane runways into the arch. In hangars already constructed these point loads amount to as much as 35 tonnes, and the ribs are thickened accordingly.

The calculation of stresses due to the point loads was made by the strict theory of shell construction, with approximation by means of *Fourier* series, and by measuring the deformations on completed structures it was possible to confirm the results of the calculations.

The carrying capacity of the shell for point loads is remarkably high, a fact which may be explained by the circumstance that the rib has the effect of distributing the load, by bending, over a large width, so that the lever arm with which the internal forces are transmitted to the trusses is a favourable one. The compressive stresses which arise in all directions due to such a load greatly outweigh the tensile bending stresses.

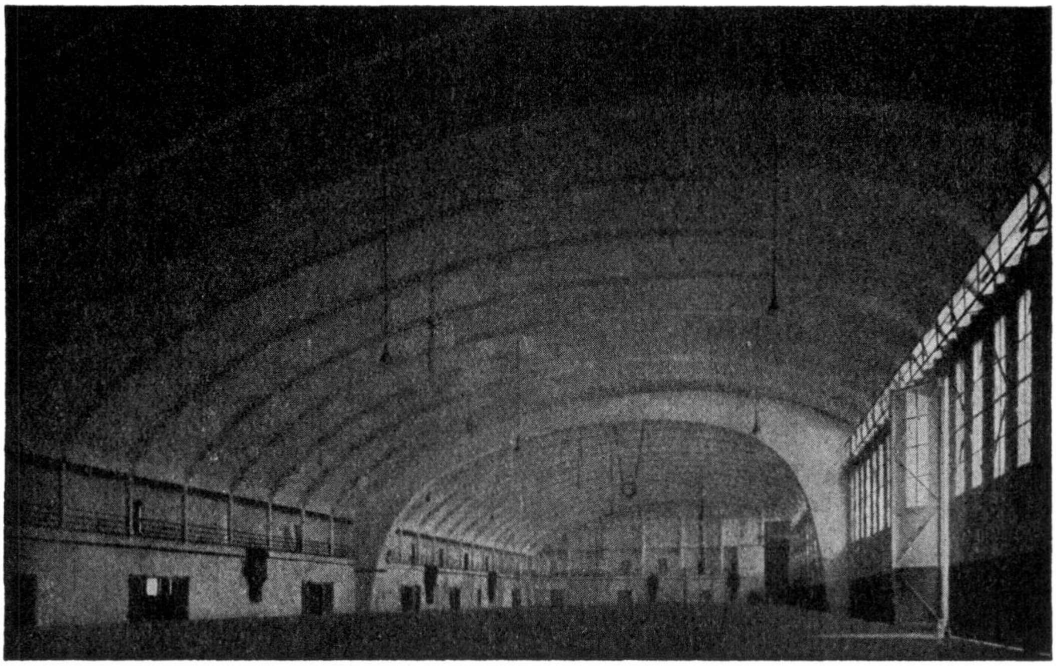

Fig. 1.

Aeroplane Hangar Area 35 × 100 m.

The effect of creep on the construction was also examined. Since the heavily reinforced parts of the structure along the edges are less influenced by creep than the remaining portions of the shell a not inconsiderable redistribution of stresses occurs, which may be estimated with close approximation by repeating the calculations with the modulus of elasticity reduced to 100000 kg/cm^2. It thus appears, both from theory and from practical observation, that the crown of the arch subsequently sinks further than the face girders which remain at an approximately constant level.

The construction of the face girder over the doorway is a problem of some difficulty and interest. In the first place the illumination of the hangar is effected entirely at the face girder; lighting from this high level on one side only ensures uniform illumination over the whole building. In the second place this face girder, in addition to carrying its vertical load, has to resist a tensile force of about a thousand tons due to its forming a tie bar for the shell, this force increasing parabolically from the supports towards the centre of the span.

In reference to lighting these hangars have furnished some particularly useful knowledge, indicating that even though the window area is considerably smaller the same lighting effect may be obtained as with the usual bands of light around the whole building. The principal reason for this lies in the smaller amount of glare, allowing the eye to make better use of the available light, and a second reason is to be found in the light coloured surfaces of the arch which — provided they lie at a lower level than the band of light — receive direct illumination and form a very effective additional source of light for the back portion of the hangar. Consequently, with 12 % clear lighting area in a hangar 45 m deep, fine mechanical work can be carried out even with the doors closed.

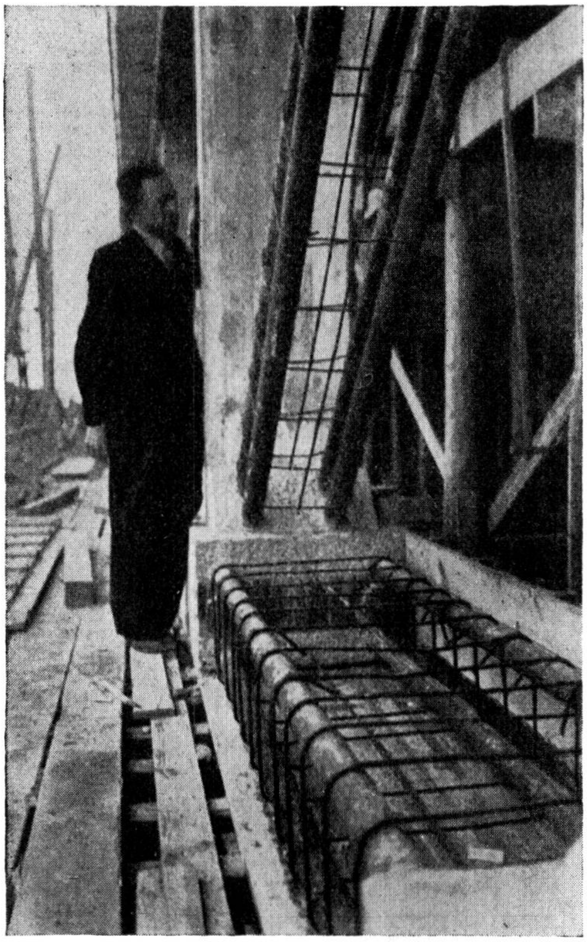

Fig. 2.
Trussed girder ever entrance door, shuttering removed.

The problem of designing the face girders was solved by the adoption of a reinforced concrete lattice girder of special construction. Such lattice girders have often been used abroad, secondary stresses being ignored, just as in steel construction, but in Germany this would not be possible as all secondary stresses have to be included within the scope of the permissible stress, and moreover the anchoring of the steel in the tensile zone is not permitted. These more onerous conditions were satisfied by not covering the bars in the tensile members of the girder until after the removal of the formwork (Fig. 2). Since the tensile members are made up of bundles of round rods, they can freely participate in the necessary angular deformations. In this way, apart from the secondary stresses, it was possible considerably to reduce the tensile stresses in the concrete, though high tensile steel (2100 kg/cm^2) was used in the tensile members. The system of truss adopted comprised tension diagonals and compression verticals, merging suitably into the stiffening ribs of the shell, so as to perform the additional function of transferring wind pressure from front of the door on to the arch. The tensile bars consist of a limited number of large round steel rods which are anchored into the concrete intersection point by means of nuts and plates. At each intersection the whole force of the diagonals is anchored, after being carried over the intersection in a flat bend; the counter force of the lower boom is likewise carried through the intersection point and is anchored on the other side. In this way the intersection point is subject to a heavy compressive stress and is enabled to equalise the forces of various members. The forces in the thin diagonal being anchored inside the intersection, and those in the wider lower boom outside the intersection, the reinforcing steel can be placed in position without difficulty. In order to avoid undesirable eccentricity, steel erection plates are built in, enabling the work to be done with great accuracy, and this being the case the verticals could be made so slender that they receive no tensile bending stresses due to secondary stresses. The economy of the trussed design lies in the fact that use is made of the qualities of the high tensile steel, thus saving considerable weight whilst at the same time increasing the stiffness in every direction. Through the introduction of the truss the possible span of a shell girder is considerably increased.

This particular example has been selected from among the many shell roofs carried out during the last few years, because it illustrates a particularly notable form and magnitude of the cylindrical type of shell developed in Germany. Every increase in the size and difficulty of structural problems must be accompanied by an extension of our knowledge of the theoretical principles and of methods of working — and last, but not least, of constructional materials. It is particularly in respect of materials that we have received such valuable stimuli from abroad: one may hope that this effect will be mutual, and will contribute to the enrichment of the engineer's art.