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Shell Structures with or without Stiffeners.

Versteifte oder unversteifte Flächentragwerke.

Ouvrages à parois minces renforcées ou non par des raidisseurs.

R. Vallette,

Ingénieur au Chemin de fer de l'Etat, Paris.

The question of thin shell-structures having been discussed at the Paris Congress, we only intend to study the tendencies which arose since this Congress.

We can distinguish between two types of thin shell-structures: first, structures in which the stiffness of the shell has been taken into account for the strength of the system as a whole; second, structures in which this stiffness has been completely neglected, the shell itself being then considered able to withstand only stresses acting tangentially to the surface, thus the shell behaving as a simple membrane.

Accordingly we have to consider:

1. — the stiff, thin walls and shells,
2. — the membranes.

We intend to examine in the present report the structures consisting of stiff, thin walls and shells, the structures consisting of membranes being the subject of a report by Mr. Aimond.

I. — Shell-Structures.

A. — Design.

Generalities.

From the beginning of reinforced concrete, the thin shells of the slab type have been taken into account for the general strength of structures. The monolithic nature of construction is, in fact, one of the important characteristics of reinforced concrete. However, a more complete use of the strength of shells has been considered later on, and these shells became the principal element of strength for structures such as load-carrying walls of reservoirs, silos, vaults and arches, etc.

Constructional applications.

1. — Reservoirs.

In the design of reservoirs, the load-carrying wall has been entirely employed for bottoms, cantilevers, covers, but the stiffness of such walls has been taken into account only occasionally.

2. — *Silos*.

For silos, the use of carrying walls, originally only partial, became exclusive after certain methods were known which were reported to the Paris Congress by Mr. *Freyssinet*. We have nothing to add on this subject, no further aspect having evolved since.

3. — *Vaulted structures*.a) *Normal vaults*.

So far as normal vaults are concerned, Mr. *Freyssinet* had already shown the tendency of like development at the Paris Congress, when he stated that if he had to design now the Orly sheds, he would adopt a ribbed design, with spans of 25 m between the supporting ribs. Such a statement is all the more noteworthy as the Orly sheds¹ in their existing form (erected 1922) can be considered as the most remarkable and precursory example of self-supporting systems with numerous short spans, such as were subsequently frequently used in Central Europe.

In fact, we find sheds with bays 7,50 m wide, spanning 90 m. The resistance of the shells being hereby entirely absorbed by the general bending conditions of the whole structure (*Freyssinet-Limousin, Contractors*).

Since the Paris Congress, this tendency has remained and it has been

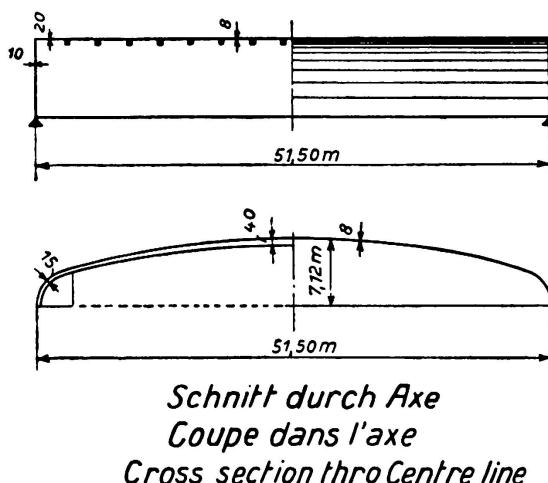


Fig. 1.

Barrel arch of
51,50 m span.

actually possible to design a reversed cradle vault of $51,50 \times 51,50$ m supported only at the four corners, the vault being entirely self-supporting and containing only small stiffening ribs of a purely secondary character, without any end beams contribution to the strength of the structure (Fig. 1) (*Boussiron's scheme*). We can consider this type of construction as the outcome of the type of roof design used in France since 1910. by several designers, using a portion of the vault itself as supporting beam (end beam), between more or less widely spaced columns. Originally, the height of the acting portion of the vault OA taken into account was small (Fig. 2) and a beam ON was necessary to establish

¹ *Génie Civil*, Sept. 22 to Oct. 6, 1923.

the required strength of the structure. Gradually, the height OA was increased, while the supporting action of the beam decreased. The span between columns was notably increased as well and at present, the whole of the shell is utilized for any span and without the use of supporting end beams.

b) *Other types of vaults.*

1. An alternative to the Orly sheds has been adopted for the construction of a twin-shed for airplanes at Cherbourg. The vault consists exclusively of thin shells (Fig. 3) which, as at Orly, are alone responsible for the strength of the structure: the shells became self-supporting, between widely spaced columns (Société Rabut-Subileau).

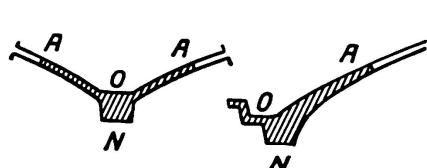


Fig. 2.
Beams supporting shells.

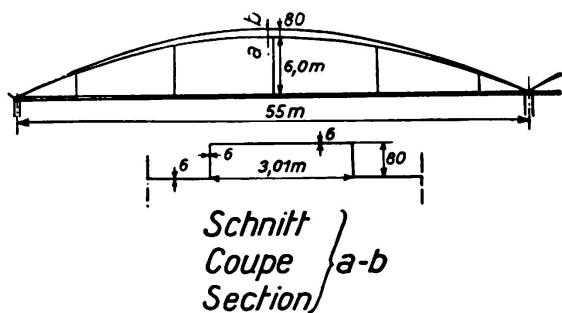


Fig. 3.
Twin hangar. Cherbourg.

2. The conoidal shaped shells (Freyssinet-Limousin) were applied for a great number of structures (Works at Montrouge, Caen, Fontenay, etc.); This type of shells has been studied by Mr. Fauconnier in a report published in the second volume of the "Publications" of our Association, which leaves us only to say that these shells are self-supporting, even if resting on columns far apart.

4. — *Other types of structures.*

Other types of roof shells, such as for domes with square plan, cross vaults, cloister vaults, etc., have been considered by different designers in connection with competitions for aerodrome schemes, for airplane hangars; however, with competitions for aerodrome schemes, for airplane hangars; however, such types are not sufficiently developed as yet to allow for definite conclusions.

A very remarkable construction, of quite a different nature has been erected near Paris for the testing of airplanes; it is the Aerodynamic Tunnel of Chalais-Meudon². This tunnel consists of a certain number of thin walled, self-supporting elements, among which an elliptical diffuser tube of imposing dimensions (Fig. 4), which has its supports in two places only. These supports are 34 m apart whilst the self-supporting structure has walls only 7 cm thick, stiffened by ribs, 3,60 m apart (Limousin).

5. — *Conclusions.*

Concluding, we can distinguish in France between two tendencies in the development of shell construction. On the one hand, exists an undefined tendency

² Génie Civil, Nov. 3, 1934.

to search for new types of roof shells, without the definite trend to find a particular type. On the other hand, with such types as are now definite, a marked tendency exists for taking full advantage of the load-carrying properties of the walls. This tendency is going as far as using the whole of the section of a structure (great vaults, tunnel at Chalais-Meudon), if the span allows of it. At the same time the character of shell constructions should be maintained without the necessity of requiring end- and other beams as supporting members. This can be regarded as one of the characteristics of French constructional tendencies.

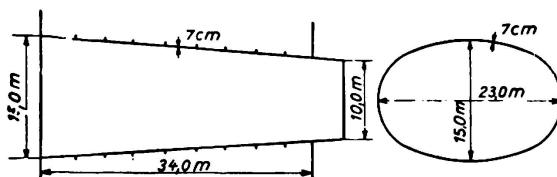


Fig. 4.
Tubular wind channel,
Chalais-Meudon.

B. — Calculation.

1. — Flat shells.

As regards the calculation of flat load-carrying shells, we refer to the method suggested by Mr. L'Hermite (Génie Civil, April 29, 1933).

2. — Self-supporting shells of different types.

The use of the shells of a vault to act as end beams in particular, for transmitting to the supports the loads of the structure, was a feature introduced in concrete shell constructions right from the introduction of such structures.³ These beams, making only use of a small portion of the shell, were calculated by the designers as ordinary independent straight beams leading this way to unnecessarily heavy structural members. For short spans between supports, such excess of material does not render it advisable to apply advanced methods of calculation.

For the case, otherwise rare, where the purpose of the structure demanded long spans between columns, the height of vault to be taken into account caused profiles of pronounced curvature, calling for special methods of calculations. We know that some designers (particularly Mr. Boussiron) succeeded in evolving special solutions for such problems, though they did not publish their investigations. We have ourself indicated, later on, a method⁴ concerning the calculation of such a beam and which applies at the same time for calculating shells of the cradle type of any shape, supported only at the extreme ends.

This method allows to extend the theory of bending to thin shells of curved sections and permits investigations into the consequences of secondary stresses. With this method the means are given to study specially the transverse bending stresses introduced in a sectional element of the shell by tangential forces acting along the directrices of the shell. This particular mode of calculation applied for large spans was found complete and reliable. The results obtained with this

³ Génie Civil, January 27, 1934.

⁴ Génie Civil, January 27, 1934.

method are in accordance with observations made on models, of experimental shells, as well as on actual structures.

3. — *Other structures.*

The same method of calculation can be applied to structures forming complete tubes and we have shown this method which was used also for the calculation of the diffuser tunnel of Chalais-Meudon (described above) in the reports concerning this structure.⁵

With regard to domes, the normal type of which requiring but a simple method of calculation, the stiffness of the shell has to be taken into account only for concentrated loads acting in a confined zone. In most cases, the problem leads to the class of membranes on account of such systems being composed of meridians and parallel circles.

With regard to other types of stiff surfaces for roofing purposes, there can be found, in French technical literature, no statement of any method of calculation; these types are still imperfectly studied and remain a field of exploitation to the designer.

4. — *Conclusions.*

Methods for the calculation of thin walled and stiff structures have retained in France the character of simplicity which has so far been the rule for the design of reinforced concrete structures. In fact, we are dealing with materials and systems of complex and varying nature and it would be vain to search for laws and rules expressing all phenomena possible which take place in a structure under the influence of loading. It suffices to retain the principal facts which can be considered as characteristics and expressed by means of simple laws (Hooke's law, Navier's law, etc.), such laws being imperfect, but safe.

The aim is not to obtain a purely mathematical solution of a problem; it is only a question of calculating sufficiently well all important influences which appear in a given system, in order to prevent useless surplus material or noticeable underestimation. The endeavour to find such a practical solution, on the simple basis indicated, should however be guided by making use of all the possible resources of the art of calculation, with the aim to arrive at a definite solution, safe and easily applicable. It is worth pointing out that in the history of reinforced concrete structures, definitive and clarified methods of calculation have only been established after the actual execution of structures carried out by our big contractors.

Imagination, technical sense and a true conception of the internal working of a structure are inseparable foundations for the creation of new types of structures, and are sufficient to the designer for the calculation and design of any new type. It is in fact always possible to value an acting force if its action is fully perceived. It is this point which calls for the most careful investigations into the nature of the numerous parts which form a reinforced concrete structure. The solution of these problems demands that practical technical sense which makes the prerogative of a good designer.

⁵ Génie Civil, November 3, 1934.

The calculation of thin and stiff shells has followed this development and has retained the definite tendency to keep on the lines of simplicity and clearness, required for the investigation into the problems with which the analysis of such types of structures is concerned.

Summary.

A study of shell constructions under consideration of the actual stiffness.

After summarising the development of shell construction, the author shows that in France nowadays only self-supporting shells are used without the aid of any border beams, even if it is a question of systems composed of small multiple shells (Halls at Orly) or single shell constructions of wide spans, or closed shells composed of rings (wind channel at Meudon).

The author points out that shell constructions are calculated in France with the same clarity as is usual for other reinforced concrete constructions. This permits the designer to employ and develop this new type of construction in an unrestricted manner under proper consideration of all the forces.