TECHNICAL MEMORANDUMS

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

No. 333

CONCRETE AIRSHIP SHEDS AT ORLY, FRANCE

By Freyssinet

PART II

SUPPORTING STRUCTURE AND METHOD OF MOVING

MECHANISM FOR MOVING THE CENTERING

APPARATUS FOR HANDLING THE MATERIALS

REMARKS ON CONSTRUCTION DETAILS

From "Le Genie Civil," September 29 and October 6, 1923

Washington
October, 1925

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS.

TECHNICAL MEMORANDUM NO. 333.

CONCRETE AIRSHIP SHEDS AT ORLY, FRANCE.*

By Freyssinet.

PART II.

Supporting structure and method of moving.- The form adopted for the wall of the shed theoretically enables the removal of the inner form in a single piece. Its transfer, however, from one element to another, is possible only after removing it from the vault a distance at least equal to the depth of the corrugations in the wall. For this reason, we divided the inner form into five sections, a central section (which is the longest) and two side sections each, in turn, divided into two parts.

Foundation.- It was first necessary to excavate the foundation trenches, which were filled to only half their depth by the foundation slabs or mattresses. This was accomplished by making a first section of wall two meters high on the intrados and ending at a plane perpendicular to this surface. It was made with the aid of a rigid exterior form in two parts assembled by bolts and resting on the foundation (Fig. 28). The inner wall, on the contrary, was made with semi-flexible panels, as already mentioned. The stresses of the concrete

---

* From "Le Genie Civil," September 29 and October 6, 1923. For Part I, see N.A.C.A. Technical Memorandum No. 332.

in this small section being zero, the forms were removed after one day, except in freezing weather, when it was necessary to leave them two days. In order to remove the forms, the inner panels were first removed and the outer form was separated into its two sections. The forms were then readily removed, from the bottom up, with the aid of a small crane, which also transferred the forms from one section to another (Fig. 28). This beginning of an arch is likewise shown in Fig. 29, in the lower left-hand corner. The essential point in the first operation was the correct laying of the foundation, since any error here would subsequently interfere with the correct placing of the forms.

<u>Side walls</u>.- The side walls of the vault, considered as sections fixed in the foundation, are stable so long as their height does not exceed a certain limit and may therefore be constructed separately. For this part of the work, the form can be easily shifted from one section to another, by moving it at right angles and parallel to the wall of the shed.

The previous pouring of the side walls, which can be done by the simplest method, reduces the volume of the central portion by a large amount. It also renders it possible to remove the inner form from the central section in a single piece, by a vertically downward motion. On account of these considerations, we decided to pour a height of about 17 m (55.8 ft.) for which the conditions of maximum stress, under the action of its own weight and the force of the wind, are nearly the same as for the finished vault, or R_b = 13 kg (28.7 lb.) and R_a = 2 kg (4.4 lb.), for the weight alone, and R_b = 24 kg (52.9 lb.) and R_a = 12 kg (26.5 lb.) for a wind pressure of 150 kg/m² (30.7 lb./ft.²). These conditions enable an extremely rapid removal of the forms.

For this portion, it is important to define the shape of the wall by the inner form, which can be easily shifted in one piece from one element to the next. The outer form consists of panels about 1.6 m (5.25 ft.) high. The shifting of this form, 17 m (55.8 ft.) high and 7.5 m (24.6 ft.) wide, is accomplished as follows (Fig. 29): Parallel to the side walls there are four pairs of rails on wooden ties with gravel ballast. On each track there are steel rollers, 80 mm (3.15 in.) in diameter, separated by wooden frames to keep them parallel. On these rollers, central with each track, there rests an inverted rail, imbedded up to its head in a movable structure of reinforced concrete. This structure consists of two identical parts connected by flexible reinforced bars, so that each section can conform to the slight inequalities in the height of the tracks, without generating bending stresses. Each part consists of two longitudinal girders, corresponding to the above-mentioned rails, and five girders, normal to the first, each supporting a rail which receives a cast-steel roller, making a total of ten rollers in two rows of five each.

These rollers support a frame consisting of a lower rolling platform, an inclined form fitting the intrados of the shed and an upper platform carrying a derrick which can lift two metric tons at 12 m (39.4 ft.) from its axis of rotation. The inclined form provides a casing for the part BC of the rib and for the parts A'B and CD' (Fig. 27). For the elements AB and CD, the elements ABA' and CDD' of the form are firmly held by means of nailed cleats and hook-bolts.

These elements of the form were first made in a single block on a full-sized model. This block was then sawed into four pieces to facilitate its transportation, each piece being put in place by a single operation with the derrick. The inclined form was assembled in a horizontal position. After completion, it was made to pivot about a hinge at the bottom by pulling with a cable passing over the top of masts located near the axis of rotation (Fig. 30).

In order to pour a section, the lower platform of reinforced concrete was brought into place, an operation easily accomplished with the aid of the rollers and a small windlass operated by one man, although it weighs 70 tons (154,323 lb.). The principal resistance almost always came from the wind. By giving the rollers slight inclinations to their theoretical position perpendicular to the rails, we could guide the platforms at will and give them any slight rotary motion required for perfect adjustment. After this had been obtained, the form support was advanced in the direction of the second series of rails until it brought the lower edge of the form, too long at the bottom by about 10 cm (3.94 in.), against the portion of the arch already constructed. It was then secured firmly in place by means of jack-screws and cleats. First the bolts for joining the two walls of the mold, the perforated blocks of concrete, the reinforcements and the outer wall of the form, were put in place to about a third of the height. Then a corresponding quantity of concrete was poured, the second third of the mold was constructed, and so on. These operations were performed very rapidly. A single gang with two sets of apparatus (one for each side wall) constructed, on an average, five elements a week.

Between each two successive operations, the form was carefully cleaned and liberally oiled. This operation was necessary in order to prevent the concrete from adhering to the mold, an essential condition for walls of satisfactory appearance.

Construction of the side doors.- The side doors of 4 m (13.12 ft.) width were cast in advance in a special mold. Their shape having been designed so as to present no inside projection, they did not interfere with the installation of the inner forms for the side wall. Their presence entailed no other inconvenience than the use of a few special forms on the outside (Fig. 29, left foreground).

Central part of structure.- The pouring of the two 17 m (55.8 ft.) side walls amounts to the placing of about two-sevenths of the volume of the entire structure. These walls now have to be joined by an arch of 75 m (246 ft.) span and 114 m (374 ft.) developed length, with a volume of 150 m^3 (5297 $ft.^3$) for each 7.5 (24.6 ft.) section and of 265 m^3 (9358 $ft.^3$) for the end elements.

For the construction of this part, we hesitated between two systems. It is possible to conceive of a system of centering supporting a half-form integral with it and another half-form susceptible of being dismantled by means of a system of hinges. Under these conditions, the shifting of the centering, after a very slight vertical displacement for clearance, can be accomplished by a simple translation. It is necessary, however, to reconstruct the form for each operation by replacing and readjusting a very large number of pieces, which would require much labor and time and involve the risk of faulty functioning of the hinges and incorrect assembling of the interior forms.

These difficulties led us to prefer a form completely fixed on the centering and absolutely identical, in all respects, with the one employed for the side walls. This assumes, for the disengaging of the portion near the crown, a vertical lowering of at least three meters. This is sufficient, however, to release the lower portion of the form, which can only be effected by a combined operation, assuming the bending, division or articulation of the form, or by a greater lowering (about 11 m = 36 ft.). The latter method seemed to be the simplest and easiest. A form support designed on this plan must satisfy the following conditions:

1. The gradual filling of the form must produce only slight deformations. If large deformations are produced, they must be corrected. In fact, it is necessary to obtain an identity of shape as perfect as possible between the edge of the last part poured and the free edge of the form.

2. The form must be easily adjustable, both vertically and horizontally, since, in spite of all precautions, we cannot be sure that the distances to the tops of the two opposite sections of the side wall will always be exactly equal.

3. The vertical displacement must be effected by sure and very simple means.

4. It must be possible to remove the form gradually, by deforming it and without great effort. This point is important. The adherence of concrete to oiled wood, although slight, is appreciable. On the other hand, there may accidentally be points locked simultaneously in the concrete and in the form, or joints of planks covered with concrete connected with the main mass and attaching the form rigidly to it. This may be all the more important since the form is wedge-shaped and since it is moved very obliquely to the surface, especially at the bottom. In order to release the form all at once, it

would be necessary to overcome the sum of all the forces of adhesion. On the contrary, the removal by deformation of the form brings the force of adhesion into action only on a line without thickness, which shifts progressively. This operation is analogous to the removal of a freshly placed poster. When lifted by one edge the effort required is small, although the total adhesive power of the poster may amount to several tons.

5. The whole structure must be able to withstand the force of the wind at all times. We first contemplated a maximum wind pressure of 150 kg/m^2 (30.7 lb./ft.^{2}), but after the hurricane of March 7-8, 1922, during which gusts of the order of 250 kg/m^2 (51.2 lb./ft.^{2}) were observed, we adopted the latter figure, with a minimum safety factor of 2. All these requirements, some of which seem contradictory, were perfectly satisfied by the method we are about to describe.

<u>The centering</u>.- The form is supported by a wooden arch. During the process of lowering and of raising, it functions like a hinged arch, but when the pouring of the concrete begins the connections established by the forms, the reinforcing and the concrete produce, almost immediately, a complete rigidity.

This arch is made up of four parallel latticed trusses whose members are formed by planks 7 cm (2.76 in.) thick and 20 cm (7.87 in.) wide for the central trusses and 25 cm (9.84 in.) wide for the lateral trusses. For each truss member, the number of planks varies from three in the central part to seven in the bottom parts where the loads are greater.

In order to construct such a truss, a series of heavy jigs (Fig. 31) is constructed, firmly anchored in the ground. Successive planks are placed against the parts A and forced to take the desired curvature with jack-screws and wedges supported against D on the pieces of the opposite truss member.

After three pieces have thus been put under pressure, there is produced, by hammering, a perfection contact of the 6- to 8-meter (19.7 to 26.2 ft.) planks composing the members. The planks are then double-nailed from both the outside and inside. Then the fourth, fifth, etc., planks are introduced and nailed in turn, while being held by jack-screws and wedges. Then one face of the bracing is nailed and a temporary bracing is nailed to the second face. Then the truss is inverted and the bracing is completed.

The height of the trusses in the middle is three meters (9.84 ft.) and decreases to 1.34 m (4.4 ft.) at the supports. They are spaced 2.5 m (8.2 ft.) between centers. Their ends rest on a reinforced concrete girder (Fig. 32), having a semicircular section at the bottom and capable of withstanding and transmitting all the reactions from the trusses. It serves also to lower the center of gravity of the whole.

The joining of the wooden trusses with this girder is accomplished by means of planks arranged in steps and having

20 cm (7.9 in.) spikes projecting from them. These are fitted to the form before the concrete is poured. Moreover, for a certain distance between the planks, there is a core of reinforced concrete connected with the girder by reinforcing rods and attached to the planks by numerous 20 cm (7.9 in.) spikes imbedded in the concrete for a portion of their length (Fig. 32).

The trusses are joined, at both top and bottom, by two double rectangular cross-bracing trusses of planks, leaving spaces measuring 2.5 m (8.2 ft.) diagonally. The thickness of the bracing truss on the top of the arch being offset by strips of the same thickness, we constructed on the arch a wooden framework formed by a series of planks attached to the trusses by wooden cleats nailed to both. On this framework there is nailed a board forming a wall of the form for the central wall of each rib, as also for the inner wall of the top ribs. The form is located on this board in exactly the same way as for the side walls.

This truss of 100 m (328 ft.) length and 3 m (9.84 ft.) maximum height would be very deformable. At the time of filling the form, it would produce a sagging of the sides and a raising of the crown, which it is important to prevent. On the other hand, this arch exerts on its supports an oblique thrust, which would render its displacement very inconvenient.

In order to obtain permanence of shape and balance the horizontal thrusts, we completed the system by a double series of stays made of cables of coarse steel wires, 18 mm (.71 in.)

in diameter, without hemp cores, issuing from the axis of the semi-cylinder terminating the lower girder (Fig. 33). Eight of these stays directly connect the two girders O and O'. The others pass from one girder to the other, but after passing around two pieces of wood A and B (Fig. 34) of sufficiently large cross-section, bolted to the members of the two trusses (these bolts being, moreover, the only ones entering into the construction of the scaffolding) and protected by a strip of steel under the cable. This device assures sufficient independence of the tensions in the cables, while saving one anchorage for each cable. For the lowest cables, a cable issuing from O simply passes around two trusses and returns to O near the second.

The cables were anchored in a rather novel manner. The wires, untwisted and freed from pitch, cold, were considered as simple reinforcings of a small mass of iron-bound reinforced concrete connected at its other end, to a threaded nut, by other reinforcings, the length of the stays being thus adjustable at will (Fig. 35).

The study of the reactions of the concrete on the centering is rather difficult, because we do not know the true physical condition of the concrete in the different parts of the form, during the different stages of filling. We made such a study on different assumptions and first on the assumption of a perfectly liquid concrete, in which case the reactions were easy to evaluate with precision and were practically normal to the intrados. We then assumed various obliquities of the reactions of the concrete on the centering. In all these assumptions, we traced the funicular curves, corresponding to the various stages of filling, by the usual methods.

These studies gave us the maximum values of the tensions of the bracing cables and the values of the corresponding deformations, the latter by neglecting the inherent rigidity of the centering. The deformations actually observed hardly ever attained more than a quarter of the calculated deformations, which fact may be attributed to the rigidity acquired by the centering from its union with the form and with the side walls, through the first portions of concrete poured.

Mechanism for moving the centering.- The total weight of the centering is about 130 metric tons (286,600 lb.); that of the inner form and the apparatus for handling it (supported by the centering) is of the same order of magnitude; that of the reinforced girders, which receive the extremities of the centering, amounts to about 80 tons (176,370 lb.). All this weight must be lowered and raised, at will, about 11 meters (36 ft.), and be secured at its upper position in such a manner as to enable the pouring of 360 tons (793,663 lb.) of concrete for the ordinary ribs, attaining nearly 700 tons (1,543,234 lb.) for the end ribs.

It would have been unreasonable to double the strength of the centering and consequently increase the weight of the whole, just to handle the end ribs. It was decided to pour them in two sections, first the part ABCD, and second, the part CDD' (Fig. 38). Nevertheless, the stresses on the centering in the first operation are decidedly greater than in the succeeding ones. A large part of the reactions of the concrete is absorbed directly by the side walls, thus diminishing the reaction on the supports of the centering. This reaction has a vertical and a horizontal component. We have absolute control of the latter, due to the possibilities of adjusting the stay wires. As to the vertical component, what we said on the subject of the stability of the centering shows that it cannot be known very precisely. We were, however, able to determine that the vertical load transmitted to the supports of the centering never exceeded 350 tons (771,617 lb.) for each side wall.

The double motion of the centering is accomplished in the following manner. The reinforced-concrete girder is terminated at each end by two rectangular elements 0.4 m (1.31 ft.) wide, 0.9 m (2.95 ft.) long, and 1.3 m (4.27 ft.) high. Each of these elements has two contiguous supporting surfaces 0.4 x 0.4 m, utilized alternately. The distance between their centers is 9.2 m (30.2 ft.) for the inner surfaces and 10 m (32.8 ft.) for the outer surfaces. Between these supporting surfaces, the girder is reinforced in order to support all the reactions of the centering, vertical and horizontal (including a portion of the wind stresses) and especially those resulting from the initial support of the form against the top of the side wall, a very powerful support obtained by the use of strong pieces of wood prolonging the forms and embedded in the concrete girder. These were designed to prevent the elastic deformation, due to the overhang of the side walls, and to oppose deformations of the same nature, which the pouring of the first portions of concrete would tend to produce.

One very great difficulty is due to the smallness of the end portions of the girder. This slenderness is necessary for other reasons, especially in order to avoid over-dimensioning the supporting pieces of the girders, which will be described farther on and which it is important to keep very manageable. These terminal portions must, in fact, withstand considerable vertical shearing forces (it being possible that the maximum total reaction of 350 tons (771,617 lb.) may be thrown, through the action of the wind or by a false maneuver, entirely on one support) and still more dangerous horizontal stresses, because, in this sense, the reactions of the support are applied at the exact level of the contact surface, i.e., very eccentrically with reference to the cross-section.

In order to overcome this difficulty, we placed the supporting surfaces nearly at the level of the center of the circle limiting the cross-section of the girder at the bottom and gave them a solid structure of steel plates and angles, going from one supporting surface to the other without interruption and provided them with riveted angles to prevent the slipping of the concrete against these elements, especially at their ends.

This structure, embedded in the concrete of the girder, acts as part of the longitudinal reinforcement of the girder, protects the concrete of the end portions against shocks and friction and furnishes the necessary resistance to shearing and to horizontal flexures in the plane of the reactions. It furnishes, finally, the principal part of the reinforcement for preventing the vertical flexure of the terminal elements of the girder. Due to this device and to suitably distributed reinforcings of the ordinary type, we could accept with impunity a mean shearing stress of 350,000 kg ÷ 40 × 1.3 = 67 kg per cm^2 (953 $lb./in.^2$) of the total cross-section, with an actual maximum of about double this figure.

The centering being thus supported on a girder terminated by supporting elements separated by about 10 m (32.8 ft.) of manageable dimensions and possessing, nevertheless, a fully sufficient strength, even in the event of a false maneuver, each end was supported by two supports, each support engaging one of the contiguous 0.4 × 0.4 m (1.31 × 1.31 ft.) surfaces, one of the supports being movable and the other fixed.

The first is furnished by vertical pieces of wood having a straight square section, with rounded corners, of 0.4 × 0.4 m, operated by a vertical hydraulic jack, of about 2 m (6.56 ft.) stroke. The second support is furnished by an oak intertie 0.4 x 0.4 x 1.25 m (1.31 x 1.31 x 4.1 ft.), working in bending, supported on the concrete walls and forming a movable key. The girder rests first on one and then on the other of these supports.

For receiving each end of the girder, there was constructed a sort of car S of reinforced concrete (Fig. 39), rolling on two triple rows of rails supported by strong wooden ties, very close together and ballasted with the utmost care. On each triple row, a set of 80 mm (3.15 in.) steel rollers, kept approximately parallel by wooden guides, supports a double row of inverted rails embedded to the head in the reinforced concrete of the movable portion. There is a space of two meters (6.56 ft.) between the two cars. They are connected by two flexible concrete members strongly reinforced with steel.

Toward the center of the car there is solidly encased a sort of tower of reinforced concrete, whose horizontal cross-section resembles the letter U opening on the side of the girder supporting the centering along a channel 0.45 m (1.48 ft.) wide by 0.85 m (2.79 ft.) deep (Fig. 40). It is provided with two vertical guide rails, placed 20 cm (7.87 in.) from the opening of the channel, and with a series of vertical rectangular notches in each side of the U for receiving the oak beams 0.4 x 0.4 m (1.31 x 1.31 ft.) already mentioned. The center of these notches is situated at 0.6 m from this same opening. The notches are placed at vertical intervals of 1.85 m (6.07 ft.).

The hydraulic jacks are placed along the axis of the vertical guides. The cylinder, made of cast steel and encased in reinforced concrete according to a Limousin patent, is embedded in the base of the car. The pistons carry, at their lower end, the packing which also serves as a guide, and, at their upper end, a spherical head receiving a supporting plate which forms a second guide. This arrangement, which imposes certain difficulties of construction, especially as to the bore of the cylinders, has the advantage of keeping the upper guide at a constant distance of two meters from the lower guide, which prevents jamming during the maneuvers, without requiring absolute precision in the mounting of the head guides composed of vertical rails simply embedded in reinforced concrete. Each jack has a maximum lifting power of 120 tons (264,554 lb.).

This assembly functions as follows: The jacks raise the girder about 1.9 m (6.23 ft.). They are driven by an electric pump which produces a pressure of about 100 kg/cm^2 (1422.3 lb./in.^{2}). We then put in place the oak blocks or keys, whose handling is facilitated by boards carrying well-greased guides, on which they are easily moved.

Each jack is then released, the girder comes down on the oak supports, the piston descends and a spruce block 0.4 x 0.4 m (1.31 x 1.31 ft.) is placed on its head. The guiding is assured by steel plates on its ends, having two grooves for the guide rails and a central pin jutting into a hole in the wooden block. The jacks are again operated and, by means of the wooden blocks, raise the girder another 1.9 m (6.23 ft.). The oak supports are again put in place and the jacks released. The pistons descend, but the wooden blocks already placed are retained on their steel guide-plates by a ratchet attached to the rails, which allows them to ascend but not to descend. A second block of wood, similar to the first, can then be very easily put in place. This operation is performed six times in succession, in order to obtain a total lift of 10.8 m (35.43 ft.).

After the centering has reached its topmost position (Fig. 36), it is caused to rest on stronger blocks (0.5 x 0.4 m) by means of oak wedges, well set up in such a manner as to render it possible to control exactly the height of each support and the verticality of the centering. This done, it is necessary to adjust the span of the form, i.e., to make it exactly equal to the distance between the tops of the opposite walls. For this purpose, there is placed, between the two rails carrying the reinforced-concrete supports, a series of screw-jacks 80 mm (3.15 in.) in diameter, whose cast-steel threads are embedded in the reinforced concrete. These jacks press on the bottom rails through steel shoes.

The scaffold is inclined toward one wall or the other by means of one or the other row of jacks, it being possible to supplement this operation by means of the turnbuckles on the cables, which is rarely necessary. We produce, by this means, a strong pressure of the lower part of the form against the walls already built, while at the same time raising the cars a few centimeters above their rollers. The precision of these operations is such and the deformations of the centering during the pouring are so small, that we can adjust perfectly and all at once the edges of the form to the edges of the concrete previously made throughout the whole length of the centering.

It only remains to put in place the bolts, the concrete blocks, the reinforcing and the panels of the outer form (the latter in successive zones) and to pour the concrete exactly as for the side walls. After 24 hours for setting, we remove the outer form, which is lowered to the ground to be cleaned and oiled, and to mount the windows. After sufficient hardening, which requires from three to five days, according to the temperature, the lower form is removed by a series of alternate maneuvers with the screw-jacks, which slightly deform the mold and produce its gradual separation up to the crown. The supports are then lowered into contact with the rollers. Then the centering is lowered by reversing the moves made in raising it, namely, by alternately removing the oak blocks and the vertical supports. After the scaffold has reached its lowest position (Fig. 37), it is then shifted.

We mentioned that one end of the reinforced-concrete girder rests, in its low position, on its support, through the intermediation of an expansion car, which takes the position of the supporting block, in such a manner as to leave to the two supports a complete independence of orientation during the shifting and enables them to follow the deformations of the track.

Horizontal shifting of the centering and wind-bracing.- We have already mentioned that the total weight of the centering and lower form (empty) is about 340 metric tons (749,571 lb.). The weight of each reinforced-concrete support is about 110-120 tons (242,508-264,554 lb.). There is therefore a total weight of nearly 800 tons (1,763,696 lb.) to be shifted horizontally a distance of 7.5 m (24.6 lb.) at each operation.

On a well-laid track, the force required for the shifting is only about 1% of the weight to be shifted. The whole centering exposes to the wind an area of over 1000 m^2 (10,764 $ft.^2$), against which a 250 kg (551.2 lb.) wind can exert a force of 250 tons (551,155 lb.). The bare plain of Orly is extremely exposed to the wind and we will assume that the force of wind gusts can attain this order of magnitude, especially at a considerable height above the ground. As to winds of the order of 25 kg/m^2 (5.12 $lb./ft.^2$), they must be considered a normal condition, which should not interfere with the progress of the work. Such winds exert, however, more force than is required to move the centering.

For these reasons, the problems of wind-bracing and the shifting of the centering are intimately related. We solved them by making the strength of the wind-bracing sufficient to care for a pressure of 250 kg/m^2 (51.2 lb./ft.^{2}) during every part of the shifting, whether vertical or horizontal. For this purpose, the centering was anchored at both top and bottom, under the following conditions:

1. <u>Bottom anchorage</u>.- Both the front and rear supports of the same arch are solidly connected, as already mentioned, and are anchored by means of heavy cables of soft steel wire, of 10 mm (0.4 in.) diameter, by means of 8-strand tackles, with 13 mm (0.5 in.) cables and sheaves of large diameter designed for high efficiency, attached to a chain having 7.5 m (24.6 ft.) links, each composed of 16 steel-wire strands of 10 mm (0.4 in.) diameter. The welds of the wires necessary to close each link are each protected by an 0.8 m (2.62 ft.) section of helically reinforced concrete, the rest of the link being bare. The links are joined by easily removable steel shackles. The last link is anchored to a large piece of hardwood buried deep in the ground. Since the tackle cable is operated by a hand winch able to exert a force of 2500 kg (5511.6 lb.), the traction for each tackle can attain about 20 metric tons (44092 lb.) and a passive resistance of at least 50000 kg (110231 lb.) (for each side) to an accidental stress can be counted on before rupture.

2. Anchorage for the top.- In the central zone of the centering, there were firmly fastened two sets of four very strong sheaves of large diameter, distributed over about 30 m (98.4 ft.). There were established 80 m (262.5 ft.) in front of and 80 m behind the centering, on roller paths similar to the ones for the scaffolds for the side walls, two reinforced concrete platforms, loaded with earth, each forming, with its load, a movable mass weighing about 150 tons (330,693 lb.) (Fig. 41). To each platform, there are firmly secured three pulleys like those of the centering, plus two leading blocks. These platforms can be blocked in place by a very simple device. The concrete has a series of notches at the bottom inclined at 45° to the horizontal. Pieces secured by screws to the railway ties carry a series of wedges having one face with the same inclination. A series of oblique blocks is introduced between the notches and the wedges. For every motion in the direction of the arrow, there is created an absolute solidarity between the loaded platform and the ties which support it and the coefficient of rolling, below 1%, is replaced by a coefficient of adherence above unity.

A single flexible cable, 18 mm (0.7 in.) in diameter and 2000 m (6561.7 ft.) long, is used with the two 8-strand tackles composed of the sheaves just described. This cable, of the best quality made by the Chatillon-Commentry Company, showed in the tests, a breaking strength of over 26 tons

(57,320 lb.). Each tackle has, therefore, a theoretical strength of over 200 tons (440,924 lb.). Both ends of this cable are wound in the same direction on the drum of a winch A. The horizontal cable going from one platform to the other, makes six turns around a second drum B. These drums are operated by hand by means of a double hand-crank gearing which renders it possible to exert forces of 3-4 tons (6614-8818 lb.). They are provided with automatic brakes composed of cables wound on the drum and operated by counterpoised levers, capable of absorbing the breaking strength of the cables which are wound on the winches.

By operating the winch A, the lengths of the two stays are changed equally. We can thus follow the operation of lifting and lowering the centering. By operating the winch B, we lengthen one of the stays by an amount exactly equal to the shortening of the other and thus produce a horizontal shifting of the top of the centering. The drums and frames of these winches are made of reinforced concrete and are mounted on a reinforced-concrete platform, movable or fixed, according to the system already described. This platform also carries the winches for the lower tackles and the pumps for the hydraulic jacks and protects them, under a wooden roof, from rain and the possible falling of small objects.

Under these conditions, the superintendent of the work has directly at hand all the means for moving the centering and the possibility of stopping it instantaneously in any position, in such manner that it can withstand a wind of 250 kg/m² (51.2 lb./ft.²). When resting on its supporting blocks or even on the jacks, with valves closed, the centering is stable, from its weight alone, under a wind pressure of 150 kg/m² (30.7 lb./ft.²).

Apparatus for handling the materials.- The masses to be put in place are the concrete, the panels of the outer form, the reinforcing and the windows. Their relative weights are about as follows: concrete, 80%; forms, 16%; steel, 3%; windows, 1%; or, for each 7.5 m (24.6 ft.) section: concrete, 360 tons (793,663 lb.); forms, 70 tons (154,323 lb.); steel, 5 tons (11,023 lb.); windows, 1 ton (2204.6 lb.).

After a comparative study of various systems and especially of the American system, consisting of a central tower and inclined chutes which could have been employed under especially favorable conditions, we decided to perform all the operations with the aid of four derricks just like the ones already described in connection with the side walls, mounted on wooden platforms supported by the centering and entirely cantilevered on the free side. The zones of action of these derricks overlap in such manner as to enable the transportation of any object from any part of the surface of the arch to the ground and inversely.

In particular, the delivery of the concrete is accomplished with the aid of special tipping buckets which the derrick places at exactly the right point for pouring. A pin is removed and a slight lift of the load automatically effects the pouring into the form, without any effort on the part of the man in charge. This method is better than the one with the inclined trough or chute. It requires much less material and is easier to keep in shape. It enables the employment of a less liquid concrete and a considerable saving in the number of workmen. Moreover, the same derricks can be used for handling the forms, the reinforcing and the windows.

Erecting the framework of the centering.- This was done outside of and at one end of the shed. The reinforced-concrete supports were cast on their rolling carriages, by the erection of which their construction was begun. The centering was made in three sections, two lateral sections of about 45 m (147.6 ft.) of developed length and a central section of about 30 m (98.4 ft.). The lateral sections were erected horizontally near the ground, then raised by pivoting about the reinforced-concrete girder forming their lower end (Fig. 43), one after the other, for lack of space. The central section was then lifted into place on the lateral sections (Fig. 44).

In order to accomplish this, two reinforced-concrete horses were built on the ground and, on these horses, the reinforced-concrete girder was constructed, including the wooden blocks required for its ultimate union with the framework of the centering. We have already mentioned that this girder is terminated by a cylindrical surface. This surface was so constructed as to be tangent to the upper face of the horses, formed half of concrete and half of soft wood arranged in the direction of the grain (Fig. 42). The rotation of the elements of the centering caused the rolling of the concrete girder on this surface, with a slight resistance due to the partial crushing of the wooden part on the surface, to increase the friction. Cables, wound around the girder and anchored to its temporary supporting horses, prevent any displacement toward the rear, especially from the effect of a squall during the raising. The location for the pouring of the girder was determined in such manner that rolling brought it into position.

This having been done, the elements of the lower truss, about 45 m (147.6 ft.) in length, were brought in a single piece, from the working place to the point of erection, on two trucks and then assembled to the fittings of the end. The planking was then laid and the supporting platforms for the derricks installed and, at the end of the section, a small bracket for attaching the tackles for raising the central portion. All the work for the whole centering was thus done on the ground, with the exception of the forms proper.

The adjustment was effected by means of the hydraulic jacks already described, which had to serve subsequently for raising the centering. For this purpose, they were placed obliquely in a trench. They lifted the element of the centering by means of hoisting sheers, formed of light wooden members, and applied a little beyond the middle of the section of the frame to be raised, which had a weight of about 40 tons (88,185 lb.). Wooden pieces were bolted to the frames and notched to form a hinge for each of the hoisting sheers designed to act on the centering. The reinforced-concrete girder, weighing 40 tons, formed a counterpoise and assured a considerable preponderance of load on the pivot side.

The first hoisting sheers employed were 6 m (19.7 ft.) high and just passed under the centering. The jacks raised it about 1.6 m (5.25 ft.) along sloping wooden guides, held in place by a light frame. At this point, the sheers were held in place by temporary supports, formed of pieces which engaged in the notches on the right and left of the guides, forming a sort of crane, and the jacks were lowered. By means of pieces placed on the guide between the above-mentioned temporary supports, the jack raised the hoisting sheers another 1.6 m (5.25 ft.), etc. After four raisings, amounting to about 6 m (19.7 ft.), another hoisting sheers of 12 m (39.37 ft.) could be put in place, a little ahead of the first, in the notch following the contact piece of the centering, which was still supported by the 6 m sheers.

As soon as the second sheers picked up the load on the jacks, the first became useless and was dismantled. The lifting with the second sheers was continued until it was possible to introduce a third and then a fourth, the latter having a total length of 21.5 m (70.5 ft.), which rendered it possible to bring the section of the frame into its final position (Fig. 43). The second lateral element was erected in the same way. These elements then stood opposite each other, held by sheers a little above the middle of their height (Fig. 44).

After this was accomplished, the central section was suspended from the lateral sections (by means of two brackets installed on each element) by four 4-strand tackles operated by hand winches capable of exerting a pull of 3000 kg (6614 lb.) and carefully controlled. The load was raised slightly in order to measure the elastic deformation of the lateral elements, which then functioned as cantilevers. From this we corrected the position of the side walls and braced them solidly in the corrected position. We made a final test, by raising the load on only two of the winches, disposed diagonally, and then began the raising, which occupied about three hours (Fig. 44).

After the central section had thus been brought into position, it still remained to effect its union with the lateral sections. At this moment, all three sections of the centering showed elastic deformations, due to the loads sustained during erection, which gave them a shape differing very perceptibly from the original design. It was necessary to remove these deformations, which would have caused pronounced inequalities in the form of the intrados and which, moreover, indicated stresses in the timbers which should be eliminated. For this purpose, we first assembled the lower member by means of planks and oak wedges, in order to remedy the errors in length and create an initial compression in the member. After this was accomplished, we almost completely unwedged the lateral parts. By this operation, we concentrated the whole weight of the centering on the lower member working as an arch, which resulted in eliminating the loads and the deformations produced during the erection.

We then erected the upper member and removed all supports of the lateral elements; completed the erection of the two members by two strong bolted braces, in order to oblige the ends of the elements to assume the general curvature; then completed the wind-bracing.

During these operations, we put the hydraulic jacks in their final place and brought the supporting cars of the centering nearer together, in such manner as to engage the lifting girder in its bearings, and connected the two cars. We were then able to lift the centering a few centimeters (1 cm = .3937 in.), demolish its concrete supports and bring the whole to its original position, where we proceeded to raise it, as already described.

The importance of this method of erecting lies in the fact that all the work on the frame is done near the ground without scaffoldings and without any of the difficulties experienced at great heights. The volume of the apparatus required for lifting by this means is only a small fraction of that of the timbers to be put in place. The apparatus employed, aside from the hydraulic jacks which were not especially made for this operation, is insignificant and only a few days were required to put each centering in place.

Reinforcing.- The reinforcing plays only a secondary part in the Orly sheds, the concrete being almost always under compression, and its weight is relatively small. It consists of bars of 10 and 7 mm (0.4 and 0.28 in.) diameter, parallel to cross-sections normal to the longitudinal axis of the shed, and of elements, uniformly of 7 mm diameter, normal to the first. The latter, in the form of straight wires or continuous spirals, constitute series of frames, according to the case.

The wire, supplied in coils of 50 to 80 kg (110.2 to 176.4 lb.), is unwound and then stretched (by anchoring it, at one end, to a fixed point and, at the other end, to an endless chain running over a pulley driven by a set of gear wheels and a motor) up to about 35 kg/mm^2 (49,782 lb./in.^{2}), which makes it perfectly straight. It is then cut into the desired lengths and the ones to be made into spirals are wound mechanically on steel rollers, the shape of which can be modified at will, due to the constant tension obtained by friction, which can be regulated by springs. We thus very economically obtain reinforcings of much more regular form than those made in the usual way.

They are erected in lengths of about 20 m (65.6 ft.) with the aid of special tools, which facilitate to the utmost the task of the workmen. The reinforcings of a section consist of seven elements, as shown in Fig. 45. These elements are brought to the foot of the structure and for the first 20-meter section, are put in place in a few minutes by derricks. The form is covered and the pouring begins at once, while the other elements are being erected, which requires but a short time. The reinforcing bars are kept at a suitable distance from the forms by the ends of the ties which hold the bars together.

End doors.- The forms for these are made on the same principles as those for the vaults, supported by centerings consisting of light frames made up of small pieces of wood, assembled as in the main centering, by simply nailing without using any bolts. These centerings, together with the forms, are raised in large sections with the aid of tackles suspended from holes in the vault and secured to the intrados by threaded rods. We constructed the centering for only one-half of the end, which was provided with a right and a left-hand form. This form could therefore be used eight times.

Inspection walkways.- These are important features, their length amounting to 3 km (1.86 mi.) for the two sheds. They support I-beams for tackles with a capacity of 10 tons (22,046 lb.). The walkways have a uniform cross-section, as shown in Fig. 46. The I-beams are attached to the reinforced concrete by numerous reinforcements riveted to their upper flanges and embedded in the concrete. Their solidarity with the reinforced concrete is therefore perfect. The walkways are supported on the right of each joint by a double suspension member of concrete reinforced by 10 mm (0.4 in.) rods, narrow enough to support without rupture any elongation of the walkway due to expansion.

For construction, the walkways were divided into 7.5 m (24.6 ft.) sections, with a joint of 0.4 m (1.31 ft.) between successive sections. In the vicinity of the skylights, each section of the walkways is suspended in the middle. The sections are molded on the ground on an area provided with suitable machinery, with the aid of molds made on the same plan as the ones for the sheds and with the aid of compressed-air vibrators.

After the concrete has set, the sections are conveyed to the foot of the shed, for raising by tackles and winches, so as to engage the end of the reinforced suspension members in the holes made in the concrete during the construction of the vaults. After the height has been adjusted by means of wedges passed into a part of the suspension reinforcements forming loops, the other reinforcements are bent back and the hole is filled with rich mortar. The reinforcings supporting the wedges are then disengaged, bent back and covered with a dope (Figs. 46-47). For the central walkways, which must support ten tons (22,046 lb.), the anchorage must be supplemented by a longitudinal rib, running the whole length of the shed in the longitudinal median plane.

The same construction methods were employed for the window frames, ventilating skylights, etc. These were molded on the ground, of concrete kept in energetic vibration in forms used many times, and then sealed in place after the completion of the vaults.

Remarks on certain construction details.- Special attention should be called to the systematic use of nails as the means of assembling all the woodwork, large or small, movable or stationary, used at Orly. This method has, moreover, been generally employed in all our plants for many years. We do not pretend to have invented the use of nails. It is, however, strange to find that hitherto this method of assembling has never been made the object of serious study and investigation and that it has always been considered essentially precarious and uncertain.

Assembling with nails has its faults, the greatest of which is the difficulty of dismantling, but it may be said that, aside from gluing, which is limited for many reasons, it is the only means for joining two pieces of wood, on the solidity of which we can really depend. With ordinary nails and spikes 6 to 25 cm (2.36 to 9.84 in.) long, we can make the most complex assemblies of wood in any dimensions, and rely on getting a strength equal to that of the wood employed, whatever the nature or magnitude of the loads to be transmitted, a result which is unattainable by any other known means of assembling, not only for wood but for any material whatsoever.

The investigation of these assemblies by nails is not always easy. It requires great caution and care, the same as for riveted metal assemblies, but it yields exceedingly important results, in rendering it possible to make the most of the mechanical properties of this marvelous substance, spruce, which possesses, for equal weight, in either tension or compression, twice the strength of steel, with infinitely less danger of buckling and incomparably greater facility of employment, at half the cost. The theoretical reasons for the superiority of assemblages made with nails, over every other means of joining pieces of wood, are manifest. In an assemblage by bolts, e.g., the wood yields considerably before the metal, either by compression at the point of contact with the bolt, thus allowing the latter to bend, or by shearing between two successive bolts. It is therefore important to increase as much as possible the areas of contact between the wood and the assembling medium and hence to divide the latter. On the other hand, due to the very fact of the method employed, all the nails work together and there is no play. A simple operation produces, from this viewpoint, a result superior to any which a carpenter can obtain by the usual methods. We now have abundant proof of these facts. Some of our derrick masts have been working continuously for nearly two years. The good condition and the rigidity of our centerings are remarkable. The centerings are provided with a set of very heavy plumb-bobs, in order to enable an accurate determination of their deformations at various points, by observing the sliding of the bob in a guide.

During the gradual filling of the forms while pouring the first rib of each shed (heavier than the ordinary ribs), we found at first a lowering in the haunches and a raising in the crown, which gradually increased up to maximum values of 12 and 18 mm (0.47 and 0.71 in.). Then, as the mold was filled, the deformation at the haunches was not appreciably affected, while that at the crown disappeared. For the ordinary ribs, the observed deformations are always less than one centimeter. For a curved centering of 75 m (246 ft.) span, these results are evidently very remarkable and they are certainly due to our particular methods of assembling, which allow possibilities of only elastic deformation.

Operation of the plant.- This has surpassed our expectations, without change and without accident. The construction of the first ring, of special form and with a volume at least double that of the ordinary element, to be poured in two parts with a special form, required 24 hours. The second element was completed in 16 days, including the time for hardening (in mid-winter); the third in 12 days; the fourth in 12 days. The training of the personnel and the good weather enabled us to reduce this time gradually.

At present, the centering is removed from both sheds Monday morning. The previous testing of the samples is uniformly satisfactory. At 1 p.m. the forms are on the ground and their cleaning is well along. They are again erected and adjusted the same evening. Tuesday morning the adjustment is verified, in order to correct any settling that may have occurred during the night. The reinforcing bars are put in place, the outer form and lastly the concrete. These operations are finished by Thursday. The outer form is then removed and lowered to the ground for inspection, cleaning and oiling. At the same time, the windows are put in place. This work occupies the workmen while the concrete is setting.

The speed actually attained could be considerably increased by employing more and faster derricks and a more rapid cement, which could now be readily obtained. Under such conditions, it would be possible to construct a shed, like those at Orly or even larger, in about a year, with a single form.

Budgetary considerations have retarded the progress of the work at Orly, but the present rate is entirely satisfactory and will enable the completion of the sheds during the present year (1923).

Results obtained.- The results obtained at Orly may be classified in two distinct categories, according as they pertain to the buildings themselves or the methods employed in their construction.

In the first place, we have a new and remarkably economical solution, both as to the original cost and the upkeep of the outer covering. The saving results from the employment of very simple forms and a cheap, though indestructible material, under conditions of maximum mechanical efficiency. This efficiency is demonstrated by the very moderate stresses, in spite of the fact that the buildings in question hold the world record for size and that the quantities of materials used per cubic meter of the inclosed space are remarkably small.

The stresses are not great, excepting under the action of the wind. As regards this, it may be remarked that a slight reinforcement of the sections near the intrados and extrados and a slight increase in the size of the reinforcing bars would suffice to reduce this stress one-half. Now, it is known that, by multiplying all the dimensions by a constant factor, the quantity of materials employed per square meter of inclosed space is not changed and that the stresses are simply multiplied by the factor in question.

The stresses utilized for the concrete at Orly being, or being able to be, reduced to a small fraction of those which can be accepted with modern cements under the perfect conditions of use described, we reach this first conclusion, that the absolute dimensions of the present application could be considerably augmented, without appreciably affecting the cost per cubic meter of the inclosed space. Although the immediate utility of such buildings is not apparent, it may arise in future and it is of interest to know that they are possible and at a relatively moderate cost.

Although no artistic considerations affected our decisions, since the Orly buildings are purely industrial, their architectural aspect is generally regarded with favor. The effect produced is found to be the consequence of dispositions of a purely technical origin, but so rational and simple as to be immediately comprehended and, consequently, satisfying to the eye, a judge which is, however, severe for forms to which it is unaccustomed. It may be assumed that, if artistic considerations had been coupled with the technical requirements, a still better result could have been obtained. Without interfering with the essential conditions which determine the structural merit of the forms employed, the architect could, in fact, employ numerous means of expression, such as the proportion of the ribs in width and depth, the shape and dimensions of the spaces reserved for lighting, the shape and size of the windows, their grouping, etc. Simple decorations, such as giving artistic lines to the different parts could be introduced, without impairing the structure. It seems possible, therefore, to adapt the new principles we have created to the construction of public buildings requiring an architectural character, such as exposition buildings, without greatly increasing the cost of construction.

From the viewpoint of the methods of construction, the Orly sheds mark important progress in the direction of perfecting the construction, necessarily accomplished without the competition of manual labor, whose role is considerably reduced. They likewise mark progress in the direction of increasing the construction speed of reinforced-concrete buildings. Both these results are obtained simultaneously by the use of suitable equipment, rendered possible by the repetition of a unit form. The maximum benefit is derived from the construction of a series of elements.

We can likewise find in it an example of modern methods of employing wood and concrete, a reaction against the fixing of the concrete mixtures, and a rational use of modern quick-setting cements, whose employment, enabling quicker removal of the forms, will profoundly affect the methods of construction of reinforced-concrete buildings.

Translation by Dwight M. Miner,
National Advisory Committee for Aeronautics.

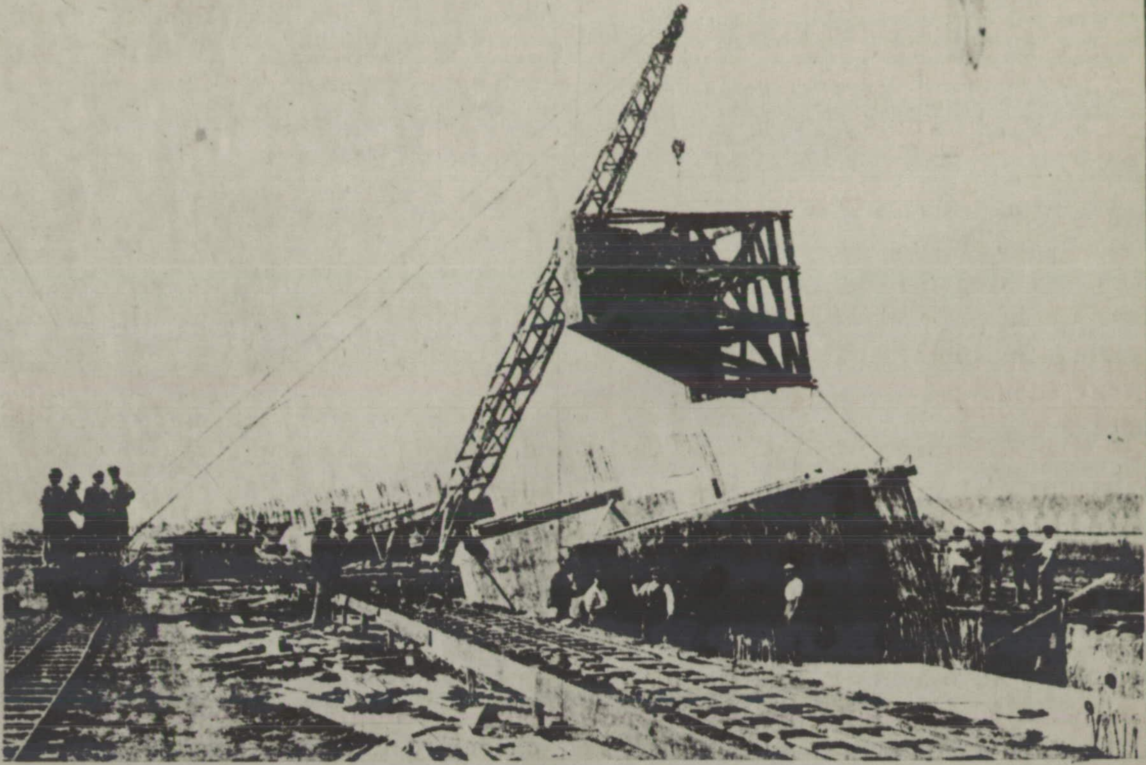


Fig.28 The beginning of the vault of the first shed

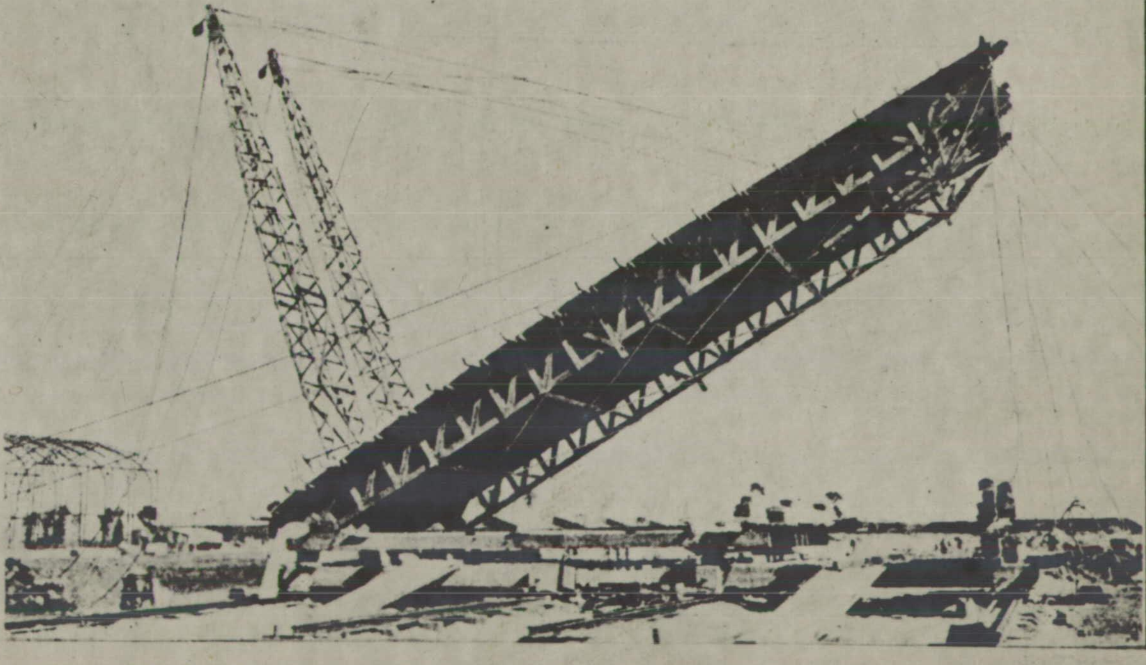


Fig.30 Raising inclined framework forming partial form for one element of vault.

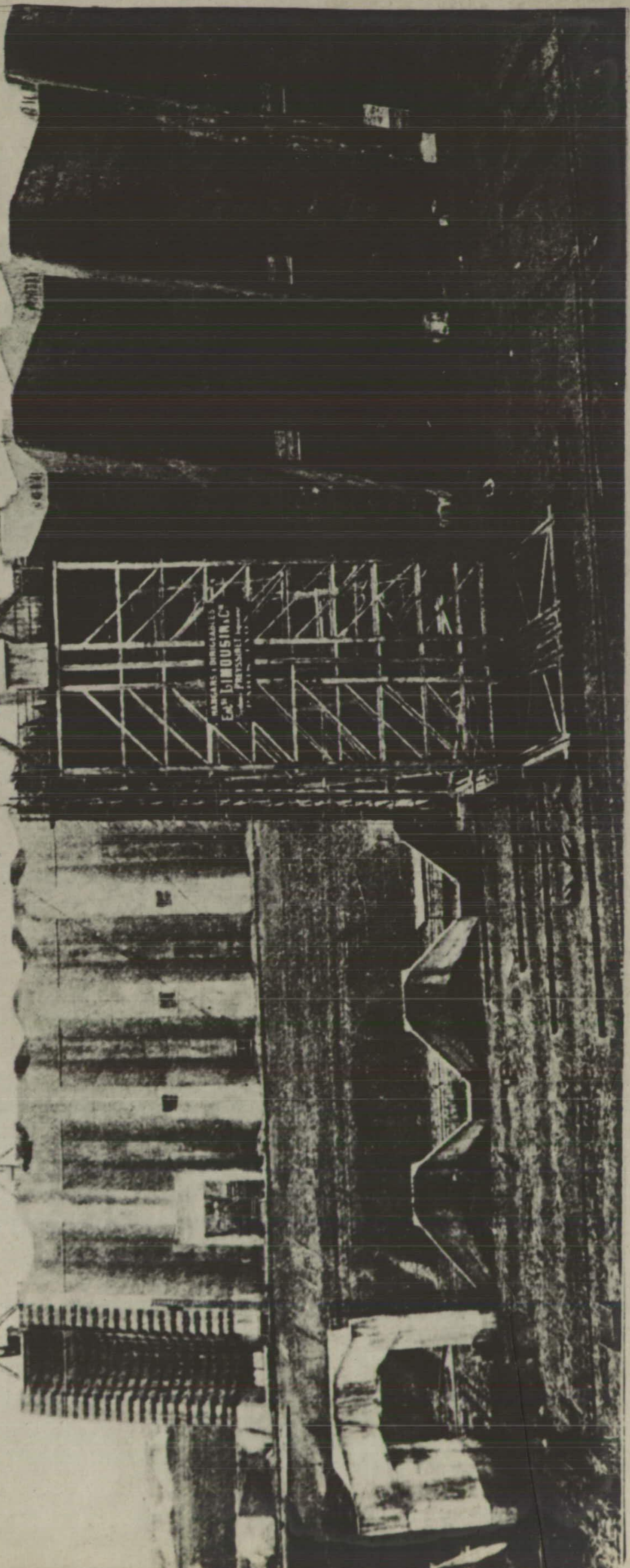


Fig.29 Series construction of vault elements 17m high.

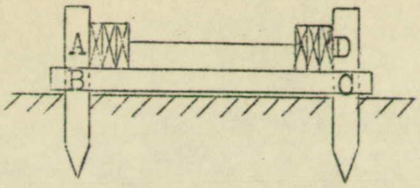


Fig.31

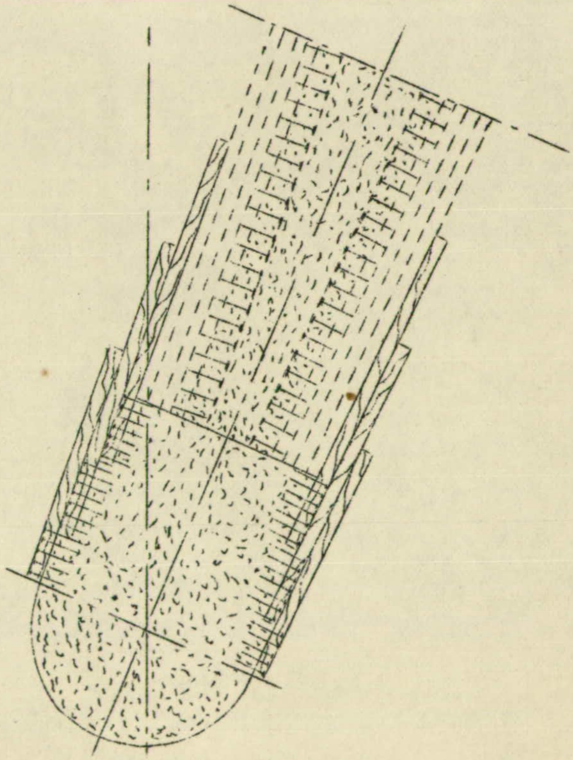


Fig.32 Assembly of lower concrete girder with wooden framework of the centering.

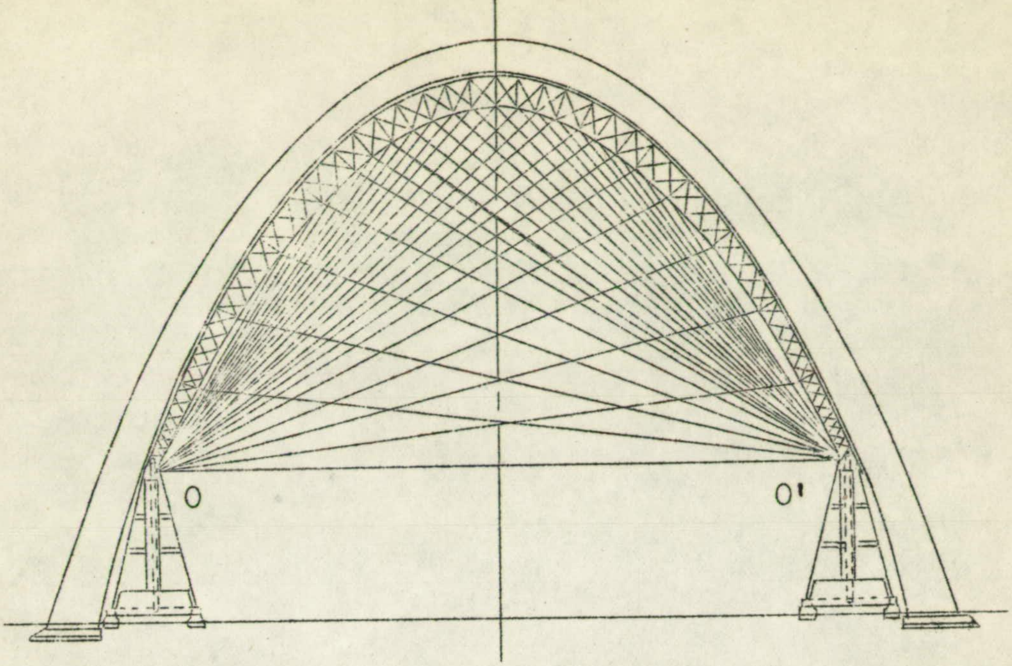


Fig.33 Elevation of centering mounted on two reinforced concrete supports and wind-braced by stay-cables.

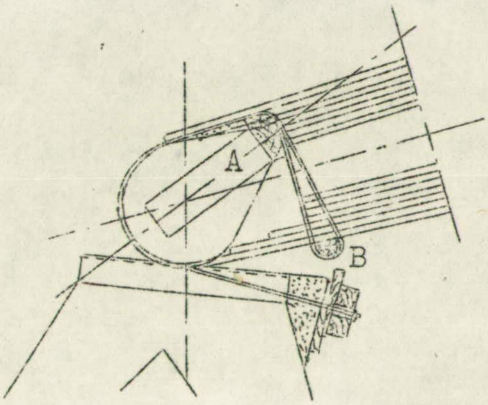


Fig.34 Manner of attaching stays to centering supports.

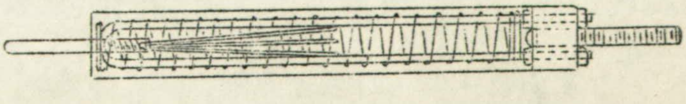


Fig.35 Cross-section of cable mooring.

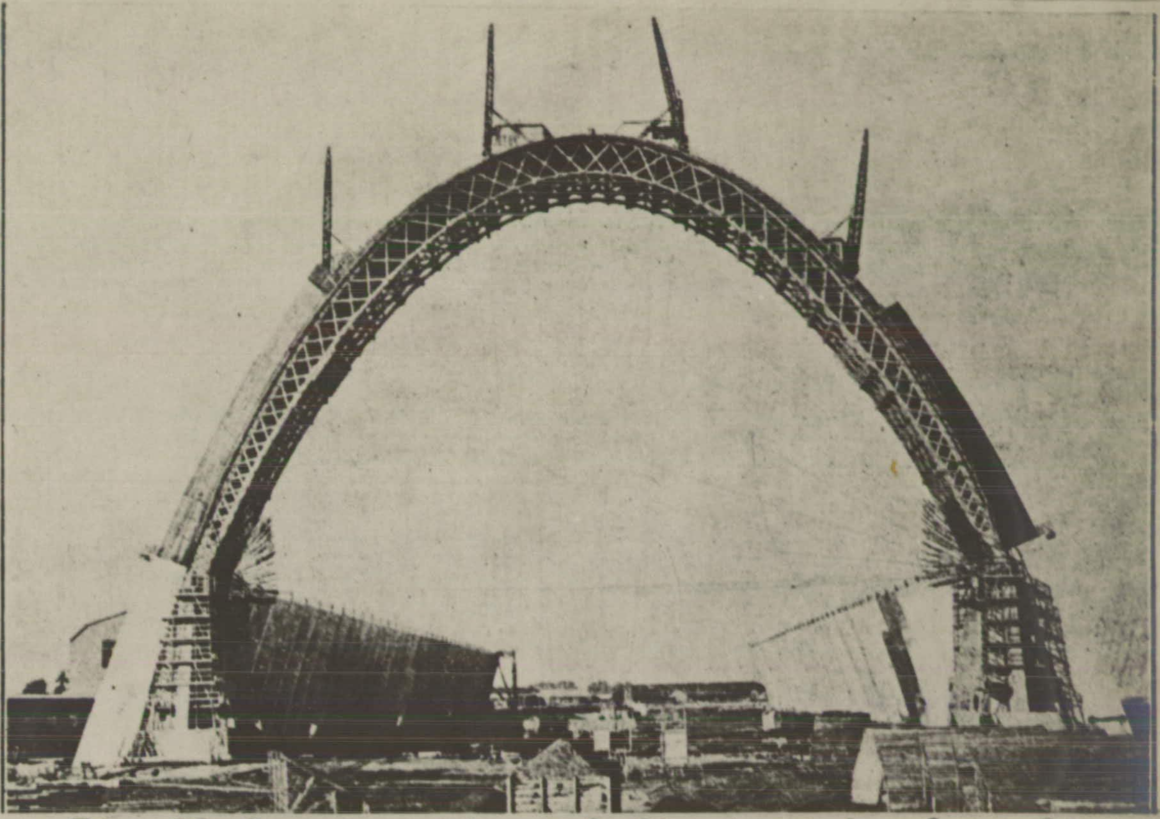


Fig.36 Construction of first arch of vault on the raised centering.

Fig.37 View of finished arch and of centering lowered for shifting.

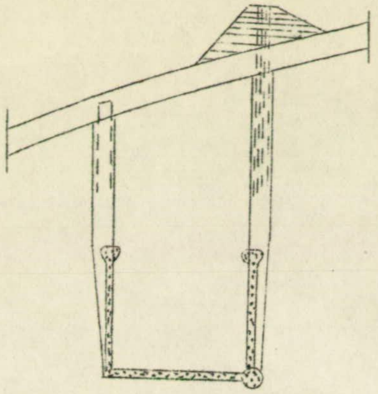


Fig.46 Cross-section of passage-way hung from roof of shed.

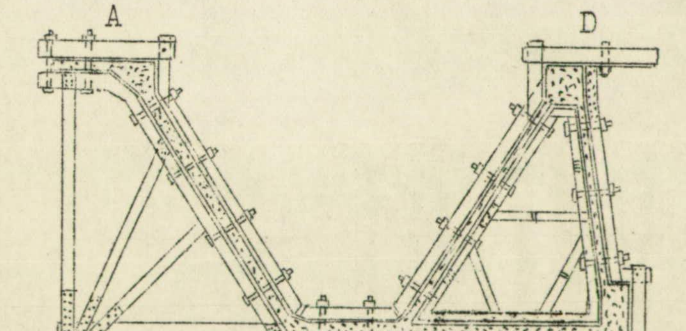
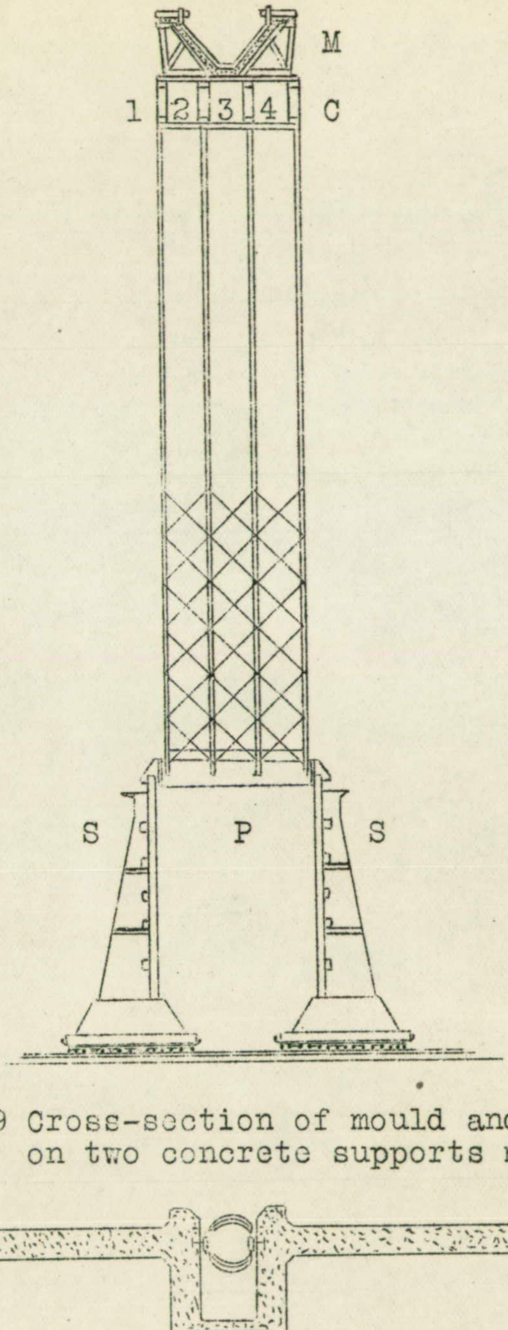


Fig.38 Cross-section of mould showing assembly of elements of wall at one end of shed.



C, centering
M, mould
P, concrete girder
S, movable support

Fig.39 Cross-section of mould and of centering resting on two concrete supports movable on rails.

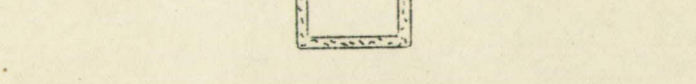


Fig.40 Horizontal section of a concrete support of the centering.

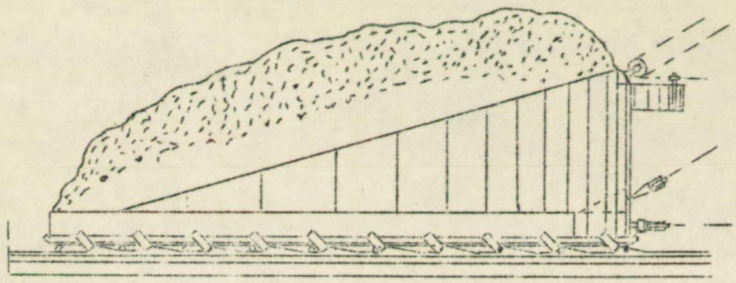


Fig.41 Concrete platform loaded with earth for anchoring end of centering.

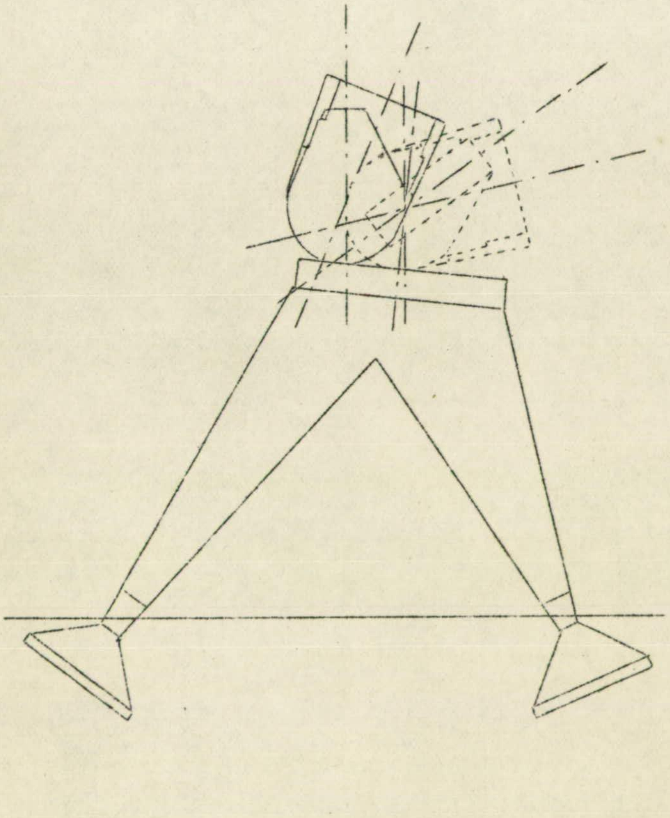


Fig.42 Rotation of one of concrete girders, forming base of centering, on a temporary concrete support.

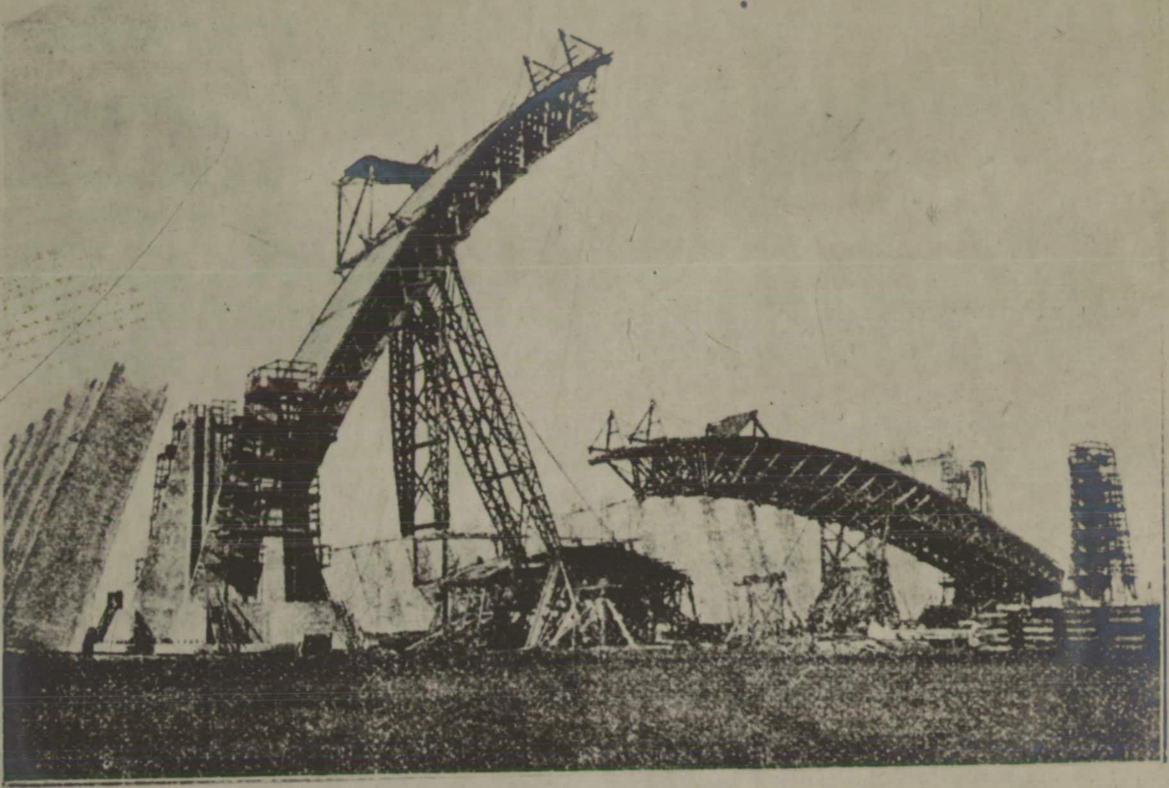


Fig.43 Raising lateral sections of centering

Fig.44 Raising central section of centering

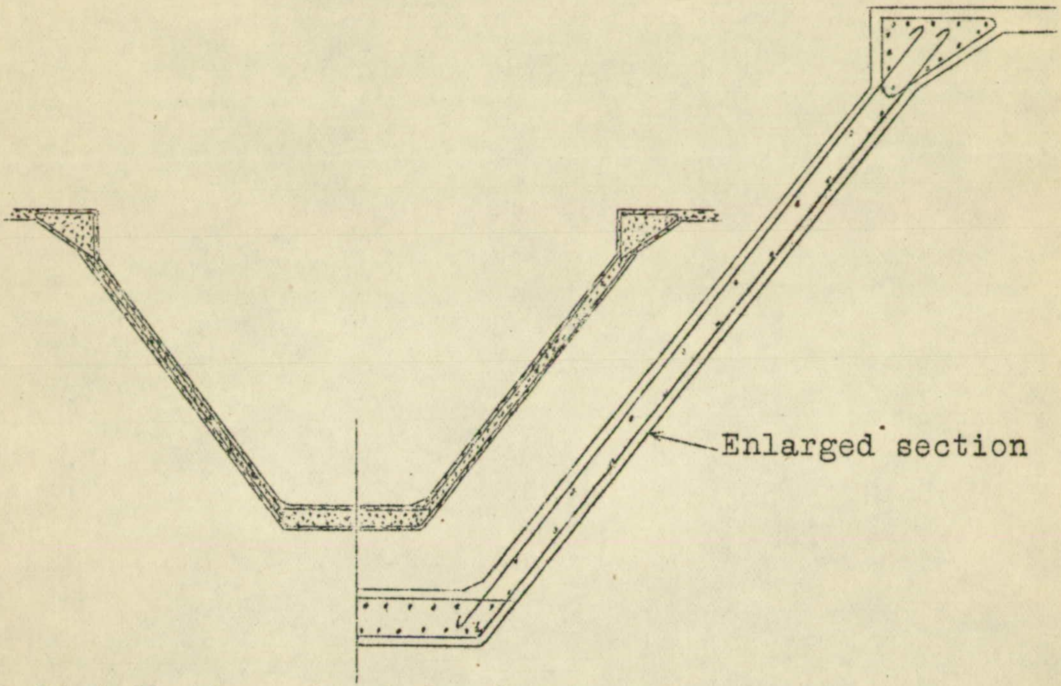


Fig.45 Distribution of reinforcing bars in a section of the vault.

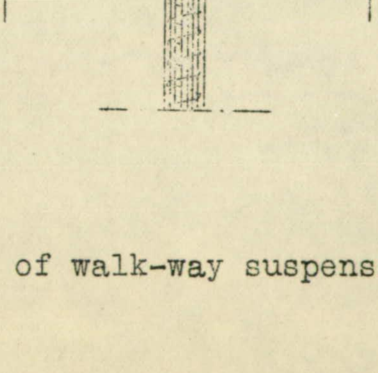


Fig.47 Detail of walk-way suspension.