Portable Hangars.

Paper read by Major H N Wylie, B Sc , F R Ae S , before the Institution, in the Lecture Room of the Junior Institution of Engineers, 39, Victoria Street, London, S W 1, on 8th March, 1927

IN opening the meeting the Chairman said Major Wylie requires no introduction from me He is a very old friend of mine, and when I was in charge of metal construction at the Air Ministry he was my right hand He is an engineer of exceptional ability and has made many outstanding inventions Since the War he has carried on his good work in the development of metal aircraft, and has also applied the ideas derived from metal aircraft, to other engineering constructions

All developments of engineering in any one branch make improvements in other branches possible , for instance, the knowledge obtained from the construction of aircraft has greatly improved automobiles, and, as Major Wylie is going to show you to-night, it has greatly improved portable structures, not only for aircraft, but for other things I now have much pleasure in calling upon Major Wylie

Introduction

Major WYLIE The portable Hangar described in this paper may be of interest to Members of this Institution for the reason that it is a Hangar for the accommodation of their aeroplanes, and it is hoped that it will also have an interest of its own in virtue of its several novel features

Its rigid structure consists largely of steel tubes of aeroplane quality and although much has already been written on this subject some simple but possibly useful information has been overlooked, or forgotten, for it is not generally known, and is presented here in the hope that it may be of interest

The portable hangar has several characteristics common to aeroplanes For instance, it is light and must resist aerodynamic forces It is designed to have as small a drag as possible, to hold as much equipment as possible, and it consists of a steel framework with a fabric covering

The weight of the roof which has a span of 75 feet is just over 1 lb per square foot, and is less than the weight of the usual aeroplane wing of the same span Compared with roofs of usual construction it is about one-tenth the weight

This lightness is essential in a hangar which is to be portable in the military sense, and it is very important in a hangar that must be rapidly erected without extraneous appliances

The Air Ministry has recognised the need for lightness from the first, and desired that some risk should be taken in assuming the lightest wind loading that was justified by the information available—or rather by the lack of information available—at the time This policy made some saving in weight certain even though subsequently some parts might have to be strengthened It also ensured that some information would be gained

These enterprising assumptions are justified by the experience so far gained

General Description

The buildings described in this paper were designed to satisfy the requirements of the Air Ministry's specification for Mobilisation Hangars

The specification required that the sheds should be canvas covered and that the canvas covering should be given adequate support by a steel framework

The steel framework was to be as light as possible, so as to facilitate transport and erection, and it was to be capable of being easily broken into small pieces which could be packed into small cases to preserve it from damage and which would be suitable for transport by mule or camel

The packing cases were to be used as ballast boxes for the completed building, and the whole building was to be capable of being assembled and erected on unprepared sites and by unskilled labour

The specification required that the canvas covering should be supported by rafters at 4 ft 4 in centres The doors were to expose an opening having a clear width of 75 ft and a clear height of 20 ft , which means that a complete gable of the building was to open up

The Hangars that have been constructed to meet these requirements are shown by the following photographs

Plate 1 is a view of one Hangar which is erected at Martlesham Heath The photograph was taken from the South East corner with the doors closed This Hangar is known as the Bagdad Hangar

Plate 2 is a photograph of the same Hangar with the doors open

Plate 3 shows the framework of the Hangar, after assembly As already stated, the covering is of canvas and the rolled up cover can be seen lying along the ridge of the roof This picture perhaps requires explanation, because in usual buildings the walls are put up first and the roof is put on afterwards, whereas here is a picture showing the roof put on first The explanation of this peculiarity is that the Hangar has to be erected by unskilled labour It has been found from past experience, that unskilled labour is not capable of clothing a hangar of this size with its canvas covering after the framework has been fully erected, and the only wav to make erection easy is to design the Hangar so that it is all put together while flattened out with its highest point within the reach of a man standing on the ground, or on some such available article as a packing case, and this plate shows the Hangar in its fully flattened out condition with the ridges less than 7 ft from the ground

Having now assembled the flattened hangar, it is necessary to unflatten it This is carried out in four stages of what may be called formation erection

Plate 4 shows the end of the first stage This consists in lifting one side of the central two-thirds of the roof which is already covered It will be seen that this is accomplished by means of a row of derricks These derricks are the stancheons which will be more fully described later

When the roof has been hoisted by the stancheons, first at one side, and then at the other, into its arched shape, wire rope connections are made in each end of each truss and these fix the truss in its fully arched form

The next stage in formation erection is to lift one side of the roof to its full height To accomplish this the stancheons on one side are bent into triangles so that the extreme tops are right down at ground level In this attitude the ends of the stancheons are connected to the ends of the roof trusses along one side The ends of the roof trusses along the other side are rested on locating pins on the bases of the opposite stancheons and by this means the roof as a complete unit is hinged about one eaves and this eaves is definitely located The other eaves, which is connected to the stancheons, is then lifted by operating a winch on each stancheon on one side of the roof

Plate 5 shows the Hangar with one side about half way up

Plate 6 is a view of the Hangar with one side lifted to nearly its full height and the other side still resting on the locating pins on the ground

The following view of the framework of the Hangar was taken when the Hangar was being first experimented with and the framework was hoisted without the cover

Plate 7 shows the stancheons in process of arching the trusses

All the above plates show a Bagdad Hangar which is the Hangar to which the description given in this Paper generally refers The following plate shows a Cairo Hangar which is smaller and is nearly of the same shape

Plate 8 is a view of the inside of the Hangar showing the stancheons

Following this general description, more detailed particulars of the construction of the Hangar are now given

The larger hangars have a clear span inside at the eaves of 75 ft , and a clear height at the same position of 20 ft , and the length of the main building is about 80 ft The total area is considerably greater than this owing to the sloping sides and ends, and the area covered is 8,500 sq ft The total weight of the framework, which includes the roof, side stancheons, side walls and all wire ropes is just over 6 tons The weight of the cover is just over 35 cwt The ballast boxes, which are also used as packing cases, have a total weight of just under 2 tons, and the total transport weight of the Hangar, including the cases in which it is packed, tools, etc , is just about 10 tons deadweight The shipping bulk is 840 cubic feet, which is 21 shipping tons The volume or bulk of the Hangar when erected is 180,000 cubic feet , hence the Hangar contracts to less than one two-hundredth of its bulk when taken apart and packed These figures compare very favourably with those of the wooden hangars which were used during the War The Bessonneau

Hangar, which had a span of only 66 ft and a clear height of only 13 ft 6 in , had a total weight of 9½ tons, without any packing cases, and its shipping bulk was 78 tons, while the Hervieu Hangar, which was also of wood, but was slightly larger than the present Hangar, had a total weight of 12½ tons and its shipping bulk was 98 tons It will be seen from these figures that the present hangar is much lighter and more portable than either of its wooden predecessors

Wind

The Air Ministry specification for these Hangars required them to be designed to withstand a 65 mile per hour wind with the doors closed, and a 50 mile per hour wind with the doors open It also required the roof to withstand a snow load of 10 lbs per square foot

The snow load was quite definite and was easy to handle in design, but wind velocities cannot be handled in stress calculations until they are translated into pressures

2 A 65 mile wind exerts a pressure of about 12½ lbs on a normal surface 1 square foot in area, and if the end of the hangar had been flat and its area equal to the cross section area of the Hangar the force exerted on the end might be 14 tons

With the doors open, nearly the whole end is open, and the Hangar is a bag If the bag be assumed to be airtight except for the door opening and a 50 mile wind blowing into it, the internal pressure is 7 5 lbs per sq ft greater than the general pressure, and in addition the pressure over the roof and round the sides and back is generally less than the general atmospheric pressure There is therefore, a considerable lift on the building amounting, on the above assumptions, to perhaps 10 lbs per sq foot over the total covered area of 8,500 square feet This gives a total lift of 38 tons

The above figures were not used in calculating either the strength of the anchorage or of the members of the Hangar, because the ends of the Hangar are not flat but well rounded, both in plan and profile, and the Hangar is not airtight, but has large ventilators which put the inside into communication with the outside at the eaves and elsewhere, and thus greatly reduce the difference between inside and outside pressures Allowance for these features had therefore to be made since the Hangars had to be portable There are a number of circumstances which would make an accurate calculation of the pressures on these Hangars difficult even if one had ample time and were expert in the methods of Prandtl, and others, but time certainly was lacking when the Hangars were designed and recourse was had to an extensive series of wind tunnel tests made by Eiffel on models of Airship Sheds Airship Sheds are different in shape from the Hangars under consideration, but from a careful study of the pressures on these and a fair amount of guesswork, diagrams of pressure distribution were obtained

Four of these diagrams out of the number prepared are shown in Plate 9 and Plate 10 They show much smaller pressures than those arrived at in the hypothetical calculation given above The total end force or drag obtained by integrating the pressure area values is 4 6 tons instead of 14 tons, with a 65 mile wind on one end, and is 6 5 tons with the same wind on one side

The lift also is less, being 26 tons instead of 38 tons, in the case of the doors being open and a 50 mile wind blowing into them

The worst condition for stability appears to be not with the wind blowing directly into the doors, but with the wind at 30° to this direction In addition to the lift of 26 tons there is a down wind force or drag of 4 7 tons, and this is the condition which makes the most exacting demand on the anchorage

In this condition the whole deadweight of the Hangar is of course, assisting the anchorage, but since the total deadweight above ground, including winches, base plates, etc , is only 8 tons, it will be appreciated that if the hangar depended for security on its own weight its claim to be portable would be rapidly realised

Considerable experience has been gained on these Hangars since they were designed One Hangar of 75 ft span was erected on the most exposed part of Martlesham Aerodrome in August, 1925, and it is still standing there, and another Hangar of a smaller size was exposed for a winter on the Aerodrome at Farnborough

Tensionmeters were set on several of the ropes on each Hangar, and readings were taken periodically

In the case of the Martlesham Hangar the highest tension recorded was on the S W guy ropes during a gust which recorded a wind speed of 50 miles per hour on the Station anemometer, which is at a height of 68 ft above ground level The maximum tension on the ropes was less than one-eighth of their strength From the measurements that have been made with the tensionmeters, it has been estimated that the total force on the Hangar which would be exerted by a 65 mile wind fair on one end would not exceed 3 8 tons and would probably be much less This figure is to be compared with the figure of 4 6 tons which was the figure used in making the design

The Hangar has been observed during a 56 mile gust and some deflection of the doors and horizontal truss occurred, but no damage was suffered The tension in the ropes was not measured on this occasion

The highest wind velocity recorded at Martlesham since the Hangar has been there is 57 miles per hour in a gust

In the case of the Hangar at Farnborough, records were kept of the tensions in various ropes in the roof Many of these ropes were pretensioned by the straining screws on the side guys, and the general tension was about half a ton These tensions were very little affected by high winds On one occasion there was a heavy fall of snow which covered the roof to a depth of 12 in This increased the tension on a main tie rope from 5 to 8 tons and this was the greatest increase in tension recorded on any rope The ropes referred to above had a strength of over 4 tons, so they were obviously not overloaded

The maximum wind velocity that has ever been recorded at Farnborough is 58 miles per hour in a gust The anemometer at the Aerodrome is at a height of

60 ft , and is stated to be somewhat sheltered There is an anemometer at a height of 147 ft in a well exposed position at a distance of about 2 miles from the Aerodrome and continuous records of the readings on this have been kept The maximum gust ever recorded on this had a speed of 82 miles per hour, and the mean speed at the time was 52 miles

There is little doubt from the observations made on the Hangars that the total force on them is less than would appear from the pressure diagrams which were used in the design, but there is some evidence that local pressures are more severe

This may be partly due to the fact that the wind velocity is less near to the ground than at a height of even 60 ft , but it is probably mainly due to the wind stream being broken into eddies and gusts for some distance above the ground, the extent of this depending, of course, on the character of the ground surface This opinion receives support from observations that have been made when standing inside the Hangar during high winds

What actually happens when a gust strikes the Hangar is that a portion, perhaps 20 ft long, takes the full pressure of the wind, while other parts facing the same way are slack or are bellying outwards This state is maintained for a second or two and then the wind suddenly drops When it comes up again a second later, it exerts its full force on a portion of the Hangar which may be different from the part at first affected Observations of this nature would lead one to expect the total force on the Hangar to be less than that calculated from experiments made on models exposed in a steady air stream It is not certain, however, whether the intensity of pressure on the small intensely loaded areas which appear to take the full force of the wind, is any less or greater than the values which would be expected from wind tunnel tests and locally recorded wind speeds

I am aware that the above observations appear to be not quite in harmony with the conclusions reached in Mr T E Stanton's paper No 4513, which was read before the Institute of Civil Engineers in December, 1924 Mr Stanton concluded from a long series of observations made on the Tower Bridge that the force exerted by a squall, even on such a large structure as the Tower Bridge, might give a pressure distribution which was not different from that which would result from a steady wind of the same velocity There is, however, a very great difference between a structure situated at a height of 150 ft above water such as the top girders of the Tower Bridge, and a structure having a total height of about 30 ft standing right down on the ground

It is interesting to note that during Mr Stanton's observations on the Tower Bridge, which extended over a number of years, the maximum wind speed recorded at Kew Observatory was 50 miles per hour In view of this figure the wind speed of 57 miles per hour recorded at Martlesham must be taken to represent a heavier gust than is to be expected at most stations, or at frequent intervals

Detailed Description

Plate 11 shows the general arrangement drawing of the Hangar A study of the drawings suggests that there are a great number of parts in a Hangar and it is admitted right away that there are

If all the pieces shown on *Plate* 11 had to be taken apart to be packed and put together again on assembly the Hangar would not be a practical proposition Actually this is not so because the Hangar is built from units each of which comprises a number of parts, and these parts always remain connected together

It will be obvious that it is simpler to assemble a number of units than to assemble a much greater number of parts, but how much simpler can be appreciated only from experience

If, say, 100 units comprise a Hangar, and there are 10 parts in each unit, then ten times as many parts would have to be connected and disconnected in the latter case But this is not all the difference, because with a great many small parts there is great difficulty in sorting them out, whereas, with the smaller number of units, these are either so much the same as to be interchangeable, or so different as to be easily distinguishable

A Hangar unit is shown on *Plate* 12 The top view is the unit folded so that it will fit into a ballast box for transport, and the lower view is the unit extended ready to be connected to similar Units to form a complete truss

The unit consists of 4 rigid members and 7 wire ropes, 2 of which are in a different plane from the others and are not shown

If the unit were transported in its extended form, it would be so liable to be damaged in transport that sufficient parts for 3 Hangars might have to be sent to enable one Hanger to be built, as has often happened in the case of wooden Hangars

It will be appreciated, therefore, that enclosing the structure in boxes for transport is essential

The use of wire ropes for tension members enables the units to be folded without disconnecting ends, and on this ground alone the use of wire ropes instead of rigid members is essential

The units shown on *Plate* 12, are connected together to form trusses of the form shown on *Plate* 13

The roof trusses are connected together by short lengths of tubular purlins, and by wire rope diagonals The connection of the purlins is by means of small forgings which are hinged to the truss in one plane and to the purlin in a plane at 90° to the first, and thus form universal joints The connection is shown on *Plate* 14

This form of connection is a very convenient one for assembly, and the flexibility it provides is essential in Hangars which must be assembled on uneven ground

There are eleven ordinary trusses and two special end trusses in each Hangar and these are spaced at 4 ft 4 in apart, because the specification required that the canvas should be supported in downward sloping lines at these centres The rounded ends are formed by trusses which are similar to the roof trusses, but which lie in a horizontal plane These are connected to the vertical trusses by means of raking purlins, as is shown by the side view The intermediate horizontal truss, which is simply two-thirds of an ordinary truss, is used to reduce the span of the raking purlins The main horizontal truss has to support very nearly one-half of the full wind pressure exerted on the end of the Hangar , that is, it has to support a wind load the horizontal component of which is 2 3 tons The actual load which the truss must support is about 4½ tons The weight of this truss is 4 cwt including purlin connections and diagonal ropes

The intermediate roof trusses which have a span of 75 feet have a weight of 2½ cwt each, including the fittings for connecting the purlins This is probably the lightest roof truss of its span that has ever been made The weight of one of the wooden trusses used in the standard wood hangars is over 11 cwt including purlin connections, although the span is only 66 ft , and the weight of a 75 ft truss of normal construction by one of the best constructional firms in the country is about 34 cwt The wood trusses according to such tests as have been made are not so strong as the light steel trusses The ordinary structural steel truss referred to is for a building in which the trusses are spaced wider apart than in the present Hangar This truss is certainly much stronger than a Bagdad truss, but the area supported bv it is not so great as the area supported by the main horizontal truss of the Bagdad Hangar, the weight of which is only 4 cwt A detailed comparison of the weights of a Bagdad Hangar with the weights of a like design steel hangar of the same size and standard construction is given in the following table

COMPARISON OF WEIGHTS OF BAGDAD HANGAR WITH A WELL DESIGNED STEEL HANGAR OF SAME SIZE AND OF STANDARD CONSTRUCTION

Weights of Standard Steel Hangar shown in Column "A "
Weights of " Bagdad " Steel Hangar shown in Column " B "
" B " as percentage of "A" shown in Column " C "

	"A" (Tons)	" B " (Tons)	" C "
Roof Trusses and Bracing	16 5	1 91	12%
Extra Bracing or Horizontal Girders	2 0	0 65	33%
Purlins	4 5	0 42	9%
Main and Door Columns	9 0	1 78	20%
Side and End Framing	4 5	1 00	22%
Door Frames	3 5	0 27	8%
Door Covering (Steel Sheeting or Canvas)	2 0	0 23	11%
20 G Galv Corrug Steel Sheeting or Canvas cover	14 0	1 57	11%
	56 0	7 83	14%

The particulars of the standard Hangar were given by Sir William Arrol & Co , Ltd , and these weights are less than the corresponding figures for a recently constructed hangar of which the author has the figures

The lightness of these trusses has been attained in two ways Firstly, by using high tensile wire rope to the greatest extent possible, and secondly by using fairly high tensile steel tubes for the rafters and short struts The steel tubes have an important advantage for canvas covered buildings in that they expose a smooth rounded surface for the support of the canvas

The roof is supported on stancheons of the form shown on *Plate* 14, Fig 4 A stancheon consists of three lengths of tubing hinged together in line The stancheons are braced at the joints by spacing tubes as shown in the side elevation, and are braced in the other plane as shown in the drawing It will be seen that the main tubes of the stancheons are not quite in line This ensures that the stress in the bracing at the back of the stancheon will be in tension rather than in compression, and at the same time it adds about a foot to the effective span of the Hangar

Raising

The action of the stancheon when it is used to lift the Hangar is shown on *Plate* 14 In Fig 1, the top of the stancheon (C) is in its lowest position and is connected to the end of a roof truss The other end of the roof truss is located on a pin at the base of the opposite stancheon as has already been described The truss, therefore, acts as a stiff radius rod which guides the point (C) in a circular arc when the two ends of the stancheon are forcibly moved apart Means for moving the ends of the stancheon apart are provided by a winch (W) and a wire rope (R) The wire rope (R) is shown passing from the winch round a pulley at the point (E) round a further pulley marked (P), which is at the end of an auxiliary strut (X), and hence to the back end of the top member of the stancheon at the point (D) where it is anchored When the winch is operated the point (D) is pulled towards point (P) and the top point (C) of the stancheon is pulled away from the lower hinge point (O) The resulting force at (C) is shown by a line (C - V) This line, it will be observed, slopes outward, but it has been found that the outward component of this force is undesirable and means are now used to reduce it

In Fig 2, the stancheon is shown with the point (C) about 12 ft from the ground At about this point the reaction of the truss begins to pull strongly inward, and this sets up a moment about (O) which overcomes the dead weight moment of the stancheon and causes the whole stancheon to rise upward about (O) Fig 3 shows the stancheon in a still more advanced stage of the lift and Fig 4 shows the stancheon fully hoisted At the end of its lift the points (D) and (E) are connected by a pin so that the stancheon is then stable without the assistance of the operating rope In its erect position the stancheon is a perfectly ordinary stancheon It could not be much simpler if it had been designed to be simply an ordinary stancheon, without having to serve also as a lifting derrick The only important additions are the auxiliary strut (X) which is shown housed in the erected stancheon, and the hoisting winch and rope The hoisting winch and rope are not used solely for lifting the buildings, but are used after the Hangar is erected for operating the doors

The complete weight of a corner stancheon which has to support half of the complete end of the building, is only 1 4 cwt This is very much less than the weight of an ordinary mild steel stancheon for a building of the same size could possibly be, particularly if it had to be broken into three lengths for transport

The description just given refers to raising one side of the Hangar when the other side is resting on the ground The second eaves lifted must swing in a different arc, because the hinge about which the roof swings as a radius rod is 20 ft above ground The arc of the second eaves is arc (C C″) on the diagram The operations of arching the roof and of raising the roof in its different stages are shown on *Plate* 15

Doors

One of the most important features of the Hangar is the doors It will be readily appreciated that the sliding doors which are usual in permanent Hangars are hardly applicable to portable Hangars, because these latter are built upon uneven ground Another consideration is weight The weight of sliding doors on a permanent Hangar of the size of the Bagdad Hangar is about six tons, which is the weight of the complete Bagdad Hangar The usual practice in portable Hangars has been to use a curtain to close the door opening and to leave this curtain unsupported by any framework The curtain method is very unsatisfactory and in the present design frameworks consisting of rigid tubes and covered with canvas are used as doors to close the door opening These doors are shown in Section in side elevation on *Plate* 16 It will be seen that each door consists of three panels which are hinged together in line, and when the doors are closed these form an arch between the ground and the horizontal truss The shape of the arch is maintained by flexible wire ropes which span from points (O) to points (B) and from point (A) to points (C) Each of these doors has a length of about 14 ft and six of these doors are used to close the opening Each door is raised by means of a separate wire rope This wire rope has one end attached to the door at point (A) and the other end passes over a pulley on a tripod which is attached to the top panel (B - C) The other end of the rope is attached to the rope which is wound on a winch Operation of the winch, which is attached to the stancheon in the same position as when lifting the building, first of all lifts the lower two panels of the door and swings them into the attitude shown by broken lines in Fig 2 of *Plate* 16 This completes the first stage of hoisting because point (A) of the door then butts up against a stop at the top of the tripod Further winding of the rope causes the complete door, including the top panel, to swing upwards about point (C) and hoisting is continued until point (D) butts up against a tube which embraces the hoisting line This completes the hoisting of the door and in this position it is held rigid

Miscellaneous Comments

It has already been stated that the rounded outline of the Hangar reduces the total force which the wind can exert on it, and the figure for this has been taken at about one-third the value that would have been taken if the ends had been flat

This is of great importance because the provision of anchorage is one of the greatest difficulties in the way of portable Hangars

The shape has great advantages on structural grounds also, and one example will be given to illustrate this With a 50 mile wind on an open end the internal pressure may exceed the external pressure by about 8 lbs per square foot, as has been shown on *Plate* 10 From this plate it will be seen that the internal pressure tends to make the truss assume a nearly circular outline However, the truss is of nearly circular form initially, and this is fortunate, because the wire rope bracing cannot develop compression, and so could hardly resist a tendency on the part of the truss to greatly alter its form

The advantages of flexibility in the structure of this Hangar have already been commented on, and are no doubt fully appreciated, but the opposite quality of rigidity is also essential in structures, and one of the problems that has had to be faced in this design is that of obtaining rigidity where necessary The horizontal trusses over the doors have required special attention with regard to its stability during the roof-raising operation

Materials

Since the rigid structure of this Hangar consists of steel tubing, it seems appropriate that something should be said on the strength properties of this form of structural member

Two qualities of tubing are used, one having an ultimate tensile strength of 45 tons or over, and one an ultimate tensile strength of 35 tons or over

The former is made from plain carbon steel containing about 45 per cent of carbon, and the latter from a similar steel containing about 35 per cent of carbon

These tubes are identical in strength properties with tubes complying with B E S A Specifications T 5 and T 1, but the ductility called for is not so great

This lesser ductility has not caused trouble in any single case, and it seems to be certain that the ductility required by Aircraft Specifications is greater than is necessary, except in cases where the tube has to be deformed in making a part, and in such cases the ductility required by T 5 Specification is insufficient

Nearly all the tubes used in the experimental Hangars were proof loaded before being passed into service Proof loading was effected by sticking one end of the tube to be tested into a hole in a beam and pressing down the other end of the tube until the beam lifted If the end of the tube was perceptibly bent it was rejected The apparatus used for this test is illustrated in Fig 17

To make this test the beam is weighted so that the moment of beam weight and suspended weight about point (o) has the value obtained by multiplying the modulus of the tube section (z) by the specified yield of the steel

In the case of the 45 ton tubes the specified minimum yield is 40 tons per square inch, and in the case of the 35 ton tubes it is 30 tons per square inch

The high ratio of yield to ultimate is due to the fact that the tubes are cold drawn, and "blued" The cold drawing process hardens the steel and the "blueing,' which consists in baking at about 400° C, raises the yield and greatly raises the limit of proportionality, particularly in compression

A stress strain diagram obtained from a tensile test on a 45 ton tube is shown by Curve 1, on Fig 18 This curve is fairly representative except for the fact that the yield is exactly 40 tons per sq inch, whereas usually it is slightly greater

It will be seen from this curve that the limit of proportionality is at about 30 tons per square inch, and that the permanent strain increases gradually, and there is no well defined yield such as occurs in annealed and normalised steels

The absence of a well defined yield led to the yield point being defined arbitrarily as the stress at which the permanent strain is 005 This definition is less arbitrary than it appears to be, because it agrees with the yield as usually detected by beam drop and by the average observer using dividers on a 4 in gauge length

It will be seen from Fig 18 that the plastic deformation at the " yield " is 1 7 times the elastic, and it might be expected that a tube stressed in bending to the yield stress would show a marked set This expectation is probably correct but the stress worked to in bending tests is not an actual stress, but is a figurative or formula stress in the same way as the ultimate tensile strength is a formula figure since it is calculated on the original cross section of the test piece What may be called the " formula bending " stress is the figure obtained by dividing the bending moment by the modulus of Section (z)

The formula stress is the actual stress in the extreme fibre up to the limit of proportionality , beyond that the actual stress is less than the formula stress

This discrepancy is due to the fact that beyond the Limit of Proportionality or L P , the stress increases less rapidly than the strain Hence, when the fibres remote from the neutral axis reach the L P the distribution of loading over the section alters, and the remoter fibres which are the more heavily strained take a progressively smaller proportion of the load

When a tube or any similar member is bent it bends in a curve and the strain in the extreme fibre, or in any other fibre, is proportional to the curvature at the point under consideration When the curvature is known, the strain is known, and when the strain is known the stress can be read off the stress strain diagram for pure tension or compression

Since the stress in each element in the cross section can thus be obtained, the moment of resistance of a tube can be calculated for stresses beyond the limit of proportionality

From the moment of resistance, the formula bending stress is obtained by dividing by (z) Curves relating " formula stress " to " strain " have been calculated and are shown on Fig 18, Curve 2 is for a thin tube in which the wall thickness is 80th of the diameter, and Curve 3 is for a tube in which the thickness is one-thirteenth of the diameter

It will be seen from these curves that when the formula stress is equal to the tensile yield the permanent curvature has a mean value of 12½ per cent of the elastic curvature

If a beam be subjected to uniform bending between two points of support the deflection is proportional to the curvature Numerous tests have been made on tubes tested in this way, and the permanent deflection has been found to be about 12½ per cent of the elastic deflection when the formula bending stress figure was equal to the tensile yield, and when the tubes have been properly blued If tubes are not blued or are under-blued the permanent deflection is much greater because in these cases the L P is low and, what is more important, both L P and yield are lower in compression than in tension In properly blued tubes they are the same

In the proof test to which the Hangar tubes were subjected bending was not uniform along the length under test, but varied uniformly from a maximum value to O Under these conditions the L P is exceeded over only a small part of the length under test and the permanent set is about 5 per cent of the elastic bending deflection when both are measured at the point of application of the load

A permanent set of 5 per cent of elastic deflection is just perceptible, and this test has been largely used by the Manufacturers of aeroplane tubes, and has proved to be satisfactory

It will be noted from the curves in Fig 19, that the ultimate moment of resistance of a tube in bending is considerably greater than Z times the yield stress It does not depend greatly on the ultimate stress unless in very thick tubes, but is usually 1 28 times the yield stress multiplied by " Z " This figure is greater in thick tubes and less in very thin tubes It corresponds to what has been named the Modulus of Rupture in Cast Iron

Struts

The strength of tubes when used as struts of lengths greater than ten times their diameter depends mainly on their resistance to bending

A tube may be accurately straight and axially loaded and may behave as an Euler strut, remaining quite straight until the critical load is exceeded, and then bending suddenly and collapsing

Practical tubes are not ideally straight and axially loaded, and they start to bend slightly as soon as end load is applied , since practical tubes, when used as struts, are subjected to combined thrust and bending

Aeroplane stress merchants who have not forgotten their elementary education are acquainted with Perry's approximate formula This formula is only an approximation when applied to a uniformly loaded length of spar, but it is an accurate formula when applied to a tube which is initially bent in the form of a sine curve and is subjected to thrust along the axis joining the centroids of its end sections

It was suggested in 1915 that tubes which were not quite straight might be regarded as sine curves and Perry's very simple formula might then be applied to calculate the load they would carry as struts

Limits to the imperfections of tubes were laid down by Admiralty Air Department Specifications both with regard to straightness and concentricity of bore, and these limits were manipulated into functions of l/k where l is the length of the strut and k is its radius of gyration

The following adaptation of the Perry formula was thus obtained —

$$p = S - \frac{py}{1 - p/q}$$

p = Compression load per sq inch of tube cross section
q = Euler stress = $\pi^2E/(l/k)^2$
l = distance between frictionless end pins
k = radius of gyration

D = outside diameter of tube
t = thickness of tube
$y = 105 + 0025\ l/k = \delta\, h/k$
δ = total eccentricity of loading $= \dfrac{\text{bore}}{40} + \dfrac{\text{Length}}{600}$
These are the limits of eccentricity and crookedness permitted
h = distance from axis to extreme fibre $= \dfrac{D}{2}$ for a circular tube

E is taken to be 13,600 tons per sq inch or $30\ 4 \times 10^6$ lbs per sq inch

S is taken as the yield stress as defined in B E S A tube specifications Values calculated from the above formula for S = 15 tons to 70 tons, are shown by curves in Fig 20

Theoretically the above formula does not apply at stresses beyond the limit of proportionality, but it will be remembered that the deflection at a formula stress equal to the yield is very little more than the elastic deflection in bending, and actually the values obtained in tests on tubes that complied with the specifications were always in excess of the values calculated Indeed the values obtained for " p " from tests on tubes chosen at random have usually been such as would be given by the above formula if values for " y " equal to about one half the values resulting from the above expression for " y " were used

The formula transformed to be explicit with respect to " p," is given in Fig 19

The curves originally published by the Admiralty Air Department Specification T 10 were calculated for the values of eccentricity and crookedness given above, but a different formula known as the " Secant " formula was used

The " Secant " formula is accurate only if the tube is straight, and the eccentricity is initially uniform throughout which it obviously is not in the case of a bent tube The " Secant " formula gives values which are slightly lower than the Perry formula, but the difference is generally just about $1\frac{1}{2}$ per cent , and this is not important in view of the fact that the amount of initial deflection and the exact value that should be taken for S are both a little doubtful

The " Secant " formula is rather inconvenient to use, and for this reason a Committee of the Royal Society on the subject of struts recommended the Perry formula

Protection Against Corrosion

Many of the tubes used in these Hangars are 036 in thick To constructional engineers it must appear that such tubes have no margin for corrosion There certainly is not much margin, but it is not anticipated that there will be much difficulty from corrosion

The tubes are coated with Bitumastic which appears to give effective protection, and which is not readily knocked off One of the Bagdad frameworks has undergone very severe exposure tests and these are reassuring

Although in many cases the tubes are only 036 in thick, this is a much greater thickness than is used on steel aircraft which are rapidly coming into use in the

British Air Force The steel in many aeroplanes is about 0 15 in thick in the main members and about one-half of this thickness in the secondary members, and though such machines have been submitted to the most exacting exposure tests they have come through with complete success

The fact is that when the metal is properly cleaned before the protective coating is supplied, as cold drawn tubes and cold rolled strip can be cleaned, no corrosion takes place if the protective coating is waterproof

After all there is much more body in a tube 036 in thick than, in the wires of a wire rope, and wire ropes have for long been used for the standing rigging of ships

Resistance to Damage

The practical engineer will object that these tubes are very readily damaged, but the Hangar tubes are not easily damaged

Resistance to damage from a blow is proportional to resilience and resilience is proportional to the square of the yield strength of the steel, thus the resilience of the tubes in the Hangars is about four times that of tubes of the same size and thickness, but of mild steel in the usual mild state If the Hangar consisted of heavy parts and light parts and the heavy parts were dropped on the top of the light parts, there would be a good chance of the light parts being damaged, but there are no heavy parts in the Hangars

The above statements are not purely theoretical They are an explanation of observed facts

The experience gained, in making about one dozen erections of these Hangars has convinced everyone that the 45 ton tubes are more reliable and are altogether a better proposition than the 35 ton tubes, and it is intended to use them more extensively in future

In conclusion, I wish to state that the Hangars were built by Messrs Ransomes Sims and Jefferies, of Ipswich, to the author's designs, and under contract to the British Air Ministry

There are probably few firms with sufficient technical ability and enterprise to have been willing to study the plans for such a light design, and to undertake to make such a construction and to ensure that it would perform all the mechanical movements as intended, and I think the firm is to be congratulated for having succeeded in this undertaking

The firm did not take responsibility for the sufficiency of the wind loadings proposed by the diagrams that have been shown This responsibility was taken by the Air Ministry

I have to thank Messrs Ransomes Sims and Jefferies for most of the photographs and for some of the drawings I have shown, and for assistance in several other ways

I have also to thank Captain A Burgess who designed the covers

Lastly, I wish to thank the Director of Technical Development of the Air Ministry, for much of the information in this paper, and for his permission that this paper should be given

DISCUSSION

The CHAIRMAN I do not know which to admire most—the skill and enterprise of Major Wylie in designing this structure, or the courage and ability shown by Messrs Ransomes, Sims and Jefferies in constructing it It is a structure which it seems to me will advance general structional engineering, and will point the way to improving many other forms of structures I am sure we all wish Major Wylie and Messrs Ransomes, Sims and Jefferies the very fullest awards for their great ability and enterprise The paper has been of the very greatest interest to aeronautical engineers, particularly the section relating to the theory of tubes That portion of the lecture is really the basic theory of the metal construction of aircraft, and it cannot be too carefully studied by all who take up this subject

After all, a steel tube is the finest possible structure one can have to resist compression It is only when one has to meet other forms of stress such as combined bending and compression, that it is perhaps desirable to depart somewhat from the pure tubular form, and in that branch Major Wylie, as you know, is a very great expert indeed, his various inventions and designs being known all over the world

I was very interested in the diagram of wind pressure on the diaphragm During the war when crossing the Atlantic in a liner, to pass the time I carefully measured the wind pressure over different parts of the liner Some of the conclusions I obtained corresponded very closely with the diagrams the lecturer has shown

Mr W D DOUGLAS I should like to emphasize one point in connection with Major Wylie's paper It seems to me that this is a very important paper, for the following reason It has fallen to the lot of the aircraft engineer to be at the expense and trouble of initiating research on all sorts of problems, which will ultimately benefit other branches of engineering Methods of construction and of calculation which have been satisfactory in other branches of engineering will not do for aircraft, on account of the absolute necessity for saving of weight The advances in calculating the strength and compression of tubes, etc , have not yet been fully applied in several other spheres such as structural engineering, but Major Wylie's paper describes a case in which the advances made by aircraft research have been successfully applied to what is essentially a ground structure, and I therefore hope that this will be an historic occasion, and will initiate a move towards the utilisation of the specialised knowledge of the aircraft designer by other branches of engineering

This hangar structure is really built on the lines of an aeroplane It is a cable braced structure with aeroplane tubing for struts and has been designed, using the refined methods of structure calculation that are now available I am only afraid that when the hangar gets out to some of the far distant service stations there will come a demand from the C/O's for the supply of service aircraft which have been designed so that parts of the hangar structure can be used as replacements

I have had some connection with the observing of one of these experimental hangars erected at Farnborough, and I am inclined to think that the one which was erected at Martlesham is the more interesting of the two, because, in the first place, it is bigger, and therefore a more difficult engineering problem, and liable to experience greater total air loads in windy weather Secondly, the station at Martlesham is in a very exposed position on the east coast, and subject to greater wind velocities, and worse gales The best position available at Farnborough was exposed fairly well to the south and south-west, from which direction the winds mainly came

The hangar was erected by Messrs Ransomes, Sims and Jefferies, and to represent the worst conditions it was given very little attention except for general observation and replacement of such things as small ropes and lanyards Any cables which appeared to slack off were not, however, tensioned up As might be expected, one of the general features of the analysis of the results of tension measurements on some of the cables was, that in general the tension slacked off from the time of erection, fairly quickly at first, and more slowly later This effect was not of serious magnitude however Apart from this (as Major Wylie has mentioned), the snow which was experienced during the December before last, and which was of rather unusual severity all over the country, caused a very considerable rise of tension relatively, but the actual tensions were not in any way dangerous

There was a fair amount of change of tension due to moisture This was noticeable in fine or wet weather, when the canvas cover became thoroughly dry, and stretched, or wet, and shrunk

I am very interested in the remarks that Major Wylie makes on the tests of steel tubes We owe an enormous amount to his work in connection with the strength of thin tubes, and I for one have a great respect for this investigation in that direction I should like to ask him whether he thinks it necessary to take account of the bending of the tube in calculating the stresses he has quoted, particularly in the very thin walled tubes

Mr COPPERTHWAITE I do feel that this is an opportunity which I can take to express my admiration of the work Major Wylie has done both in regard to the hangar and other aeroplane structures I can appreciate this because I have worked in conjunction with him a great deal and I also know a certain amount of the processes which we went through with regard to this hangar as I had the privilege of seeing the designs and criticising them long before the structure was made and I was also able to see it during construction and in its completed stage

The one thing which surprises me is the very small alteration that was made in the design of the hangar from the original proposition put forward There was one point which Mr Douglas raised with regard to the position of the hangar at Farnborough I went and selected what I thought to be a good site as there was a slight drop in the ground, which would be diagonal across the hangar, of about 3 ft The ground was rough enough to prevent the base of the stanchions being on an even line I was not able to see the hangar put up but I saw it some months afterwards and found it had been erected some fifty yards away on a level piece of ground

I will conclude by congratulating Major Wylie on the very excellent piece of work and the very clever design

Mr PICKLES I am glad to have the opportunity of expressing my pleasure at hearing this paper

I think the framework may be regarded not so much as a building, as a piece of mechanism The mechanism is solely for erecting and supporting the canvas in position When the hangar is no longer required the mechanism can be dismantled and the canvas taken away

The design is bold in conception, and great skill and ingenuity has been shown in the execution

As the lecturer proceeded, the successful features of design, construction, and means for erection gave rise to a feeling of amazement I think, however, that my amazement cannot be compared with the astonishment of those unskilled R A F personnel referred to in the paper, when they found that the structure they had erected actually stood up

Captain BURGESS This paper, quite naturally, invites a comparison between the ordinary hangar built of bricks and steel, and the portable kind which is the subject of the paper

The brick built hangar, erected once only, is a permanent structure on one site, the portable hangar has to be erected and dismantled many times, and must be equally serviceable on many different sites and under varying climates

When the Air Ministry called for a mobile hangar for service with an expeditionary force, it stipulated that at one and the same time it should possess qualities of strength, lightness, flexibility, rigidity, small bulk, ease of erection, and be weather-proof in all climates These requirements were to apply not only to the framework but equally to the covers stretched over it To take only two of these, flexibility and rigidity, as the author points out, these are opposing qualities But they are not to be satisfied at the expense of strength or of bulk, so that we are able to appreciate the fact that the problem of making a structure to answer all qualities at once, was not too easy of solution

To carry the comparison with the permanent hangar one step further, we could consider the entire life of a portable hangar Take from this period, those times in which the hangar is in use, or in store awaiting use , then close up the remaining times, in which the hangar is in transport, is being erected, or dismantled, then this portion of its life, shews it as a piece of mechanism, the moving parts of which must be accurately proportioned to the work to be performed

It is interesting to enquire in how large a measure the requirement of " ease of erection " affected the design The hangar is covered with canvas sheets The merest acquaintance with large sheets of canvas such as yacht sails, will inform anyone, that they are not easy things to handle even in a light wind, and with the best arrangement of tackle The covers of this hangar must be very much larger than yacht sails The hangar is 35 ft high, one can see that to get large sheets of canvas over a light structure, at such a height would call for the service of expert seamen

Major Wylie's method is to secure all these large sheets to his structure before it is erected as a building Of course, this makes it a much easier task because the men need not leave the ground to do it But, on the other hand, it must have entailed very close attention to the moving parts, the mechanism which extends the structure to its working and service condition, and by inference, the calculations for flexibility and rigidity were, presumably, always under revision

The selection of canvas as the material for covers does not, of course, indicate any new departure This seems to follow naturally as a result of the stipulations as to bulk, weight, and portability Any more rigid material would certainly have entailed a higher figure in each case

When canvas is properly treated by proofing it has a long life in actual service Further, when it is made up into sheets of the requisite sizes, by men who are skilled in the art of sail making, it is soundly weather-proof We have yet to know of any material which satisfies the requirements so well

There is another item in this paper which seems worthy of comment and that is its bulk It is not stated which of the Air Ministry's requirements is considered the most important, but it is certain that for a mobile hangar, bulk ranks of equal importance with any other In mechanised warfare, transport becomes assured, but never of unlimited capacity It must be an axiom for the designer to make his hangar to fit the transport rather than to leave it to " Transport " to fit the hangar One would have like the author to have shewn the hangar in transport However, from the description, it is evident that under this heading the author's design shews as great, if not greater advance, than under other headings, over the previous designs for hangars which have been carried out The device of packing all the parts into cases of equal size, is one which must score very largely in its favour That each case is capable of being transported, by other than mechanised transport, to otherwise inaccessible parts is an advantage which only the Air Force can properly appreciate The use of these cases to anchor the framework when erected is ingenious

The table of weights given by the author is illuminating It would have been still more so if he had been able to give a comparison with so-called portable hangars which we knew during the war, those of the Bessonneau and Hervieu type The transport of the bulky framework of these wood framed hangars was a matter which so far taxed the energies and patience of transport officers as to earn them an unenviable reputation To get such material out to Basra, and then carry them out into the desert called for expenditure of much supervision time, and money When these had been overcome it was found that the breakages and losses by transport aided by climatic conditions played such havoc with wooden structures that about four frames had to be dissected to complete one serviceable hangar

With such experience to guide him Major Wylie very properly discards the use of wood altogether The use of steel tubes for the principal members is a departure which seems to be completely justified There may have been some hesitation in the combination of steel members with canvas , but by considering the behaviour of each material at one and the same time, so as to avoid on the one hand, sharp surfaces when in contact with canvas, and on the other hand designing the covers in such a way that undue stresses do not result to the framework, a happy result has been obtained

Mr Hancock I should like to ask the lecturer if he can give us any idea of the cost of these hangars as compared with the cost of the other standard hangars

Major WYLIE'S Reply to the Discussion

I wish to thank the gentlemen who have attended this paper and particularly those who have contributed to the discussion Mr Douglas asked what precautions were taken to prevent circular tubes from ovalling when subjected to " Bend Test " The answer is that the tube is thrust into a circular hole having the same diameter as the tube and this holsd the tube circular at the point of maximum bending The remainder of a tube of ordinary proportions does not sensibly oval under bending forces The thinnest solid drawn tubes that can be made have a thickness of about one-hundredth theirdiameter and such tubes do become perceptibly oval under large bending forces, but the effect on deflection is not more than two or three per cent

Tubes are used in aircraft construction having a diameter as much as 300 times their thickness These tubes are built up from high tensile steel grip and are reinforced by rings to restrict their tendency to become oval

Mr Pickles must have been speaking with inspired knowledge when he expressed his appreciation of the surprise of the R A F that these hangars should have stood up At one aerodrome where a Bagdad hangar had been standing for about eighteen months the Commanding Officer has quite changed his views on the safety of the hangar and would now be prepared to put valuable aeroplanes into it For reasons connected with its situation and not with its safety the aeroplanes in this hangar at present are those which have not realised the expectations of their designers

Captain Burgess mentioned a type of hangar which was designed to be inflated or blown up This was the most exacting of the demands made on the anchorage —to ensure that the hangar would " stay put "

With regard to the question of cost it is not known at present what the hangar will eventually cost The experimental hangars have cost considerably more than standard wooden hangars of the same size but this was inevitable from the fact that they were experimental When these steel hangars are made in quantities they should not be costly The quantity of steel in their structure is only one-seventh to one-tenth of the steel used in standard types of construction There is nothing excessively expensive about the material– it is not more than four or five times the cost of structural steel sections, and most of the parts are repetition parts and the parts can be assembled easily and rapidly When the hangars get beyond the experimental stage they should be the cheapest buildings of their size procurable

The canvas covering is an expensive item One might think that a cloth covering would be less costly than one of corrugated sheeting but this is not so However, corrugated iron is much too heavy and clumsy for a portable structure and canvas is therefore necessary

The CHAIRMAN It is now my very pleasant duty to ask you to accord Major Wylie a hearty vote of thanks for giving us this valuable paper

Mr HULBERT I think we all feel that the Chairman at our meetings fulfils a very important function, because the majority of the lecturers are so modest that they would never commence their lectures at all unless the Chairman asked them to do so We are therefore, very much indebted to Dr Thurston for kindly performing that necessary duty, and I ask you to give him your thanks

The votes of thanks were passed with acclamation, and the meeting closed

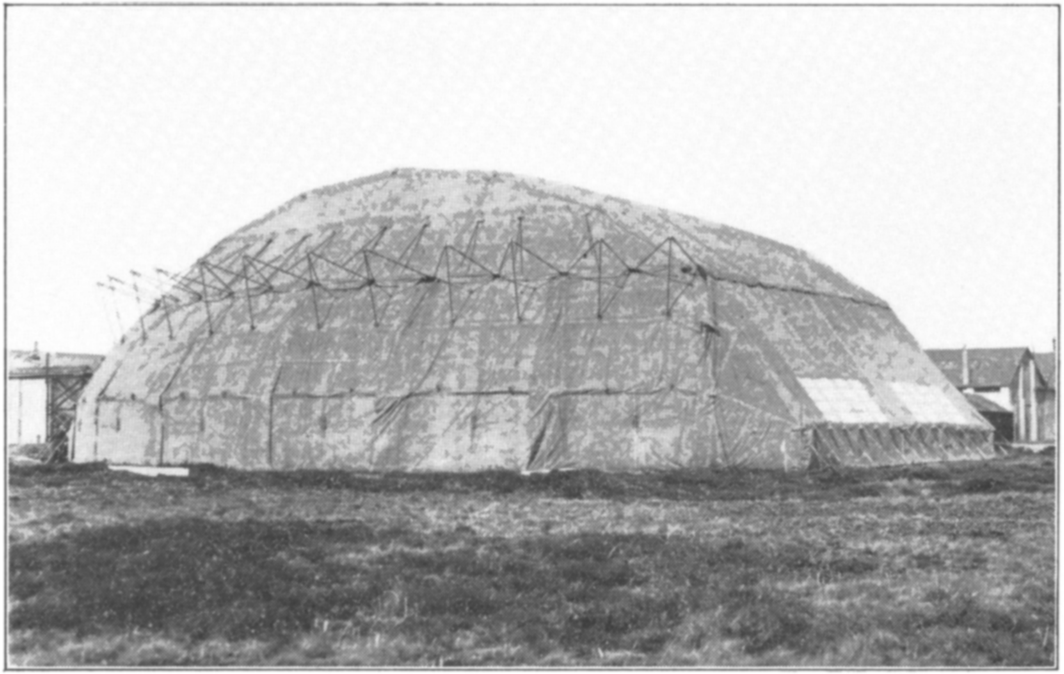


Plate I —View of Hangar—Doors closed

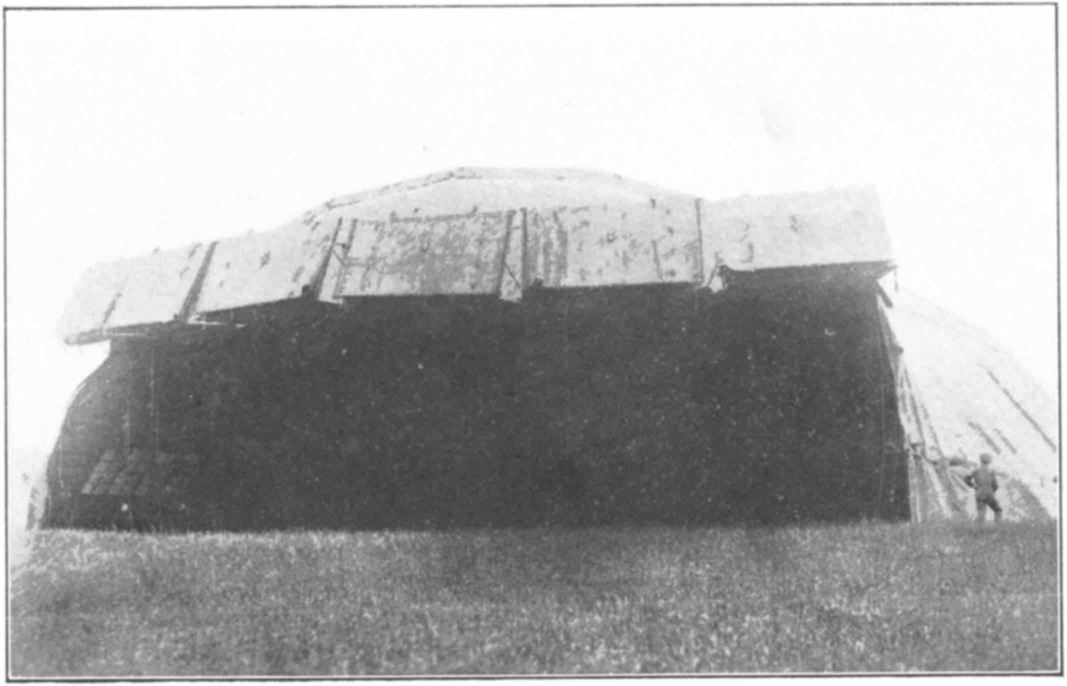


Plate 2 —View of Hangar—Doors open

Plate 3 —Flattened Framework

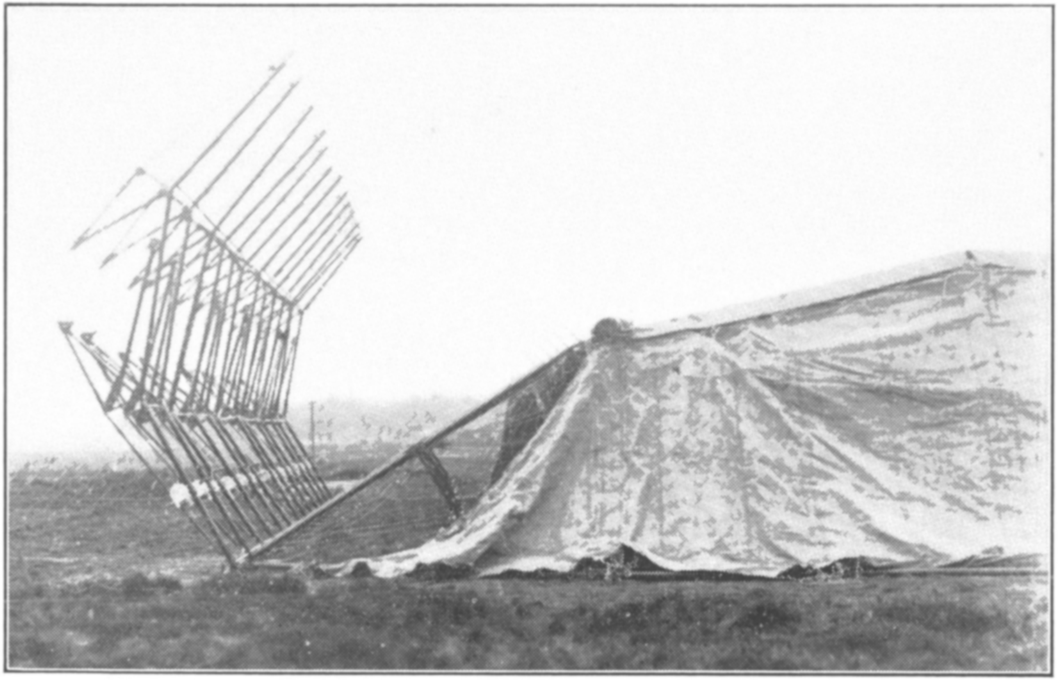


Plate 4 —End of the First Stage

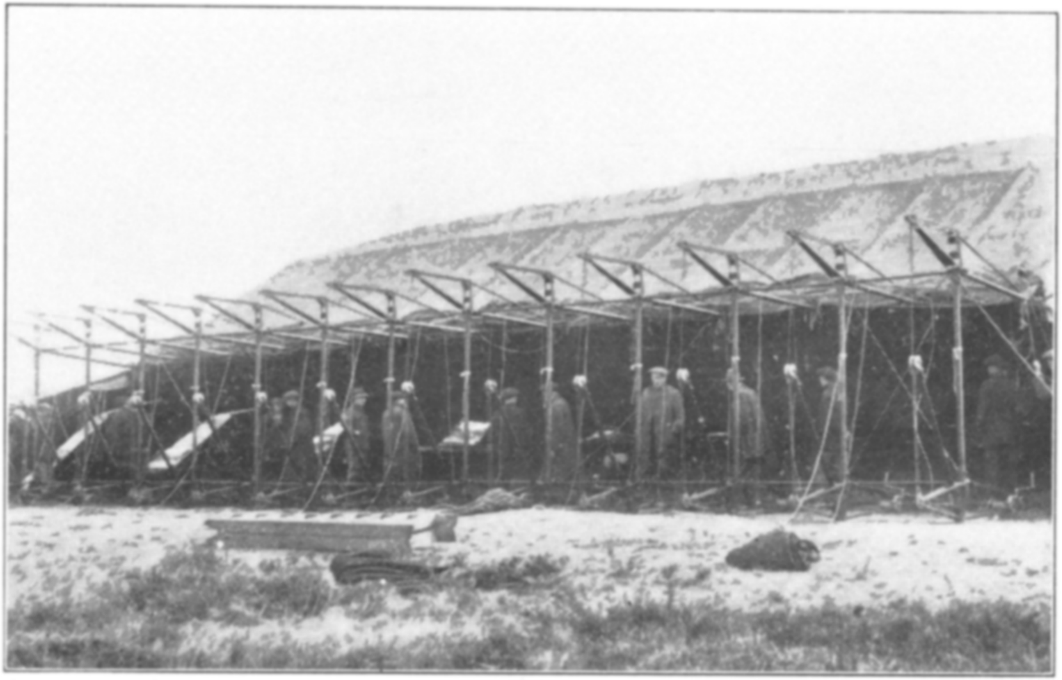


Plate 5—Covered Hangar—near side partly lifted

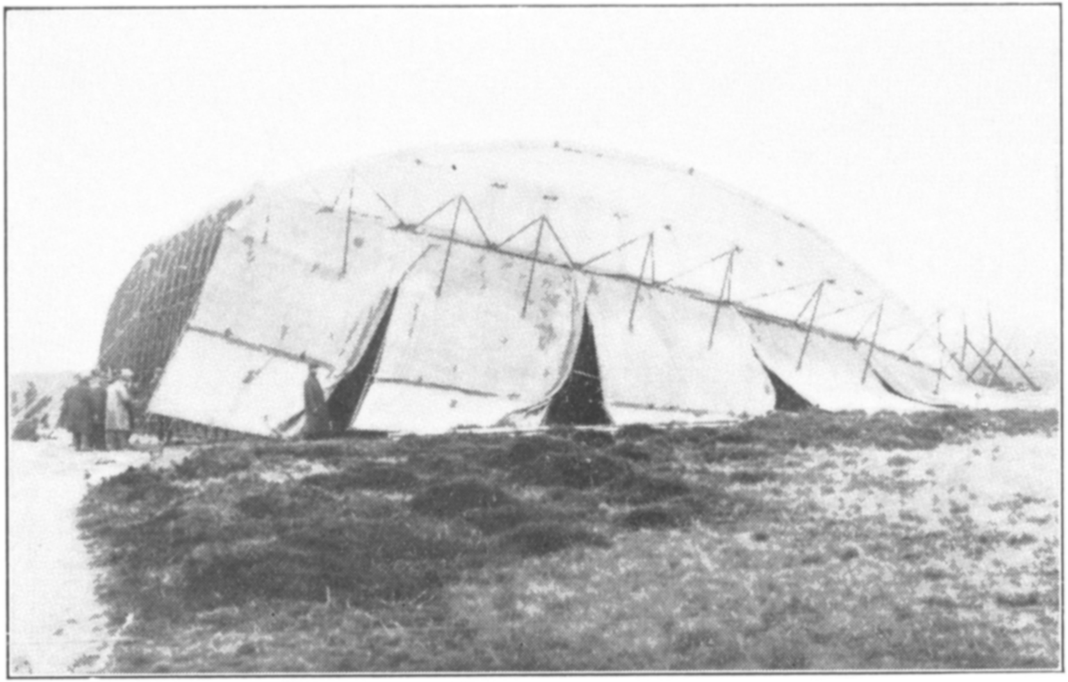


PLATE 6 —One Side lifted

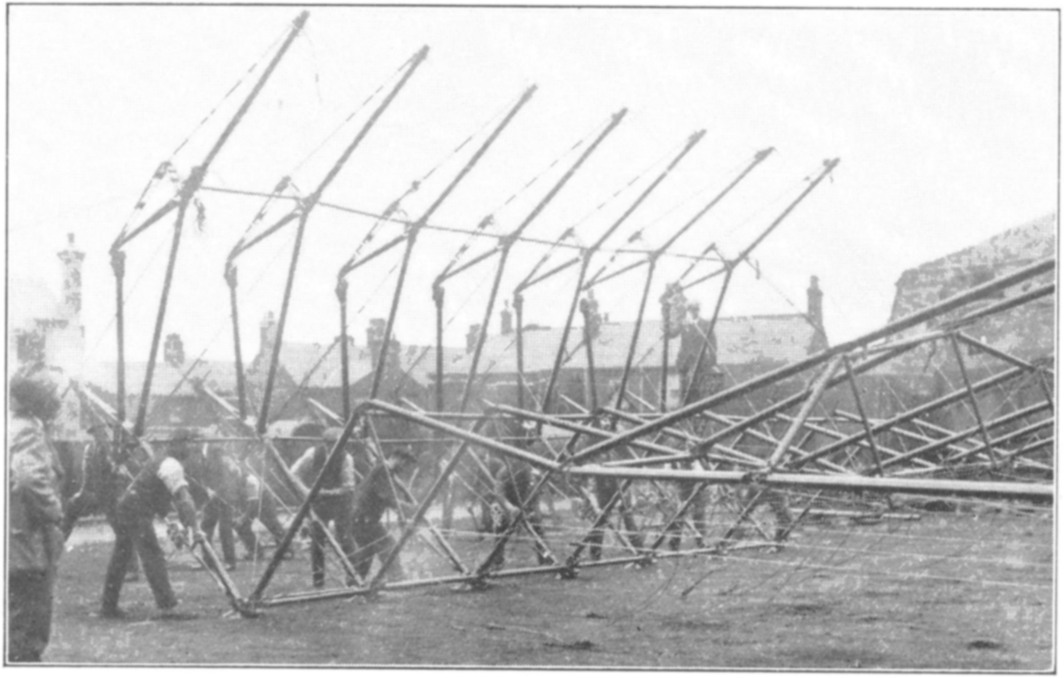


Plate 7 —Framework only Trial Arching

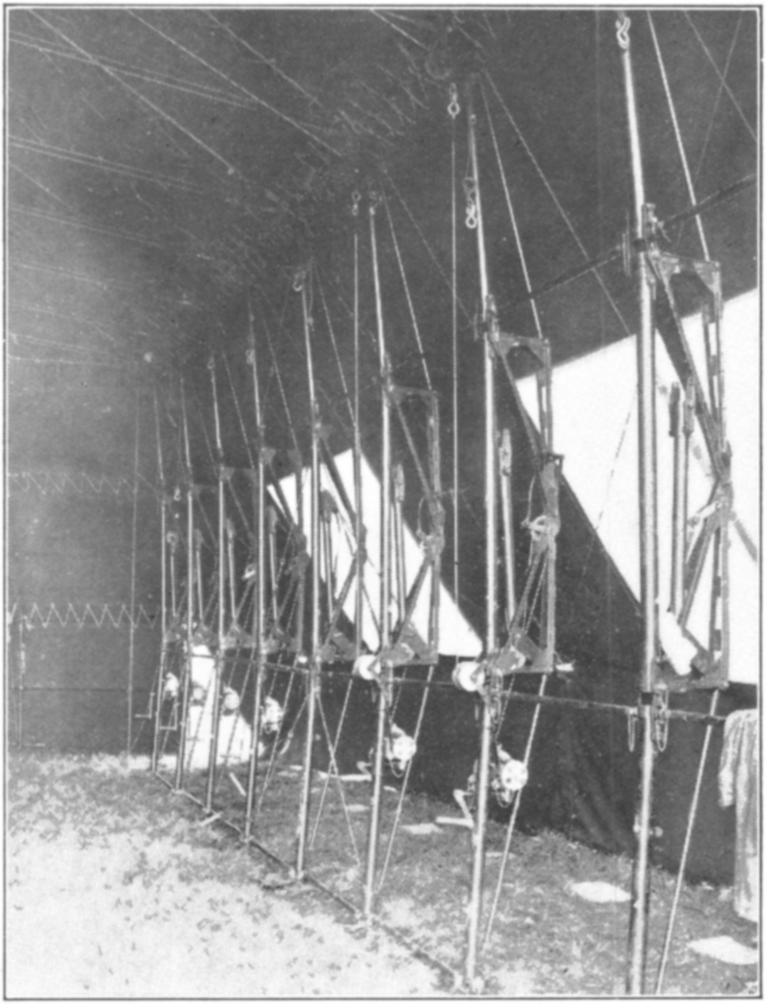
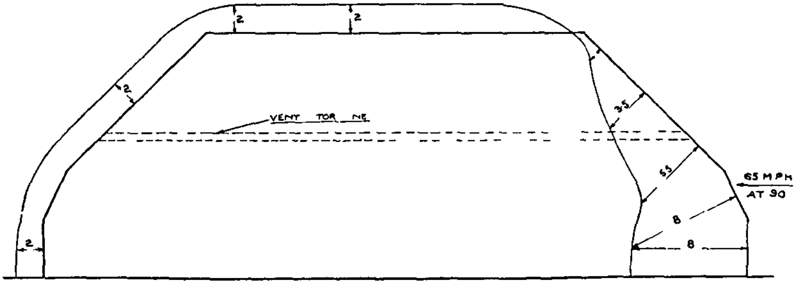
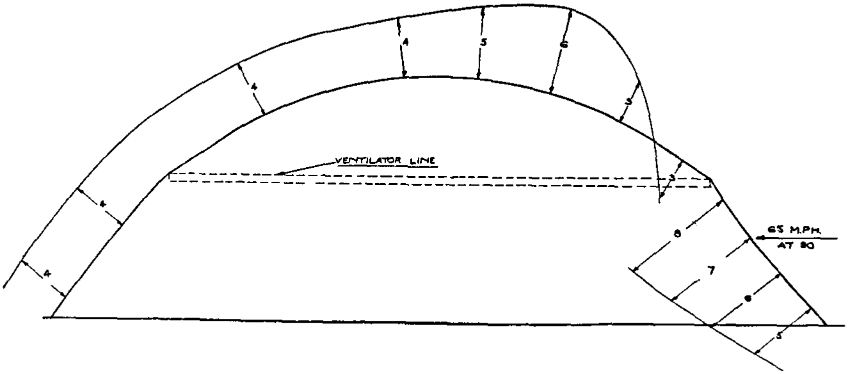


PLATE 8 —Inside view showing Stancheons

PLATE 9

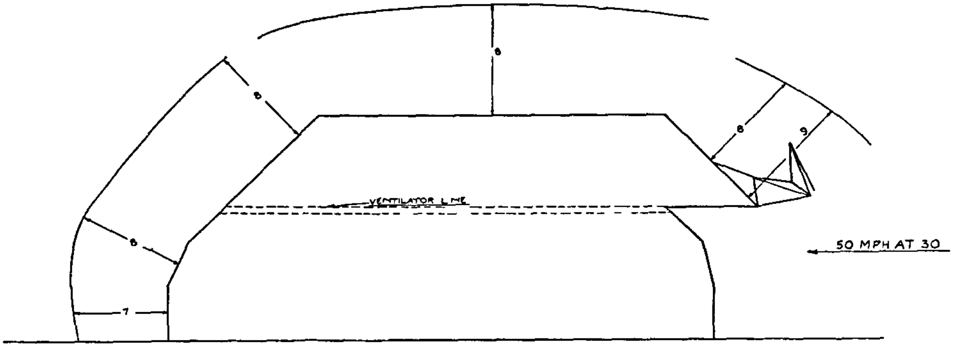


Centre Section, Wind fair on end or Section 20-ft from Windward Eaves Wind, 30° to side Ventilators at Eaves 65 m p h Wind Load Factor = I Pressure in lbs /sq ft

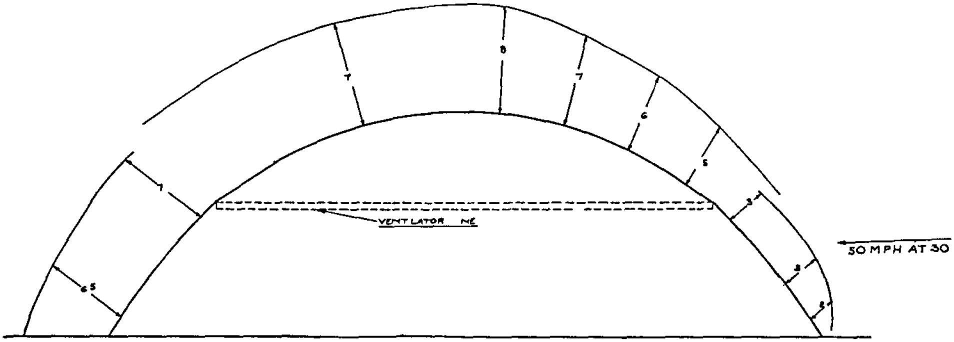


Wind 65 m p h at 90° to side Gable closed Ventilators closed (Internal Press 1 atmos) Pressures in lbs /sq ft

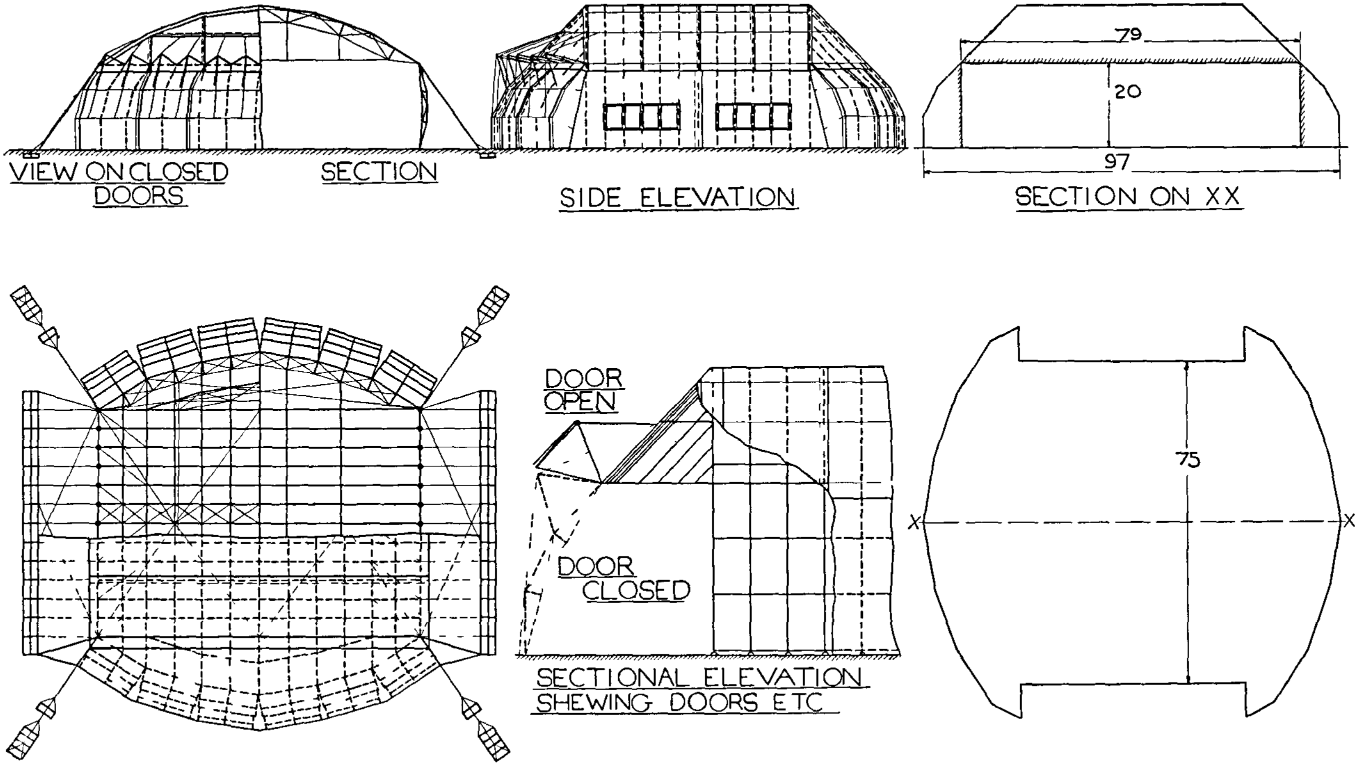
PLATE 10



Wind 50 m p h at 30° to side Gable and Vents open Pressures in lbs /sq ft

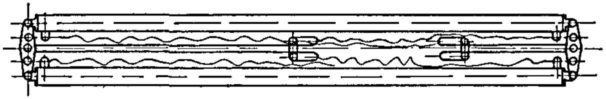


Wind 50 m p h at 30° to side Pressures in lbs /sq ft

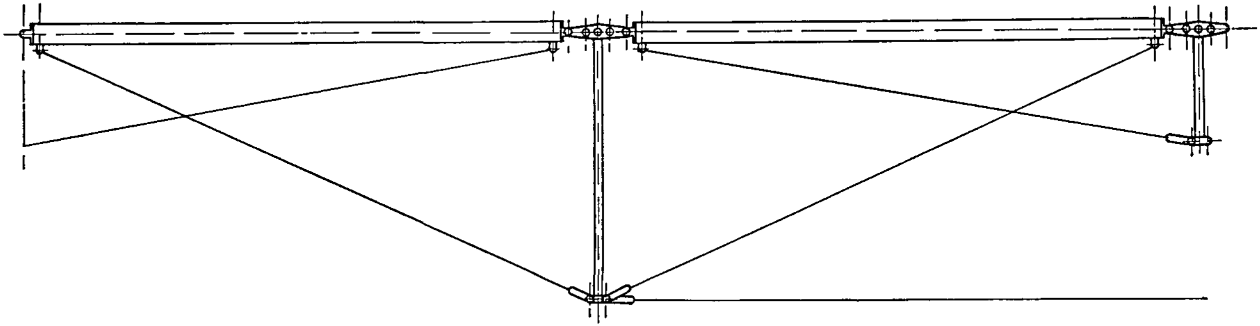


GENERAL ARRANGEMENT

FIG II



—TRUSS UNIT FOLDED FOR TRANSPORT—



—TRUSS UNIT EXTENDED—

PLATE 12

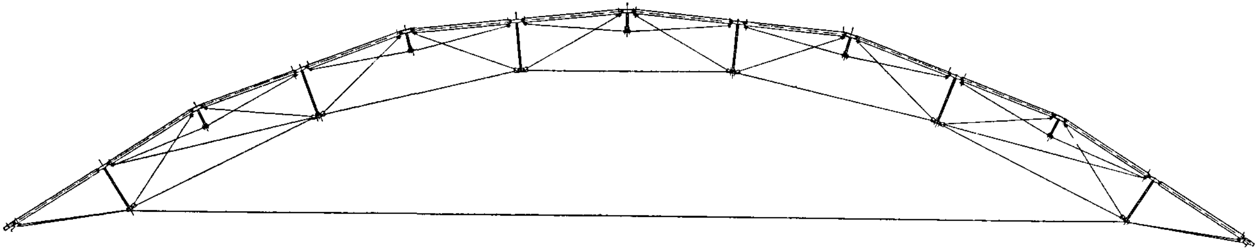


PLATE 13 —Complete Truss

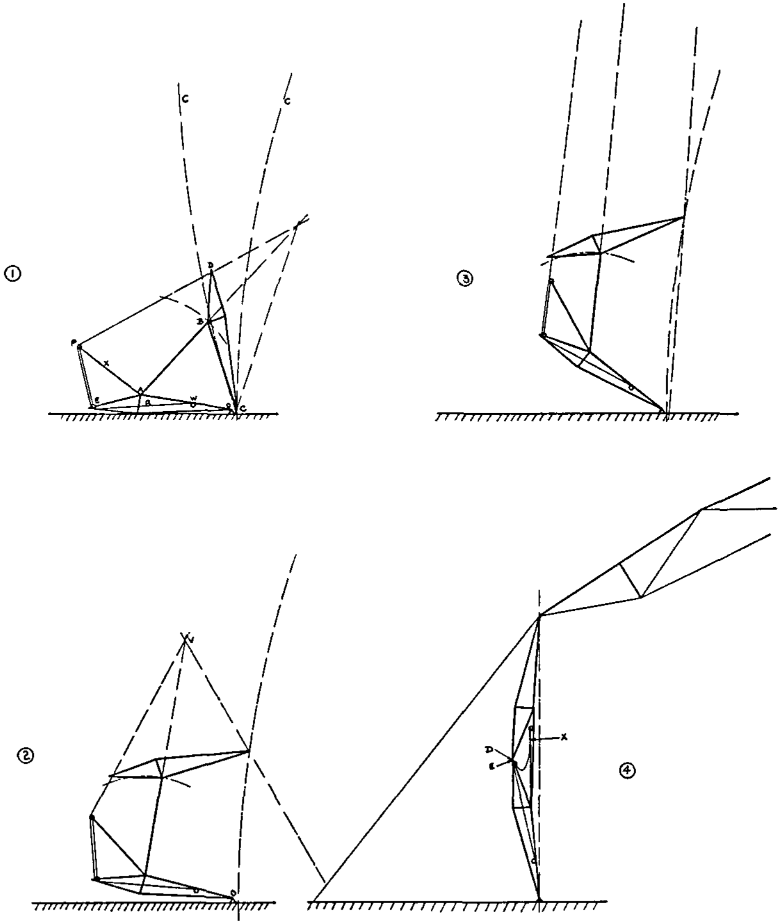


PLATE 14 —Operation of Stancheon

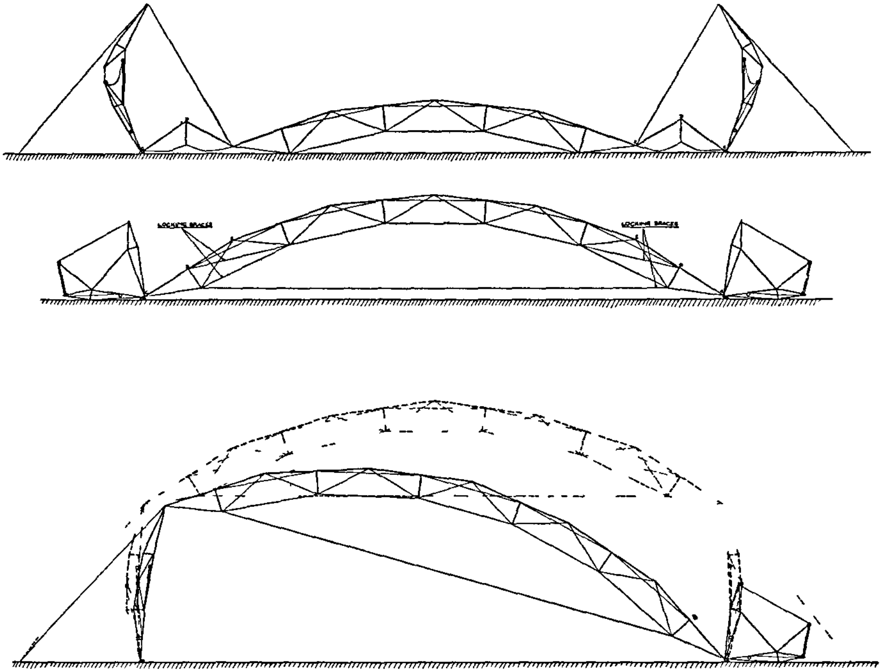


PLATE 15 —Operations of Arching and Raising Roof

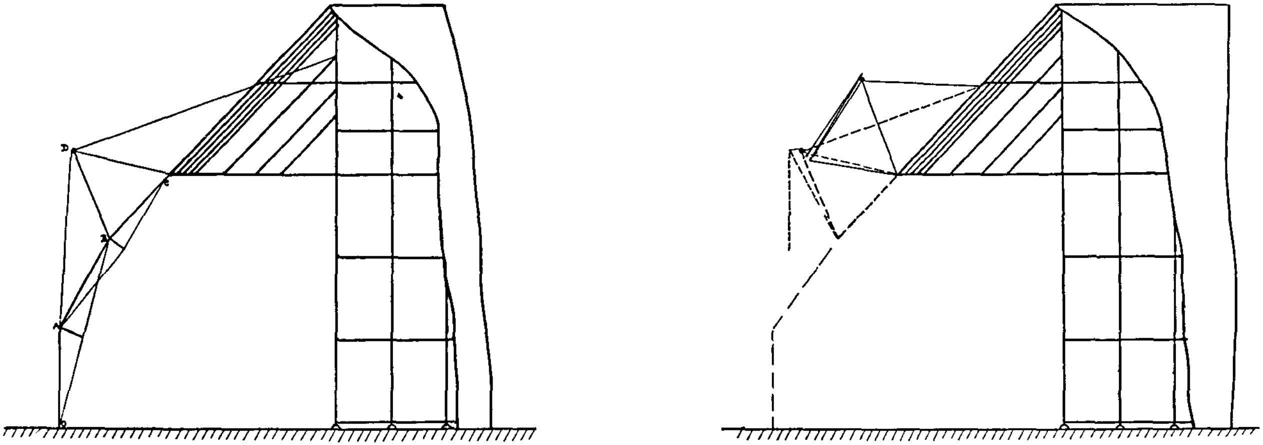
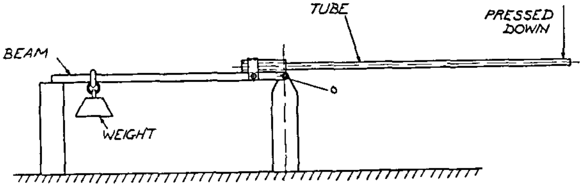


Plate 16 —Operation of Doors



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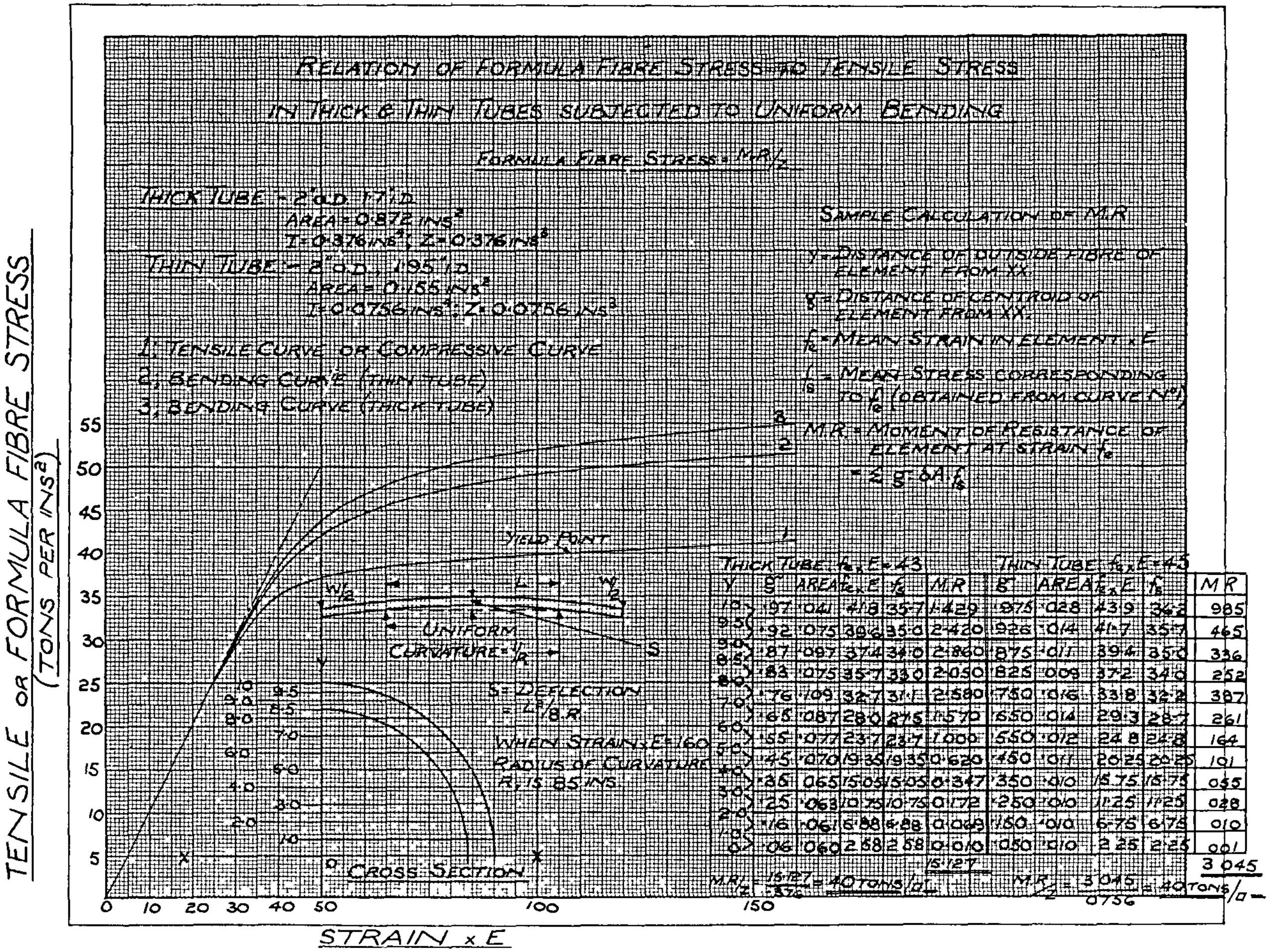

	THICK TUBE $f_e \times E = 43$					THIN TUBE $f_e \times E = 45$				
Y	g	AREA	$f_e \times E$	f_s	M.R	g	AREA	$f_e \times E$	f_s	M R
10 9·5	·97	·041	41·8	35·7	1·429	·975	·028	43·9	36·2	985
9·5 9·0	·92	·075	39·6	35·0	2·420	·926	·014	41·7	35·7	465
9·0 8·5	·87	·097	37·4	34·0	2·860	·875	·011	39·4	35·0	336
8·5 8·0	·83	·075	35·7	33·0	2·050	·825	·009	37·2	34·0	252
8·0 7·0	·76	·109	32·7	31·1	2·580	·750	·016	33·8	32·2	387
7·0 6·0	·65	·087	28·0	27·5	1·570	·650	·014	29·3	28·7	261
6·0 5·0	·55	·077	23·7	23·7	1·000	·550	·012	24·8	24·8	164
5·0 4·0	·45	·070	19·35	19·35	0·620	·450	·011	20·25	20·25	101
4·0 3·0	·35	·065	15·05	15·05	0·347	·350	·010	15·75	15·75	055
3·0 2·0	·25	·063	10·75	10·75	0·172	·250	·010	11·25	11·25	028
2·0 1·0	·16	·061	6·88	6·88	0·069	·150	·010	6·75	6·75	010
1·0 0	·06	·060	2·58	2·58	0·010	·050	·010	2·25	2·25	001
					15·127					3 045

$M.R/Z = \frac{15{\cdot}127}{{\cdot}376} = 40$ TONS/□"

$M.R/Z = \frac{3{\cdot}045}{{\cdot}0756} = 40$ TONS/□"

FIG 18

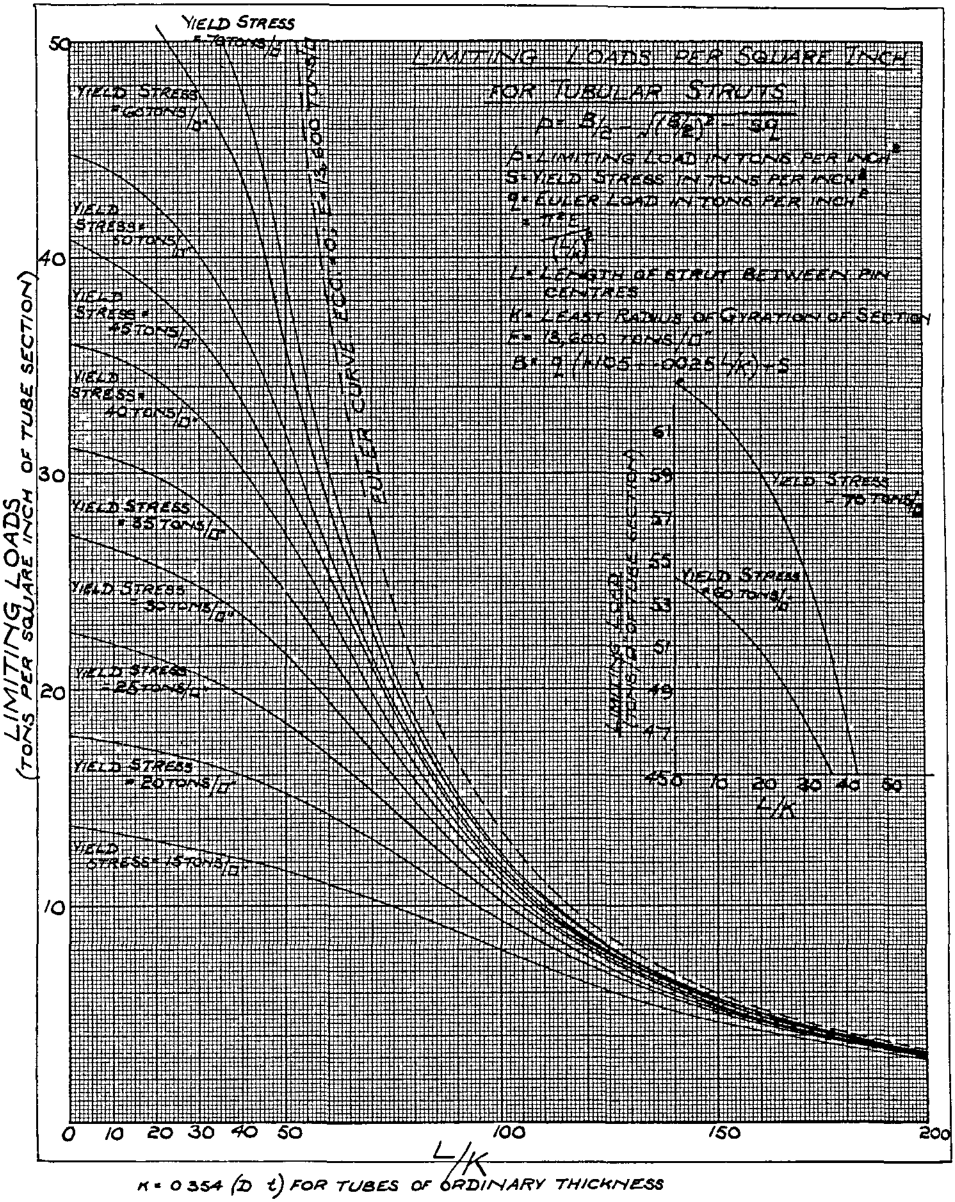
LIMITING LOADS PER SQUARE INCH FOR TUBULAR STRUTS
p = B/2 − √((B/2)² − Sq)
p = LIMITING LOAD IN TONS PER INCH²
S = YIELD STRESS IN TONS PER INCH²
q = EULER LOAD IN TONS PER INCH² = π²E/(L/K)²
L = LENGTH OF STRUT BETWEEN PIN CENTRES
K = LEAST RADIUS OF GYRATION OF SECTION
E = 13,600 TONS/□"
B = q(1·05 − ·0025 L/K) + S
YIELD STRESS = 70 TONS/□"
YIELD STRESS = 60 TONS/□"
YIELD STRESS = 50 TONS/□"
YIELD STRESS = 45 TONS/□"
YIELD STRESS = 40 TONS/□"
YIELD STRESS = 35 TONS/□"
YIELD STRESS = 30 TONS/□"
YIELD STRESS = 25 TONS/□"
YIELD STRESS = 20 TONS/□"
YIELD STRESS = 15 TONS/□"
EULER CURVE ECC.y = 0, E = 13,600 TONS/□"
LIMITING LOADS (TONS PER SQUARE INCH OF TUBE SECTION)
50
40
30
20
10
0
10
20
30
40
50
100
150
200
L/K
LIMITING LOAD (TONS PER SQ. INCH OF TUBE SECTION)
61
59
57
55
53
51
49
47
45
0
10
20
30
40
50
L/K
K = 0·354 (D t) FOR TUBES OF ORDINARY THICKNESS

FIG 19