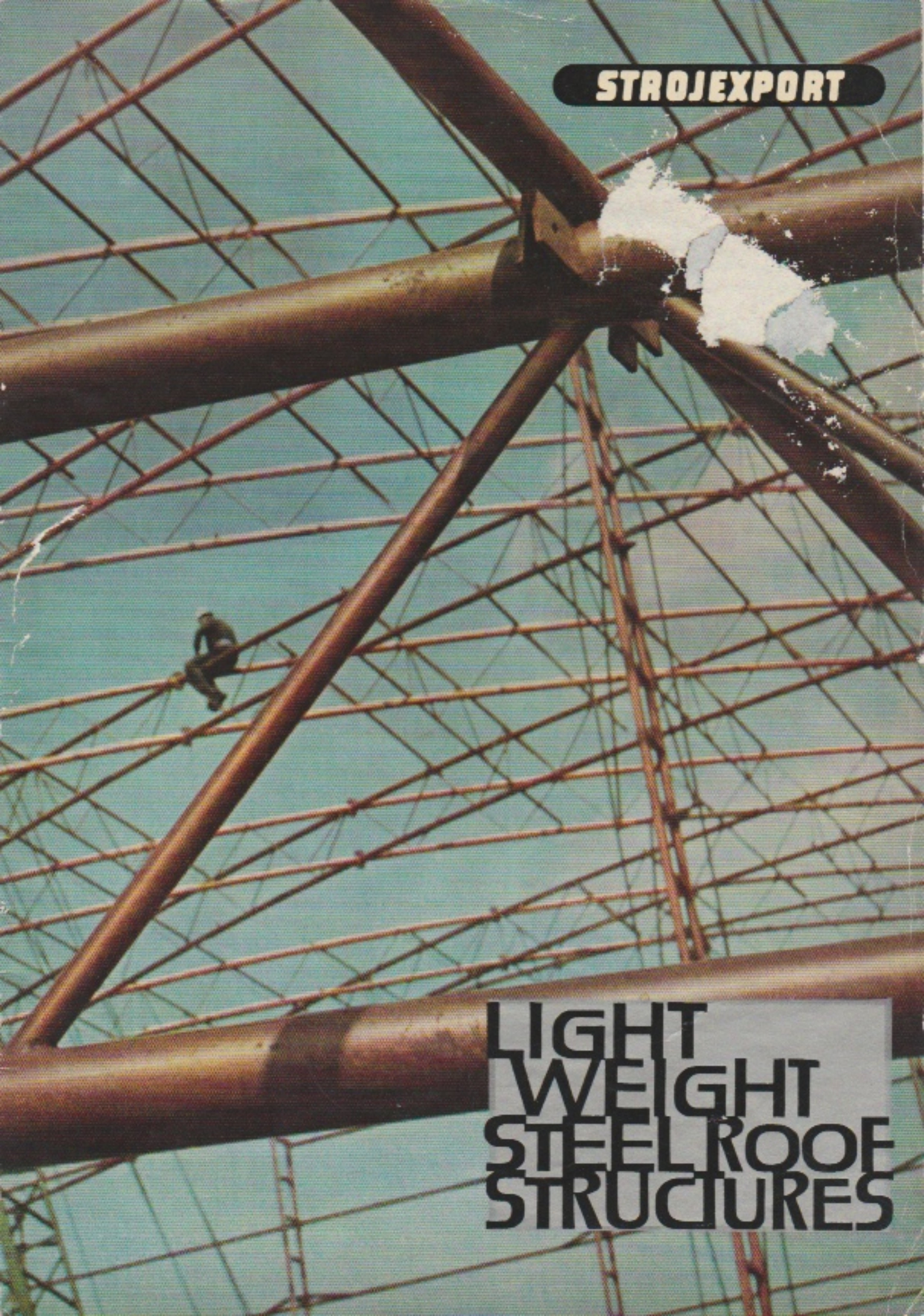
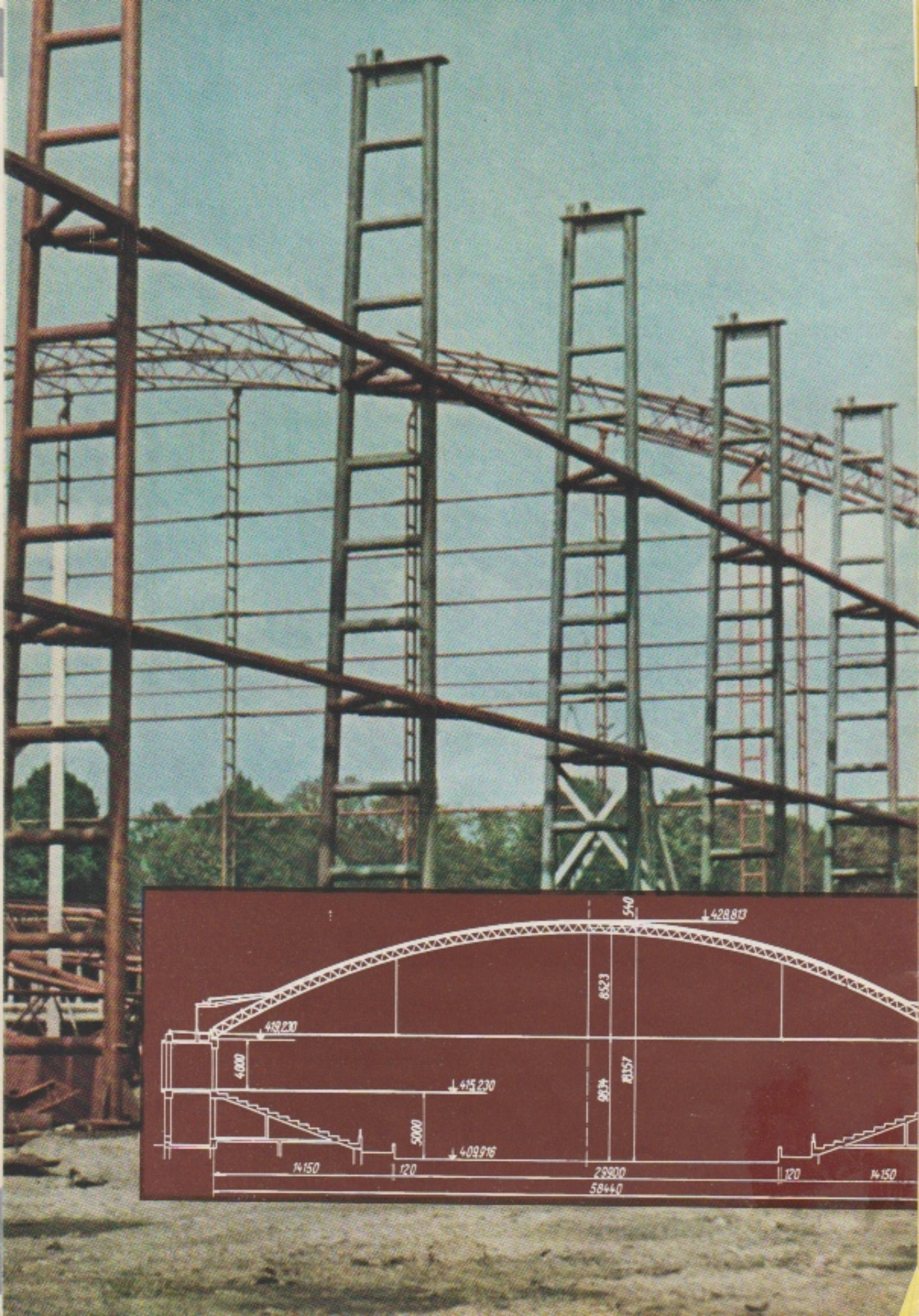


STROJEXPORT

LIGHT WEIGHT STEEL ROOF STRUCTURES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Light-weight Steel Roof Structures for Large Span Buildings

By Ing Josef Zeman

The design of roofs of the most varied public, industrial or other special purpose buildings, such as hangars, large capacity factories, sports and public halls, and similar buildings of large dimensions and further special features, is a frequent and noble, but also often very difficult task confronting the foremost specialists in this field — architects and engineers — all over the world. The requirement of large free spaces unobstructed by any supports is often accompanied by a whole number of other highly exacting requirements, which always include **a highly progressive architectural design and a structural design guaranteeing the minimum material requirements and the maximum economy of the whole building.**

Thus engineers all over the world strive to create original designs satisfying the exacting requirements of their customers and the vast documentation of this branch of design affords a good survey of the standard of progress hitherto achieved.

Roofs of buildings of this type are of the most varied designs and are mostly influenced by architectural requirements. Even structural engineers, who seek the ways of the best utilization of the load bearing capacity of the given material, have to take the architectural viewpoint into account. Although this field of design has undergone many years of development, no universally suitable system has been devised. All over the world structural systems **of a pronounced modern** character — such as suspended roofs — are applied together with systems which **can be called "traditional " or "classical"**, such as various beam or truss structures.

This "classical" system has been applied recently, for example, in the design and construction of two important sports hall in Austria, viz. the municipal sports hall in Vienna and the winter sports hall built for the last Winter Olympic Games in Innsbruck, where the structural design was greatly influenced by architectural requirements (prismatic shape, straight lines, suspended ceiling, etc.). However, economic characteristics of structures of this type, particularly the steel requirements ranging about 100 kg of steel per 1 sq.m (20,5 lbs./sq.ft.) are not very favourable in spite of large spans.

A very frequent modern structural system used in buildings of this type are **suspended roofs** in which the main load bearing members consist of steel ropes generally subjected to tensile stresses. Structures of this type are considered most progressive today and are very popular, although they have — apart from their indubitable advantages — also some drawbacks, and although their economy, i.e. economy of the roof proper, is often more than offset by increased requirements imposed on their anchorage or the foundations of the building.

When quoting the low figures of specific steel requirements per unit of the roofed area, which are characteristic of these extremely light-weight structures, it is sometimes overlooked that material of equal structural value must be embedded, often in very large quantities, in the vertical supporting structures and in the foundations of the building to ensure safe balancing of tremendous anchorage forces of a generally horizontal character. Apart from this difficulties arise connected with the aesthetic side of suspended roof structures, which are often considerable.

In Czechoslovakia the main attention has been devoted to the development of structures of the so-called classical type, such as vaults and shells, which are, of course designed in the new, modern spirit, utilizing the spatial behaviour of the structure and the load bearing capacity of the material, while respecting aesthetic requirements of a progressive architectural effect.

Such is also the character of two types of special steel roof structures for large span halls designed recently in Czechoslovakia and applied successfully in the construction of several buildings. They are new special structural systems with relatively diverse possibilities of utilization, noteworthy also for their extraordinarily effective utilization of the load-bearing material and consequently very low structural steel requirements.

Description of Structural Principle and Details of the New Systems, Their Design and Advantages.

Segmental Vault of Tubular Steel

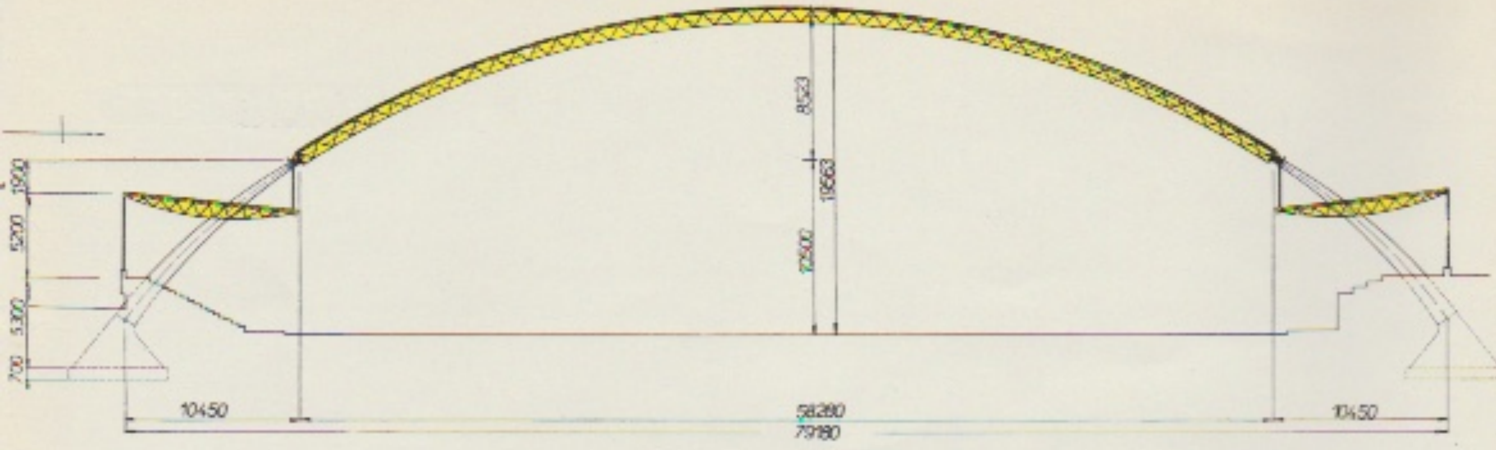
The first of these new types of large span roof structures is a special light-weight segmental vault, which represents, to a certain extent, an application of the principles of segmental structures mainly used for smaller spans in timber construction, to the specific properties of steel, which forms the basis of the design, details and selection of sections.

It was a great advantage for Czechoslovak designers that the Czechoslovak metallurgy produces a wide range of seamless steel tubes of various advantageous characteristics, which could be chosen as the best suitable structural material for the new structure. The Chomutov Tube Rolling Mills and Steel Works, producer of rolled steel materials, produced also the required material for two large span sports halls erected in Kladno (ČSSR) and in Berlin, which will be described further on.

The first tubular steel segmental vault roof structure had a span of 58.28 m (190'2") which satisfied best the required dimensions of a sports hall, sized in plan approximately 60 × 60 m (197 × 197 ft.). It was required that the building be roofed with a light weight structure without any intermediate supports and that the outer supports effected the foundations of the buildings with vertical reactions only. Apart from these structural requirements it was naturally required that the building had an effective architectural conception and that its overall appearance corresponded to the contemporary standards of economy. Therefore, a very slender vault structure was designed consisting of individual segments acting as two-hinge arches with tie rods.

The arrangement of principal load bearing arches in mutually crossing planes is actually the main deviation from the traditional conception of independent arches with perpendicular connecting members and means transition to a spatial structure whose behaviour is very near that of a shell. In the structural design this many times indeterminate structure was simply considered as a two-hinge arch with a tie rod. Although this conception did not allow full utilization of mutual spatial cooperation of all members of the structure, it was possible, nevertheless, to proportion very economically all load bearing members. It was also the arrangement of the structure and its individual members in the most suitable, almost ideal proportions that contributed to no small extent to the maximum economy of structural steel.

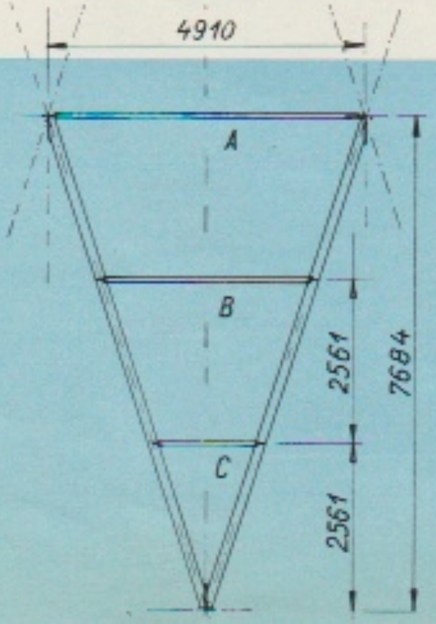
The mutual longitudinal distance of the individual arch ribs was selected at 4.91 m (16'1"), identical with the spacing of the bearings of the vault and with the spacing of the individual tie rods. This relatively small distance of the individual ribs and supports had the advantage of enabling the foundations and the supports to be very slender, too,

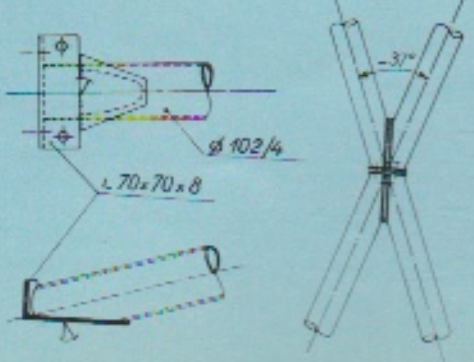


and to be designed to resist more uniform and lower stresses that it would be the case with a smaller number of supports spaced at larger distances.

The actual steel segmental two-hinge arches spanning 58.28 m (190'2") and rising 8.50 m (28') were designed as tubular steel trusses made of constant section seamless tubes throughout the whole span. In plan all main arches deviate from the transverse section plane by 18°34'34", crossing mutually under an angle of 37°. In these planes their span is 64.59 m (212'). The central line of the vault in the transverse plane is a circle of a radius of r=54.20 m (178') and a rise of 8.50 m (28'). The vertical planes of the individual arch ribs are inclined from this central line in a propeller manner, forming spatial spirals. This arrangement enabled all connections to be designed indentically and all arches to be assembled of absolutely identical repetitive components.

The whole vault built over a plan of 60×60 m (197'×197') required 100 components 8 m (26') long weighing 200 kg (440 lbs.), produced in the right-hand version, and the same number of identical components produced in the left-hand version. The identical design of all components of the structure was naturally a great asset in their production, because all components could be practically "prefabricated" by means of one single gadget. This circumstance influenced very favourably the accuracy of the individual components, which were produced with minimum tolerances — an essential prerequisite for the subsequent assembly of the structure with so many joints.

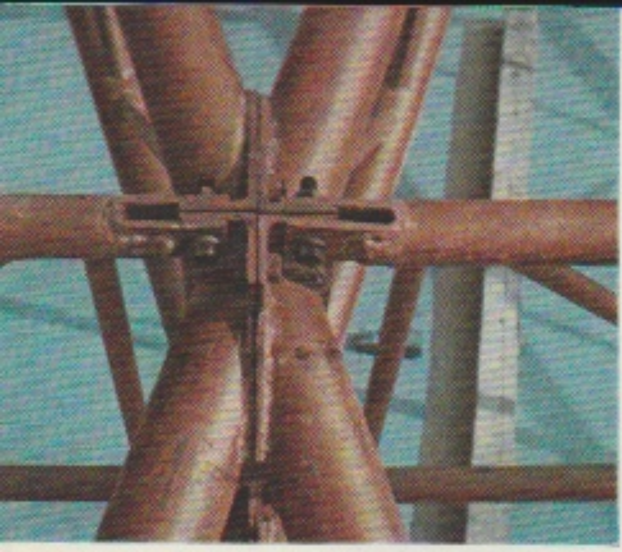




The described system of segmental arches was supplemented with another system of load bearing members spaced approximately at 2.50 m (8') and arranged in planes radially inclined from the vertical plane. These members acted primarily as purlins, stiffening simultaneously the whole structure and converting it into a spatial structural system. They were designed in the same way as the components of the main arches in the form of lightweight trusses 750 mm (2'6") high, both chords being of identical lengths.

The purlins were fastened to the main arches with a certain excentricity (approximately 10 cm (4") above the axis of the main ribs), as their upper chords were used for the fastening of the roofing material.

The most important detail, on the successful design of which the whole success of the structure depended, was the connection of the individual segments. The length of the individual prefabricated components being 8 m (26'), all four tubes were connected in one joint. This was achieved by means of a simple cross joint which connected four ends of the individual chords provided with welded steel angles for this purpose. The individual ends were butt-jointed which ensured a reliable transfer of the prevailing compressive stresses. Connecting elements consisted



of 8 light duty M 16 bolts in every joint which simultaneously connected the chords of the purlins. For the transfer of major tensile loads which may appear because of the bending moments due to theoretical wind or snow load or due to forces acting during the assembly of the structure, it is possible to use half the number of the 10 K high strength bolts which can impart to the contact surfaces the required prestress affording a reserve of strength to counter tensile stresses.

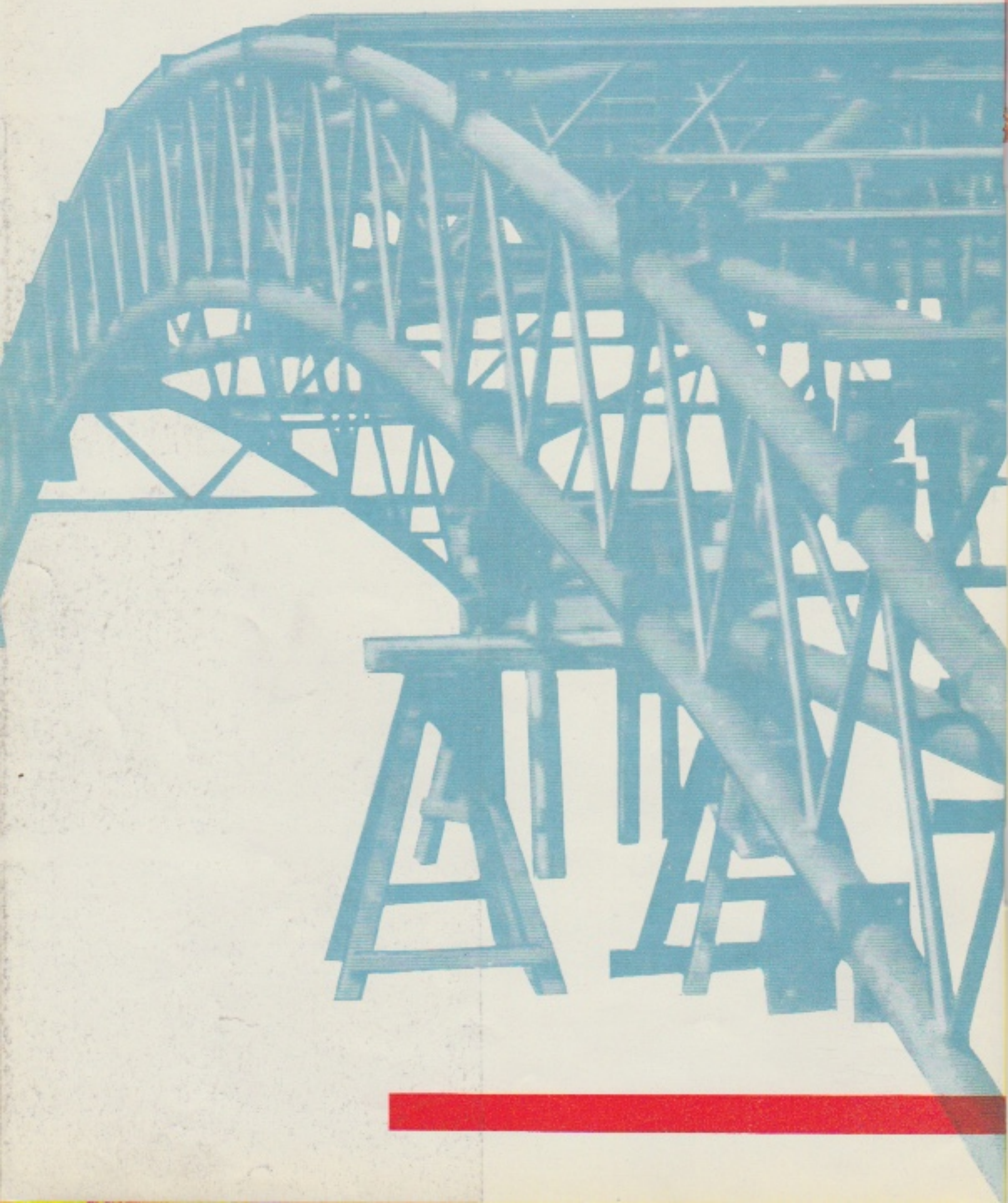
On its circumference the vault structure was supported by a plurality of light-weight supports and provided with tie-rods countering the horizontal reaction (design without tie-rods is possible, as will be shown by further examples). The bearings and consequently also the tie-rods were spaced at a relatively short distance of 4.91 m (16'1"). Apart from their structural function the tie-rods can be utilized also for other purposes. In sports halls, where it is necessary to place the lighting fixtures as closely to the playground as possible (e.g. in winter sports stadiums) the tie-rods can be utilized for the suspension of the respective lighting fixtures at a favourable distance from the ice surface, thus increasing the effectiveness of illumination and reducing the required power input. Although the individual tie-rods were spaced at a relatively small distance, they did not mar the effect of the completed structures and enhanced, particularly with evening lighting, the light-weight effect of the vault above them.

In concluding the description of this particular structure it is necessary to mention its advantages in respect of production and assembly.

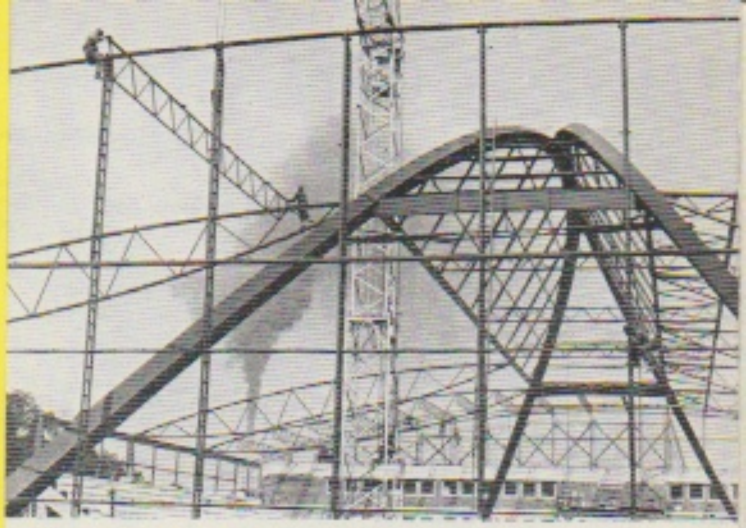
Although steel structures are generally believed to favour straight, plate members with perpendicular joints, the production of the afore described segmental structure in the workshops of the Chomutov Tube Rolling Mills and Steel Works was not connected with any difficulties. On the contrary the large number of identical members greatly enhanced their series production. This circumstance is best testified to by the high accuracy and the minimum tolerances achieved in the production of the individual mutually interchangeable components supplied by the producer to the site.

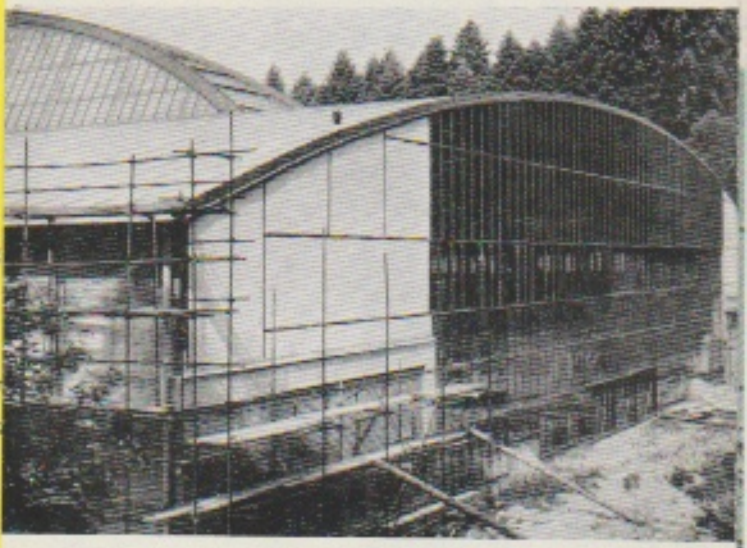
These advantages manifested themselves very favourably also in the transport of the individual components, which lent themselves easily to stacking, required little area both on the railway wagons and on storage sites, were very light in weight and could be practically handled manually.

The assembly of the whole structure was very easy and required only the simplest light-duty assembly mechanisms, such as truck cranes, which could easily lift and place aggregate parts of some 3—5 tons in weight, easily assembled of the individual prefabricated components on the ground by unskilled workers.



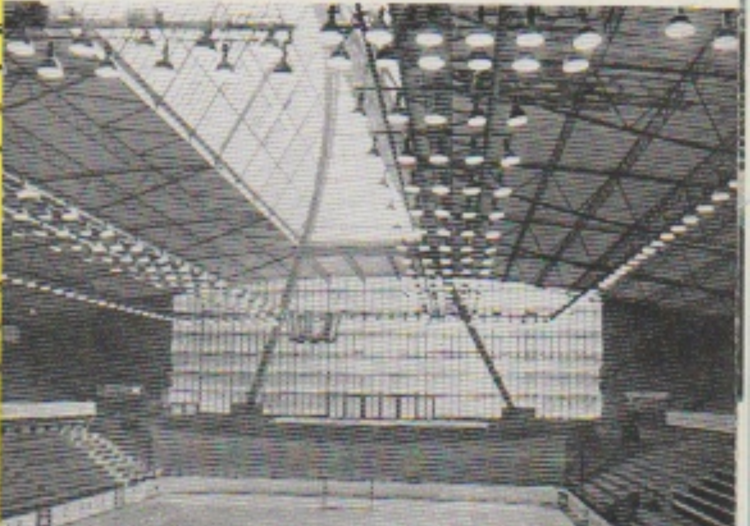
Two Inclined Steel Arches as a Load-Bearing Structure and a Roof Light of a Large-Size Hall





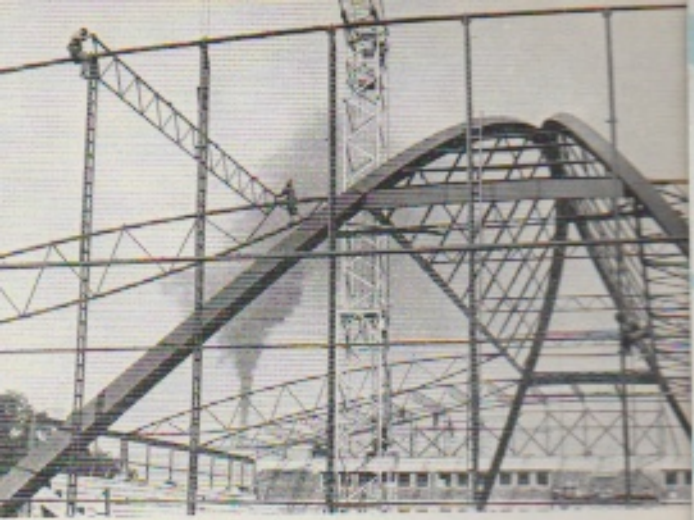
Of entirely different character is another special load bearing
and erected in Czechoslovakia.

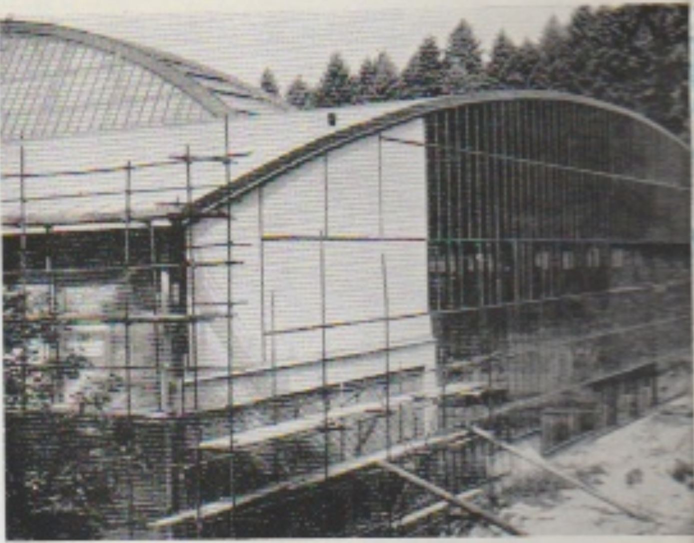
The designer was confronted with the exacting task of roofir
able structure requiring no intermediate supports and creatin
nomic as well as aesthetic requirements.

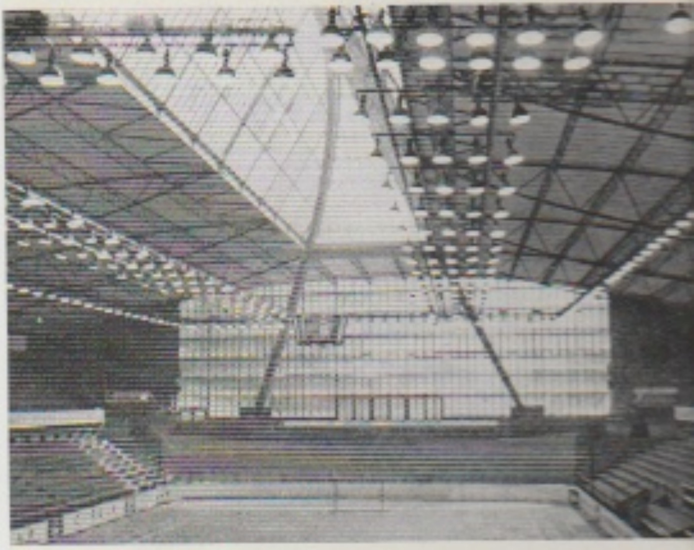


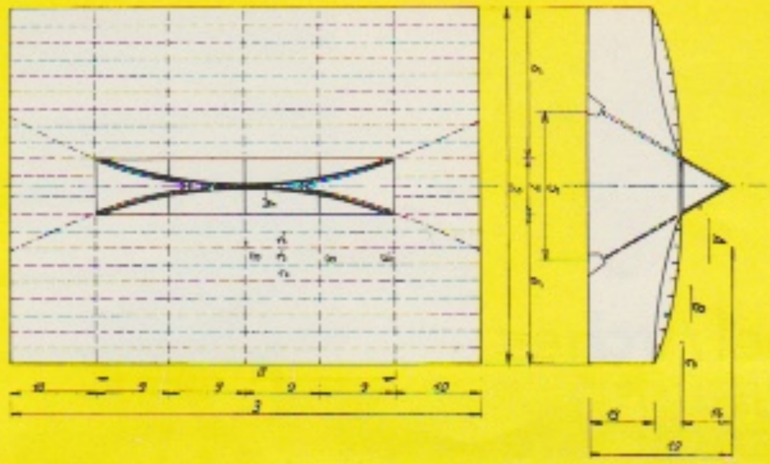
The foundation conditions along both longitudinal sides not be
load bearing structure in the form of two inclined steel arches
by footings situated in the corners of both transverse gable v
i.e. 279') than would have been the case with conventional tr
turally very effective shape it could be proportioned very ec
teristics of structural steel requirements.

Apart from the above mentioned, more or less structural rea
ture which would fulfil not only its load bearing function, but v
ing and enhance its lighting, ventilation and acoustics. It is only
ing was duly taken into consideration.



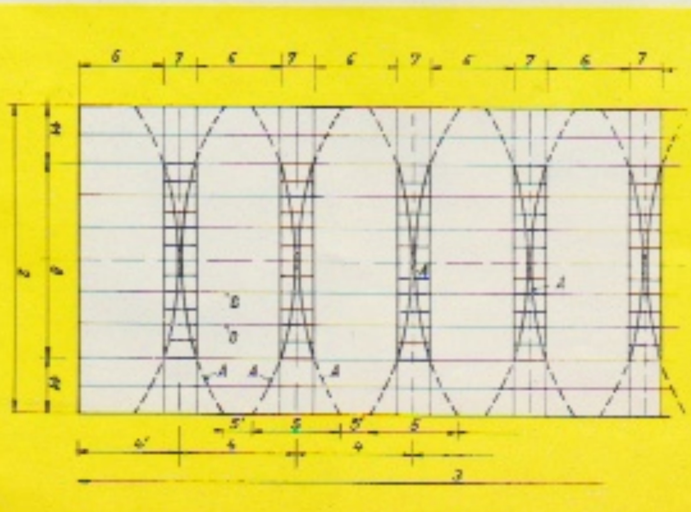


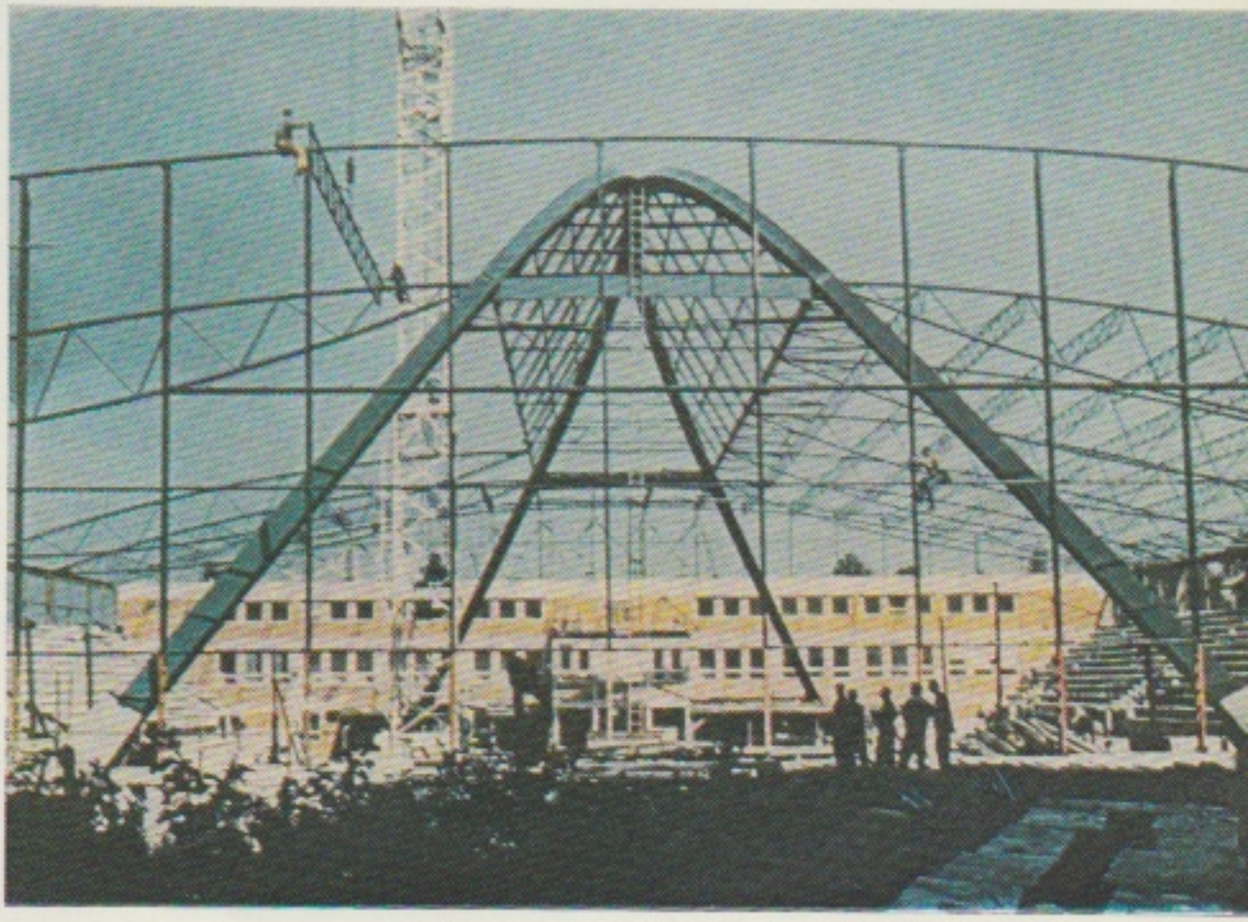




The principal characteristic feature of the design of the load bearing structure are two steel arches of very slender dimensions arranged in two inclined planes intersecting in a line passing through the apex of the roof structure. In their respective planes inclined at an angle of 30° from the vertical, both arches act as plane structures, their central line being a circle of two different diameters. Along their whole span they have a constant section — a welded box section only 750 mm (2'6") high which is only 1/113 of the span of 85 m (279'). This slenderness, which is considerable for a main load bearing member, is enabled in the first place by both arches being held in position by pin jointed trusses which prevent the arches from buckling. Great slenderness of both arches is also enhanced by their intersection in the apex, so that from the structural point of view it is possible to consider them as one spatial girder.

From the whole span of 85 m (279') the arches protrude above the roof level along 54 m (177') of their central parts, forming there an enormous roof light 10 m (33') wide, which is utilized to advantage for effective daylight illumination of the interior of the hall as well as for ventilation purposes. With its shape the roof light divides also suitably the interior of the hall, enhancing its acoustics, and forms an interesting architectural feature of the building, particularly prominent in artificial light.





The above described main load bearing system is supplemented with further structural members of conventional design — roof trusses and purlins, forming — together with the inclined arches — a rigid roof structure covering a plan of 64 × 85 m (210'a 279').While both box girders were designed as fully enclosed boxes welded of sheet steel 10 mm (25/64") thick and standard size steel angles, the supplementary members were produced of the well-proven steel tubes which are the best material for trusses and purlins not only from the structural, but also aesthetic and corrosion-resistance points of view.

Experience Acquired with the Two Afore Described Types of Special Structures. Description of Erected Structures and Prepared Designs. Possibilities of Further Utilization.

Segmental Vault

a) Erected Structures

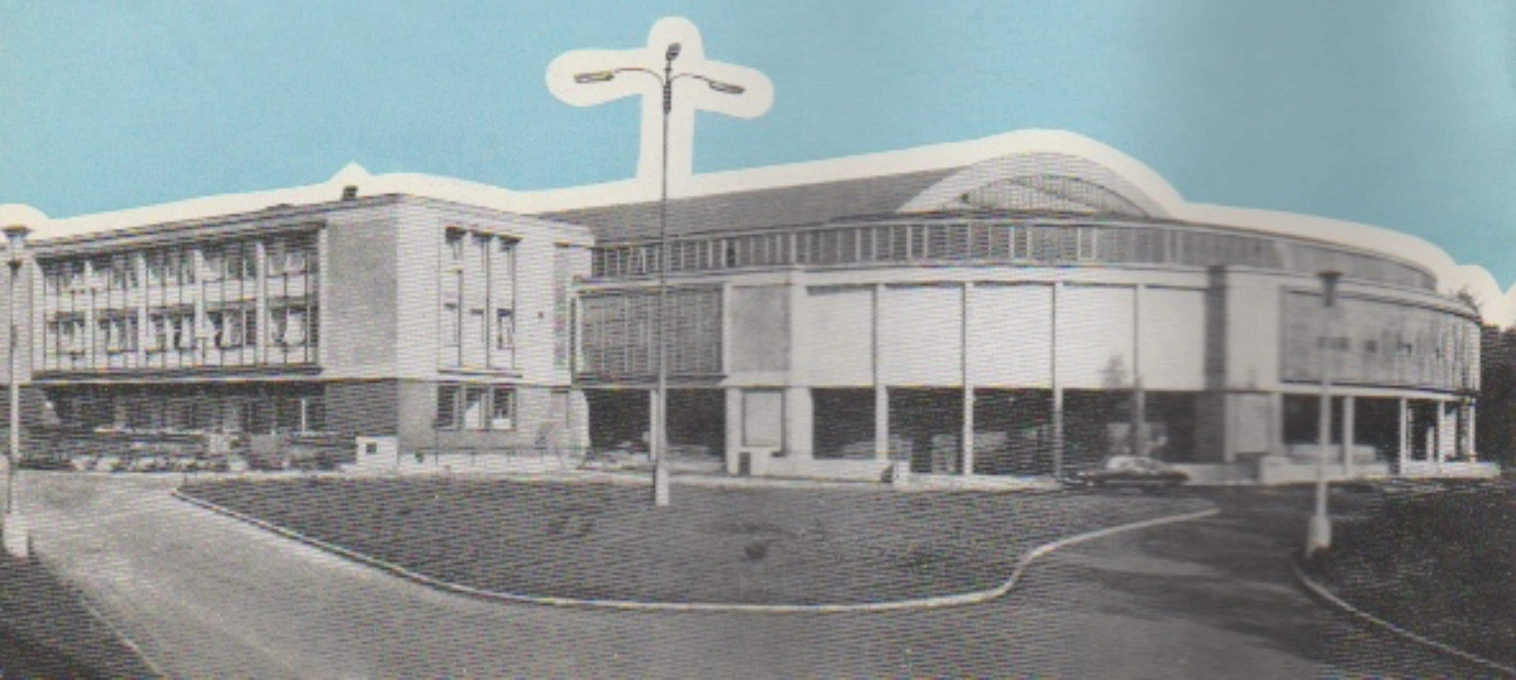
The described type of segmental vault structure spanning 58.28 m (190'2") was produced by the Chomutov Tube Rolling Mills and Steel Works and used in the construction of two sports halls, viz. the winter sports stadiums in Kladno and Berlin. Both structures have an identical vault span, but differ considerably in the individual details. It will not be without interest to describe them briefly.

Winter Sports Stadium in KLADNO

The first building to use the described segmental vault roof was the winter sports stadium in Kladno. Its plan, sized 60×60 m, is adjoined on both transverse sides by two semioval parts roofed conventionally with plate girders and rolled purlins. These two roof structures are suspended from plate girders bordering the segmental roof structure over the central area of the stadium and support also large glazed galbe walls ensuring daylight illumination of the interior of the hall.

The whole roof structure of an area of some 5,000 sq.m in plan is supported on its circumference by a slender reinforced concrete structure of grandstands and galleries which is loaded by the roof with generally vertical forces. Although the roof structure was originally designed for a load of 50 kg/sq.m, it was finally covered with the cheapest roofing material — corrugated sheet steel.

Economic evaluation of the structure with regard to structural steel requirements yielded very favourable results, given in the last part of this article.



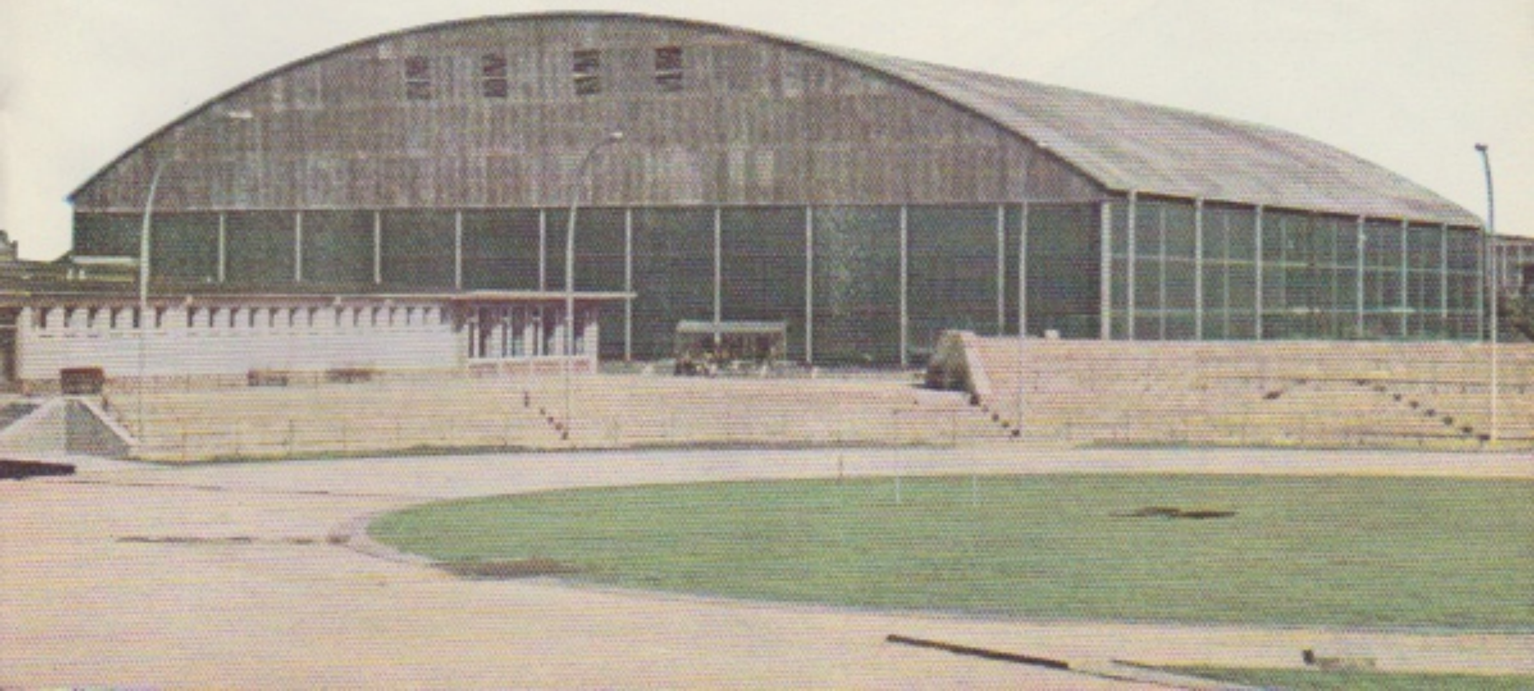
Sports Hall for DYNAMO Berlin

The Berlin Sports Hall was another building for which an analogous roof structure was selected, although large capacity buildings of this type rarely warrant a repetitive application of the same structural system. However, it was the very good experience acquired in the process of construction of the first stadium in Kladno and the extraordinarily progressive economic characteristics that led the prospective builder to select the same structure.
In this hall, although of a different planning conception, the main load bearing roof structure consisted again of a segmental vault of the same span as in the first case.

The hall is situated on a horizontal site, its architectural design stressing the simplicity of line without any major architectural decorative features. The light weight tubular steel structure is supplemented with modern materials, glass and plastics, which form the walls and roof of the building.

The tubular roof structure is supported along the longitudinal sides of the hall, some 9.0 m (30′) above the ground level, by slender columns made of tubular steel. The columns support fixed or moving bearings of the vault spaced at 4.91 m (16′1″) forming, together with horizontal spandrels, the structure of outside walls of the hall. The structure of gable walls is analogous. The whole hall is clad with special (type Copilit) glass plates inserted into the grooves in the spandrels. The cladding extends the whole height of the walls, from the ground level to an elevation of 9.0 m (30′). Above this elevation the gables are clad with corrugated polyester sheets which form also the roofing material. The transparent, slightly yellowish sheets are reinforced with glass fibres. The roofing material is laid on steel purlins spaced at 2.50 m (8′) and supplemented with further intermediate purlins to reduce the span of the roofing sheets and fastened to them in a conventional manner.

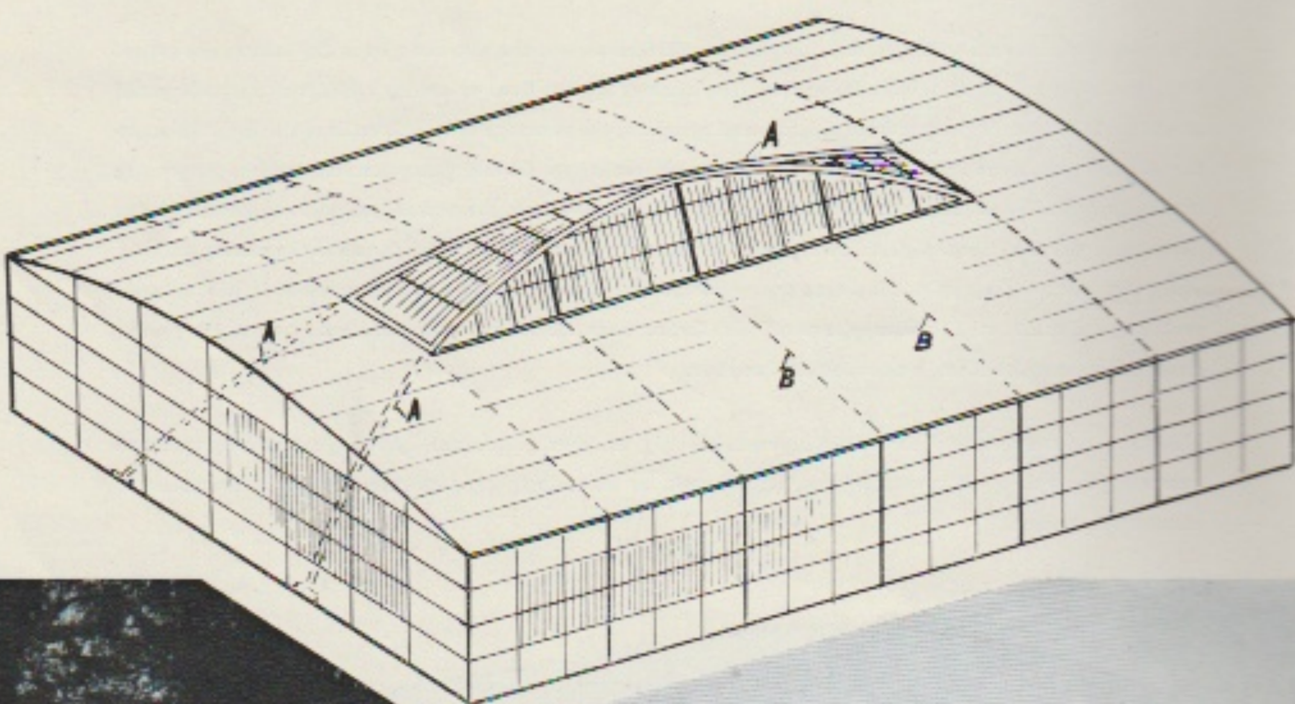
The whole structure made of three building materials only, viz. glass, plastics and light-weight steel, represents an interesting example of modern techniques, notable again for exceedingly low requirements of structural steel and economy in general.

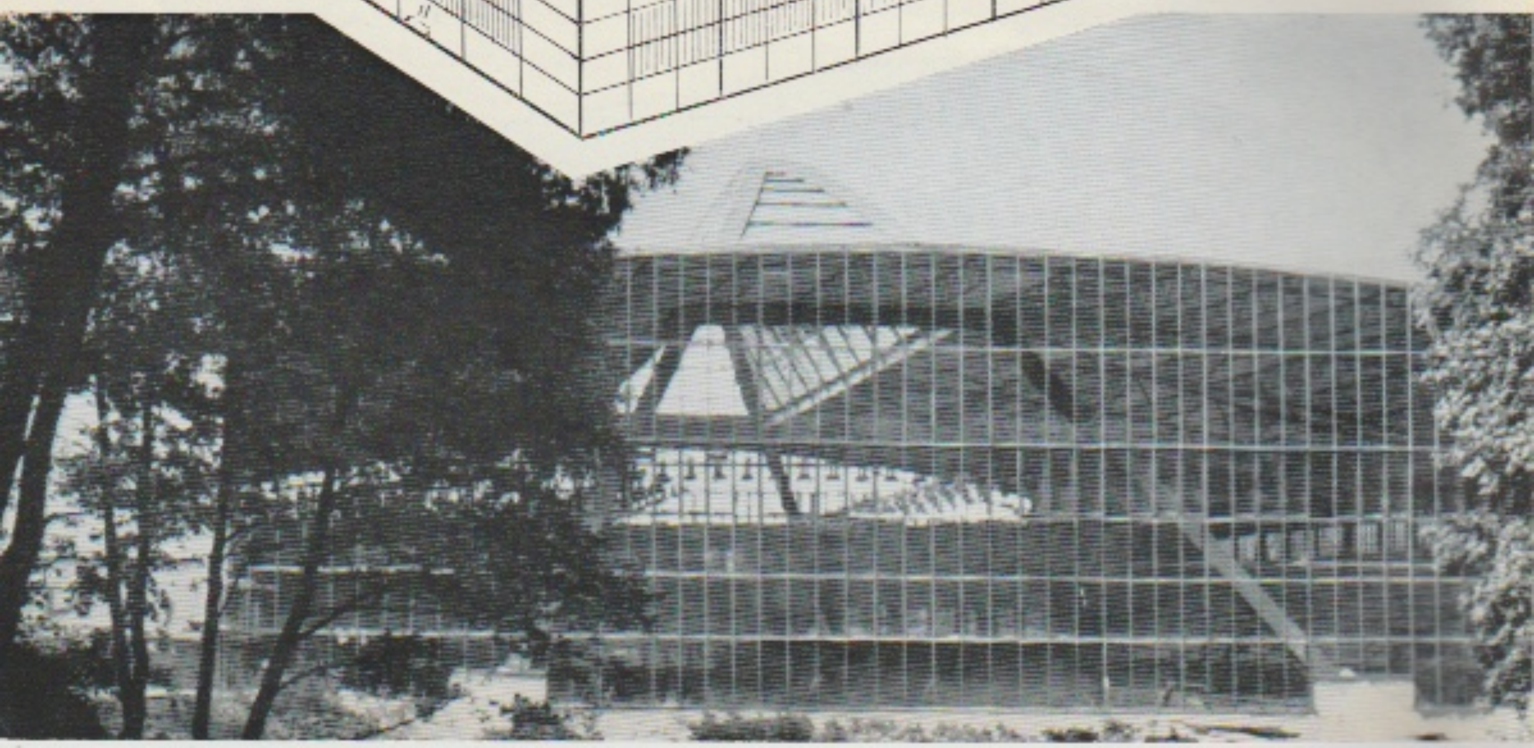


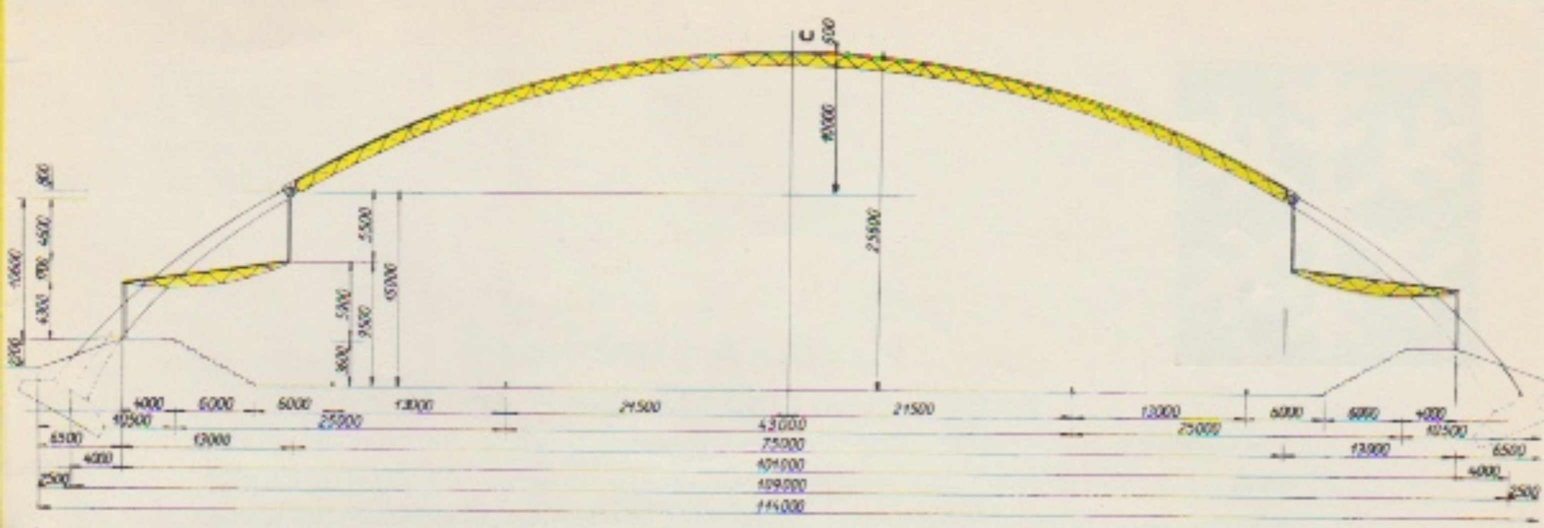
Inclined ARCHES

The afore described type of roof structure with two inclined arches has recently been erected in the well known industrial centre of Central Moravia, the town of footwear — Gottwaldov. The site presented particular favourable conditions for the application of this system, being situated in a valley, in the immediate vicinity of woods, in beautiful natural surroundings, with which the interior of the hall is closely and effectively connected by means of a fully glazed gable wall. The building has already proved its value at the time of the Handball World Championship when several matches were played in it. It attracted a certain amount of attention and was generally considered successful in the functional, aesthetic as well as economic respects.

Both all-welded box girders were produced by the Vitkovice Steel Works, the other parts of the roof structure were made of seamless steel tubes produced in the Chomutov Tube Rolling Mills and Steel Works according to the well-proven technology of tubular trusses without gusset plates. Tubular structures consist of ten lense-shaped trusses spanning 27.0 m which are best acceptable from the aesthetic point of view, being simultaneously advant-

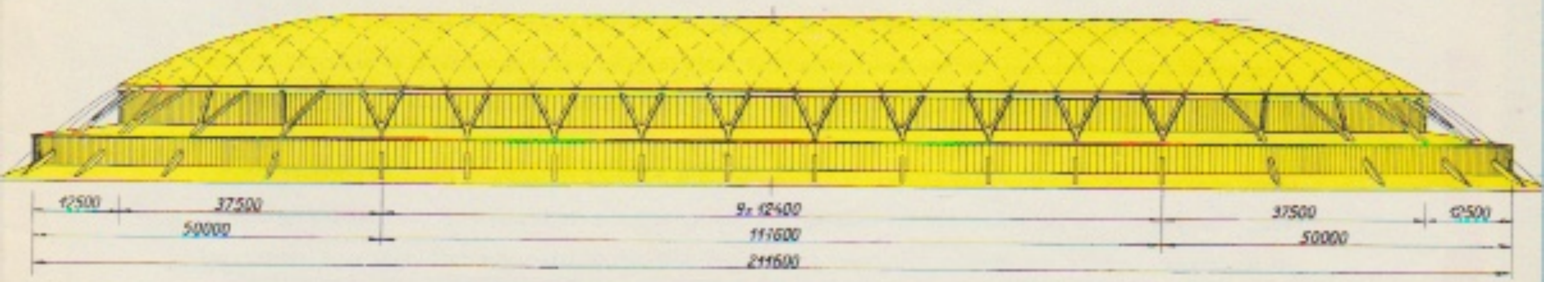






ageous also from the structural point of view, since they enable full utilization of the load-bearing material. The purlins are lattice structures with straight chords spanning 13.50 and 15.50 m (44' and 51') respectively. Also the wind bracing was ensured by steel tubes.

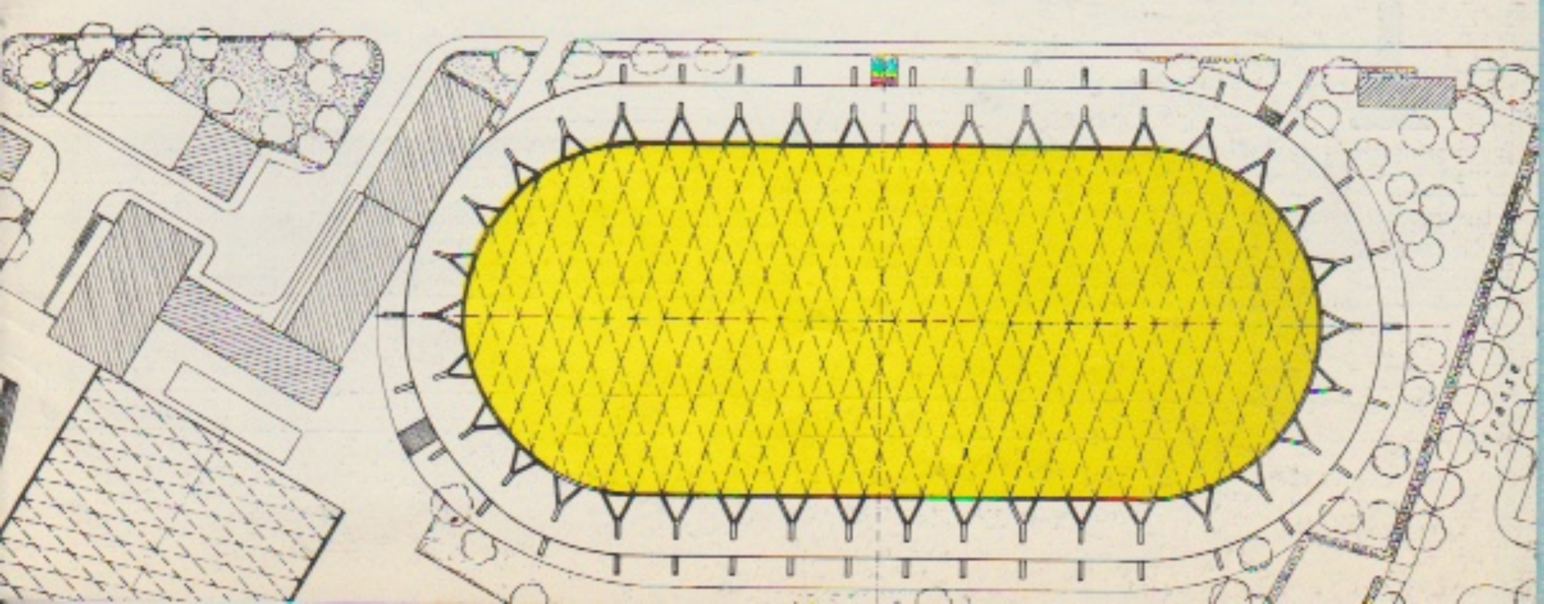
The load bearing roof structure is supplemented with steel tubes and rolled sections used as columns and spandrels in the longitudinal and transverse walls as well as in the roof light, forming a structural unit fulfilling all load bearing and structural requirements with the minimum quantity of steel.



The assembly of the main arches also presents several points of interest. The central part of both arches, 54 m (177') long and 10 m (33') wide, which weighed some 50 tons, was preassembled on the floor of the stadium and lifted into position by means of two assembly masts. The fitting of this large and heavy unit at a height of 20 m (66') above the floor level simultaneously on four end parts of both arches was a masterpiece of engineering skill of the workers which was carried out without any difficulty.

b) Prepared Designs of Similar Buildings

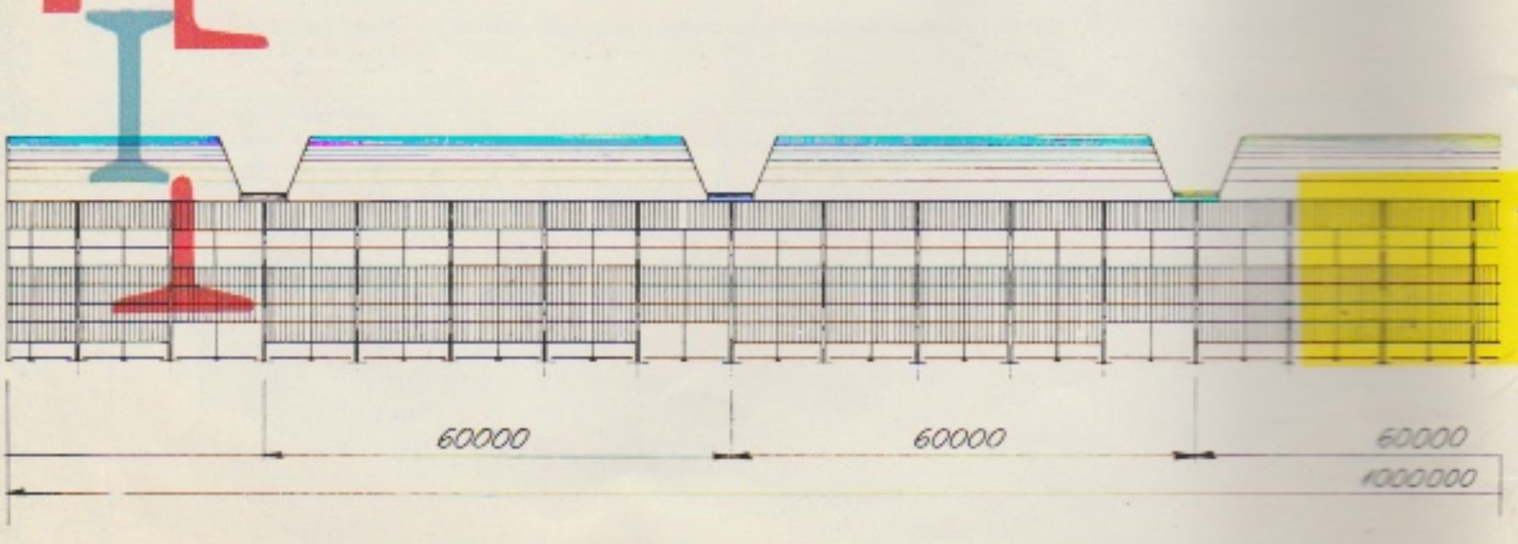
The described segmental vaults structure of the same span (58.28 m, i.e. 190'2") was used as a basis of the **winter sports stadium in Liberec.** Although the buildings is intended for the same purpose as the two preceding halls which have already been erected, the architect suggested a different arrangement of the load-bearing system, his design showing the extraordinary adaptibility of the system to local conditions and requirements, demonstrating simultaneously that even a standard vault can be used to enhance the architectural effect of a building of this type.



From the structural point of view this design finally proves that segmental vaults of this type can be used also without tie-rods. All these particular features of the design are illustrated in the longitudinal section of the hall which shows that, contrary to the two erected buildings, the vault is oriented in the longitudinal direction of the building, its basic span being supplemented by two suspended roofs to 10.45 + 58.28 + 10.45 = 79.18 m (33'8" + 190'2" + + 33'8" = 257'6"). The whole interior of the hall is free and devoid of any intermediate supports.

Of analogous conception is also a study of the roofing of a large capacity hall of a plan sized 100 × 200 m (328' × 656'). In this case the main vault again spans across the hall, its basic span of **75 m** (246') being larger than in the previous cases. By means of special prefabricated Y columns the span of the vault is increased to a total free span of **100 m** (328'). All other details are illustrated in the accompanying sketches suggesting the roofing of an **artificial speed skating track** 400 m (1212') long intended for the sports club of **Dynamo Berlin.** The size and layout suggest that such structure could be used even for a roofed football stadium and still be very economic. Preliminary calculations of steel requirements for the above mentioned study revealed steel requirements of some 420 tons for a roofed area of almost 20,000 sq.m (215,000 sq.ft.), which is a very favourable characteristic.

Another example of application of this structure is the study of the roof for a **rolling mill building** 1,000 m (3,280 ft.) long. The span and the useful height of the building fully comply with the requirements of the intended technology of production. Lighting and effective ventilation are ensured by means of transverse roof lights sunk into the roof vault at some 40—50 m (130—165 ft.).



Economic Analysis of Both Described Types, Advantages and Possibilities of Further Utilization

SEGMENTAL VAULT

The afore described buildings erected in Kladno and in Berlin enable us to quote highly exact data concerning the structural steel requirements which are the most marked characteristic of economy of structures of this type.

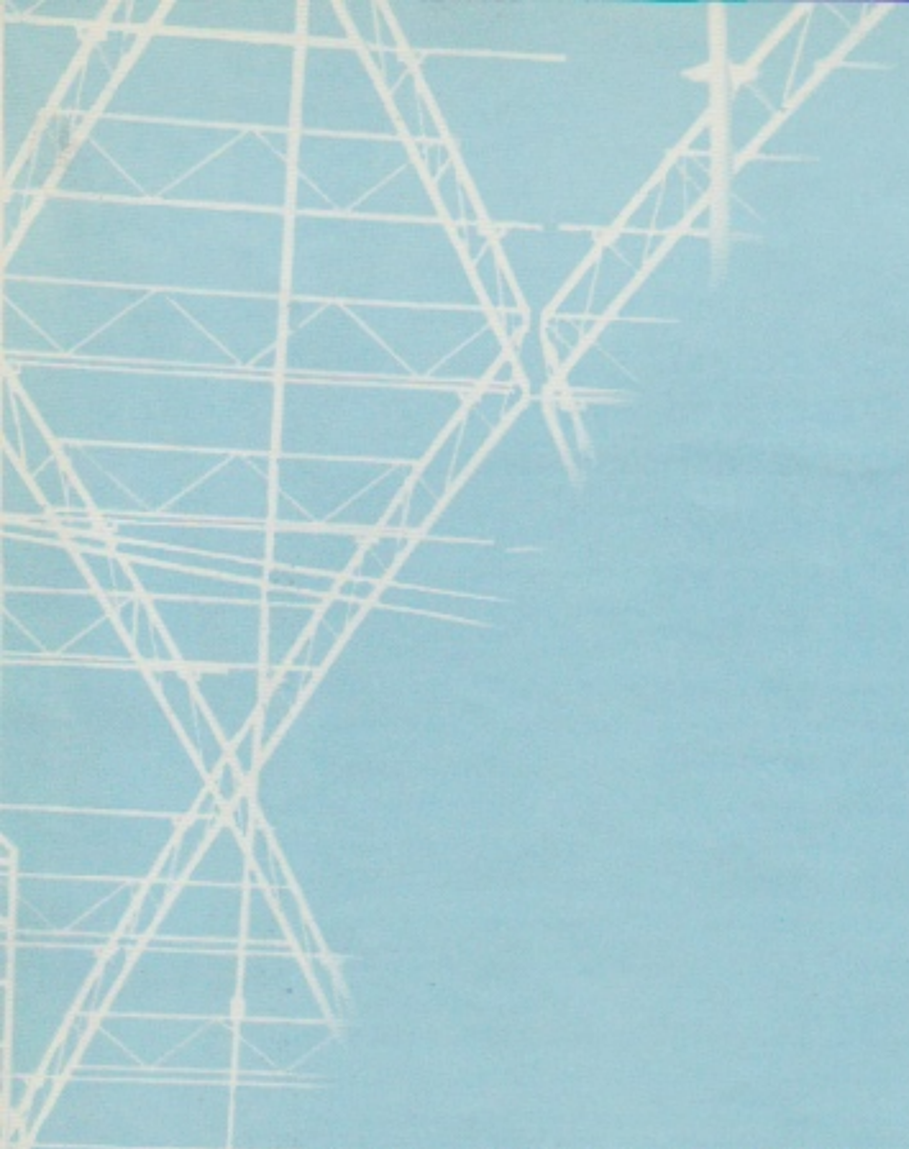
The main part of the building of the **winter sports stadium in Kladno** roofed with the segmental vault roof structure covering an area of 60 × 60 m = 3,600 sq.m (197 × 197 ft. = 38,800 sq. ft.) required a total of:

51.85 Mp of tubular steel for the segmental vault roof, i.e.	14.40 kp/sq.m	(2.95 lbs./sq. ft.)
13.97 Mp of round steel for the tie-rods and suspension rods, i.e.	3.88 kp/sq.m	(0.80 lbs./sq. ft.)
65.82 Mp Total	18.28 kp/sq.m	(3.75 lbs./sq.ft.)

In a structure with only vertical loading of the foundations these characteristic are very favourable.

In the case of the roof structure of the **winter sports stadium in Berlin,** for an area of 59 × 75 m — 4,440 sq.m (174′ × 246′ — 42,800 sq. ft.) the structures required:

94.81 Mp of steel for the roof, i. e.	21.38 kp/sq.m	(4.38 lbs./sq.ft.)
49.70 Mp of steel for longitudinal and transverse walls, i.e.	11.22 kp/sq.m	(2.30 lbs./sq.ft.)
144.61 Mp Total for the whole structure	32.60 kp/sq.m	(6.68 lbs./sq.ft.)
Specific requirements of steel per unit cube	2.18 kp/cu.m	(0.03 lbs./cu.ft.)



Similarly favourable characteristics of structural steel requirements were ascertained also for other alore mentioned buildings for which the desings were prepared. Thus the giant size sports halls requires only some 20—25 kg of steel per 1 sq.m of roofed area, which is exceedingly low for a building of such extraordinary size, and the rolling mill building would require — is spite of its considerable free span of 90 m (295 ft.) — approximately only .

28 kp/sq.m (5.75 lbs./sq.ft.) of steel for the roof structure, and
11 kp/sq.m (2.25 lbs./ sq.ft.) of steel for outside walls, i.e.

39 kp/sq.m (8.00 lbs./sq.ft.) or 1.6 kp/cu.m (0.22 lbs./cu.ft.) in total.

All of these requirements are obviously exceedingly low.

The described examples of erected structures and designs illustrate well the good and diverse possibilities afforded by this light-weight segmental type of tubular steel structure. Although the quoted examples pertain mostly to buildings for sports purposes, it is obvious that the structure could be used also for other types of buildings, such as industrial buildings, hangars for giant planes, etc. The span can always be adjusted to the requirements of the problem at hand, spans of 100 m (328 ft.) or over not presenting any difficulties. Every designed structure can even be adjusted to different spans, within certain limits, by an addition or removal of one or more rows of segmental components. Moreover, such adjustments can be carried out "at a moment's notice", so to say, without any special structural amendments or changes. The last, but not the least advantage is also the fact that the whole structure can be easily dismantled, transported and re-assembled on a different site.

INCLINED ARCHES

Although of an entirely different structural system, the economy of this roof structure is very favourable, as it is testified to by the example of the building erected in Gottwaldov.

The whole structure covering an area of 85.3 × 64.4 = 5,500 sq.m (280′ × 211′ = 59.100 sq.ft.) required in total:

48.588 Mp of tubular steel for the roof, i.e.	8.85 kp/sq.m	(1.81 lbs/sq.ft.)
16.310 Mp of tubular steel for gable walls, i.e.	2.95 kp/sq.m	(0.60 lbs./sq.ft.)
Tubular steel — total	11.80 kp/sq.m	(2.41 lbs./sq.ft.)
52.772 Mp of steel sections for main arches, i.e.	9.58 kp/sq.m	(1.96 lbs./sq.ft.)
33.668 Mp of steel sections for longitudinal walls and roof light, i.e.	6.12 kp/sq.m	(1.26 lbs./sq.ft.)
Steel sections — total	15.70 kp/sq.m	(3.22 lbs./sq.ft.)
Overall steel requirements 151.338 Mp	27.50 kp/sq.m	(5.63 lbs./sq.ft.)

The above analysis shows clearly the economy of the designed structure.

Good economic characteristics and the pleasing appearance of the completed building also recommend this type of unorthodox roof structure for further use in industrial, sports, exhibition and similar halls. It is easily possible to arrange also girders of this type in the transverse direction and use them in large industrial buildings where good illumination and ventilation are of primary importance.