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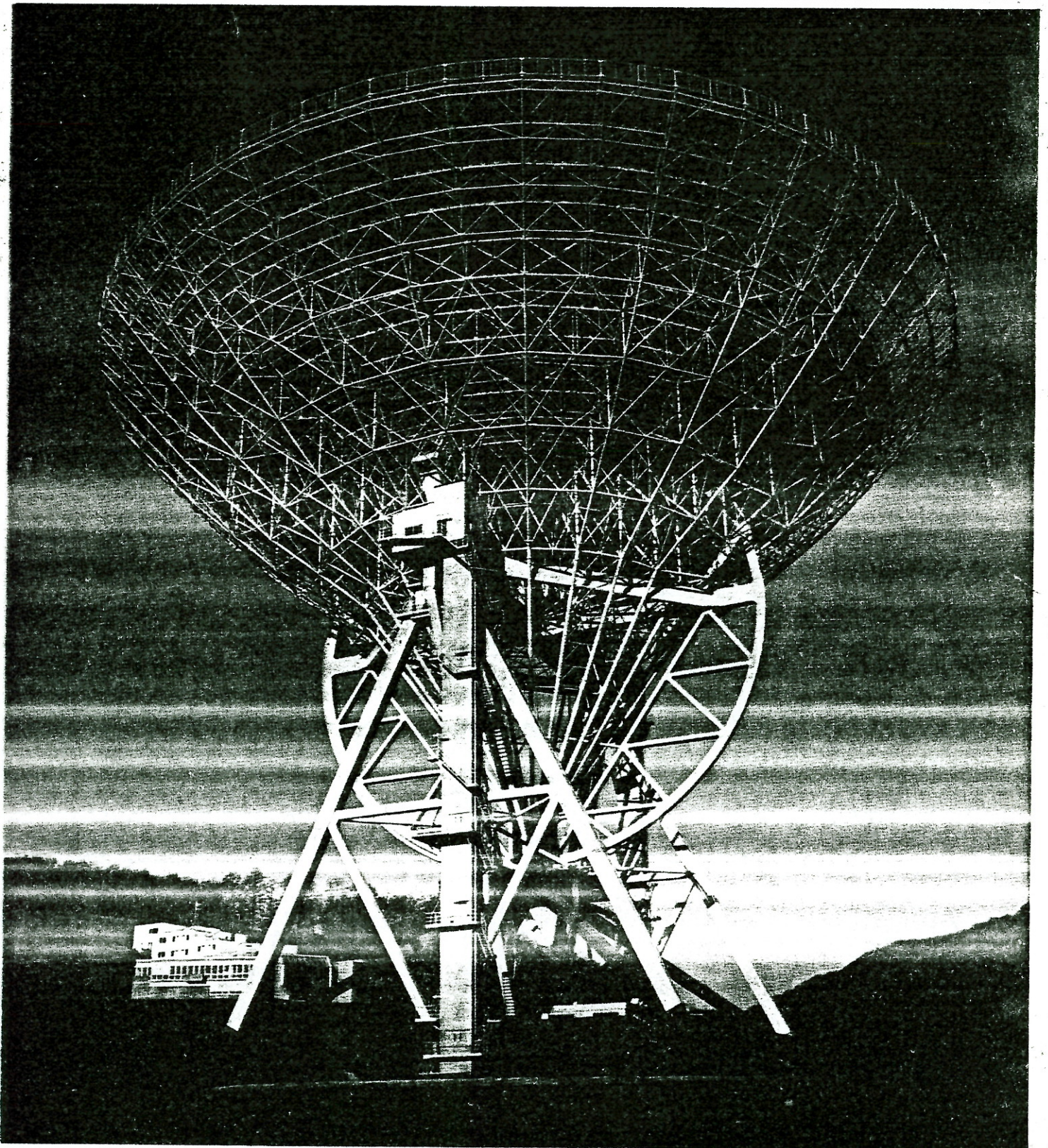
Tension Structures: Jawerth System

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Introductory

Some important examples in the natural development of structural design have been registered in recent years, including a new system of roof construction: the Jawerth System. This uses steel wire ropes of high strength as its main structural members, balancing the external loading by positive forces only, that is, by tensile stresses. The structural system—a tension or suspension type—does not, however, stand any risk of reaching a state of unstable equilibrium. The adoption of high-strength materials has the advantage of reducing weight and reducing overall costs.

In spite of the inertia which weighs against the adoption of any new constructional methods, these structures have made good progress by reason of their outstanding essential merits, wider unencumbered spans and reduced dead weight. This kind of suspended roof has found its place in the provision of large internal spaces, such as are required for a great variety of purposes, public or industrial.

It seems therefore that a general explanation of the features of this structural system is due, reserving, however, for other parties the task of developing the theme in the depth that its importance and scope demand.

Structural Classification of the Jawerth System

A. Plane Tension Structures

As will be gathered from Fig. 1a, the structural scheme consists of a number of pairs of wire ropes,
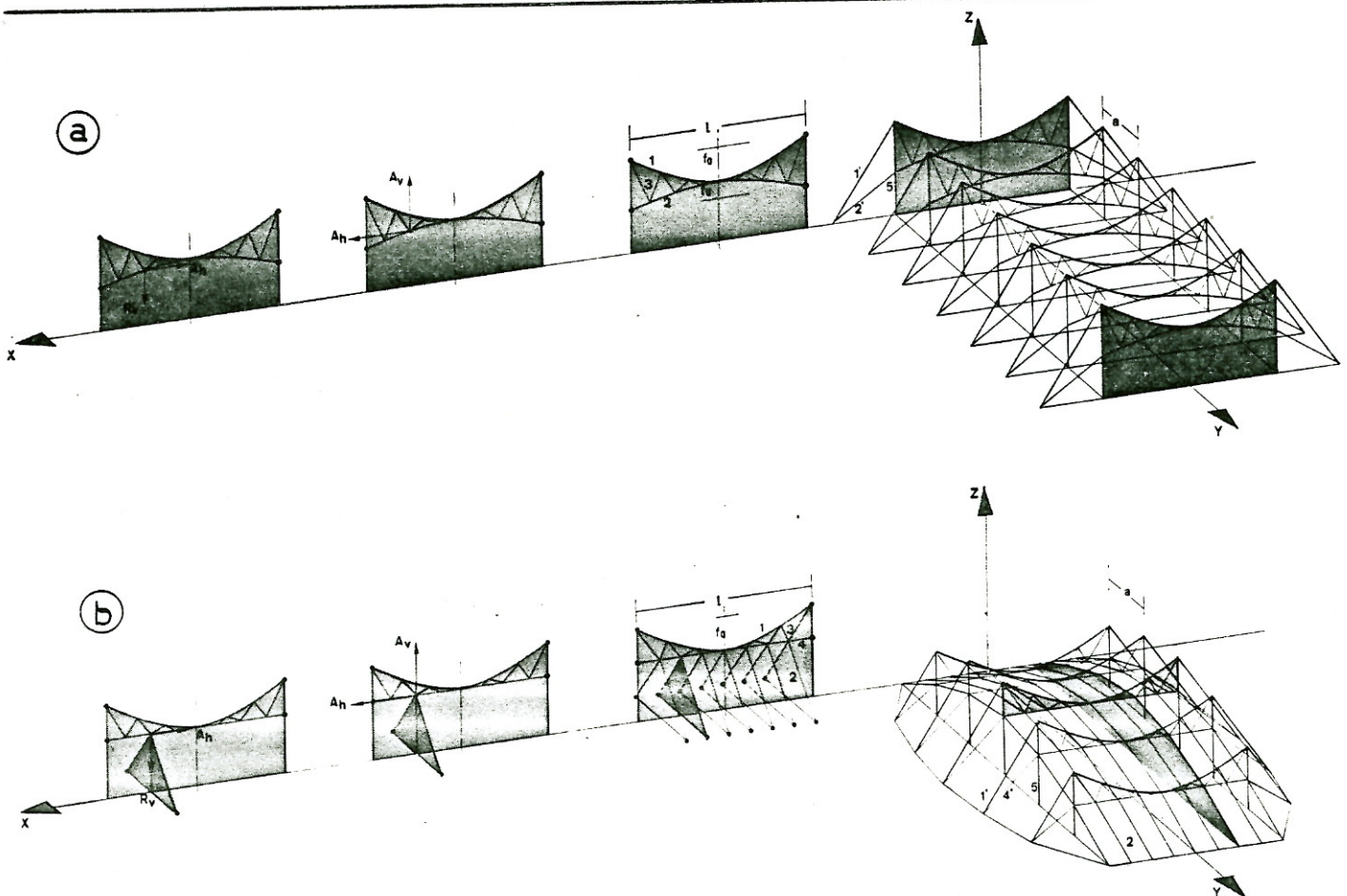
Figs. 1a and 1b. Structural scheme produced by Dipl.-Ing. Hans Hottinger of the Technological University of Karlsruhe (Germany). Reactions: Rv = Vertical component. Rh = Horizontal component. Forces: Av = Vertical component. Ah = Horizontal component. Wire-rope system: 1. Rope supporting roof. 1'. Strainer leg of supporting rope. 2. Tensioning rope. 3. Diagonal tie of wire-rope principal. 4. Stay rope. 4' Strainer leg of stay rope. 5. Mast.

with opposite curvatures, connected by diagonal ties. By suspending these wire ropes as main structural principals at intervals 'A', carefully suited to the material to be used for the roof covering, it is possible to develope surfaces of conical form, such as the Sports Palace at Johanneshov, of cylindrical form (Works building at Pomezia for Italwig) or of double curvature, such as for the recently erected swimming pool at Edmonton, Canada.

Fig. 2 illustrates clearly the structural versatility of a system of cables in one plane, designed according to the Jawerth System.

B. Spatial Tension Structures. Three-dimensional System of Cables

The Jawerth Spatial System represents a new and, at the same time, an important departure in the field of suspended roofs. It consists of a double grid of cables, one load-carrying, one stabilising, with diagonal ties to connect the two. This new type of structure presents the same static and dynamic characteristics as the plane system (Fig. 3).

The roof surfaces, which are necessarily of double curvature, have the function, dependent on the structural theories adopted, of maintaining at all points when under load the designed curvature, with only negative Gaussian deviations. The most typical form obtained under these terms is that of the hyperbolic paraboloid.

Fig. 1b shows how the structural system of the Jawerth space structure is built up. This form has been adopted by the City of Stockholm for roofing a covered stadium, 636'6" (194 m) in clear span.

Technical Characteristics

From the more recent applications of the system, it is possible to cite here a list of positive advantage, with our brief comments.

- Production of large clear spaces. Extensive areas, adaptable to a high degree and unrestricted by internal vertical structures, are required today, not only for exceptional buildings, such as hangars, covered stadiums, supermarkets, etc., but also for modern industries, which need large floor areas without internal obstructions. These must offer extreme versatility in the use of internal space and thereby add to the value of the property.
- Structural adaptability, freedom in planning and design, acceptable for new trends in architecture.
- Speedy and easy fabrication and erection with consequent savings in time and costs.
- The possibility of planning well ahead of present-day industrialised methods of building.
- The most efficient use of material. — The employment of cables as main structural elements, which do not essentially rely on strength in bending, enables us to consider axial and tensile forces only. The most important result of this is that the ratio of strength to weight is very high.
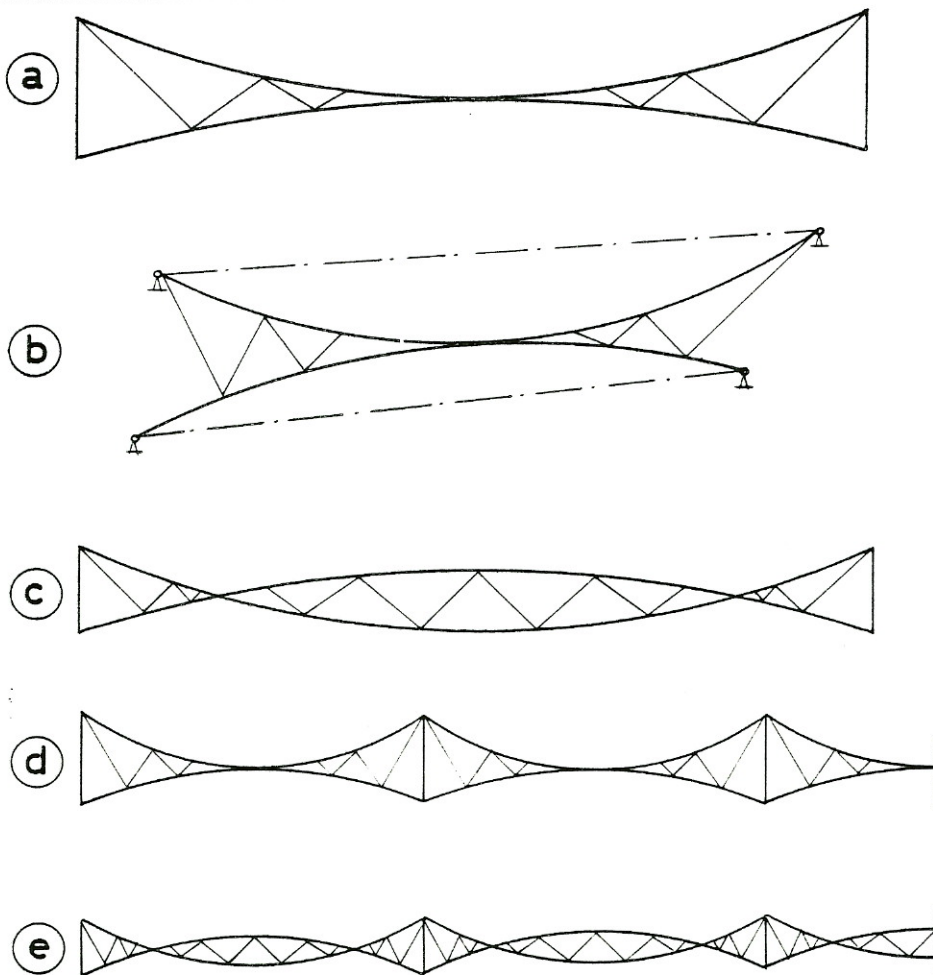- The employment of cables is in general the easiest way of erect-

Fig. 2. Classification of Single-plane Steel Wire-rope Systems. (a) Symmetrical system with intermediate web members. (b) Asymmetrical system which gives considerable latitude in composition and shape. (c) Scheme with intersecting ropes which enables the distance between the rope anchorages to be reduced. (d) Scheme similar to above, with multiple panels. (e) Scheme similar to 'c' above with multiple panels.

ing plane or space-frame steel structures.

- Elimination of reinforcement and temporary formwork, which is so expensive in the construction of thin shells in reinforced concrete.
- Suitability for use in conjunction with modern building materials.
- The increased margin of safety against collapse inherent in suspended structures. The factor of safety, calculated as a coefficient of the applied loads necessary to produce failure, is generally speaking higher than that based on the internal stresses assumed at the design stage. In traditional buildings, arches, domes, etc., any modification of curvature under applied loading implies a loss of stability, whereas, in the case of suspension structures a reserve effect is said to have been noted.
- Safety against fire. — Orthodox steel construction reaches a critical state at temperatures of 572-662 °F (300-350 °C), failing often through lateral buckling of the compression members at such temperatures. Since the self-weight of tension structures (including roof covering) is about 4.10 to 6.15 lb per sq.ft (20-30 kg/m²), the stressing tends to be mainly that due to the initial pretension. At high temperatures, the expansion of the steel cables, which remain in tension, acts only to reduce the degree of pretension. Deflection may increase, but collapse does not supervene because the aid contributed by the initial tension has yet to be annulled. The effects of fire can thus be resisted for a much longer period and the chance of collapse significantly minimised. The structure could suffer damage, but not seriously enough to hinder evacuation of the building or to impede the fire-fighting services.
- Special suitability for zones liable to earthquakes. The effects of momentum due to undulating movement or tremors caused by earthquake or seismic

shock are very minor, because the shock wave acceleration acts on unusually light masses, compared with those of conventional structures.

- Sound performance even in the case of unequal settlement of supports. — The cables adapt themselves automatically to new

conditions of equilibrium, without undergoing any appreciable changes in tension.

- Savings in transport charges, since the main structures, that is, the cables, are coiled on drums for carriage to the site.
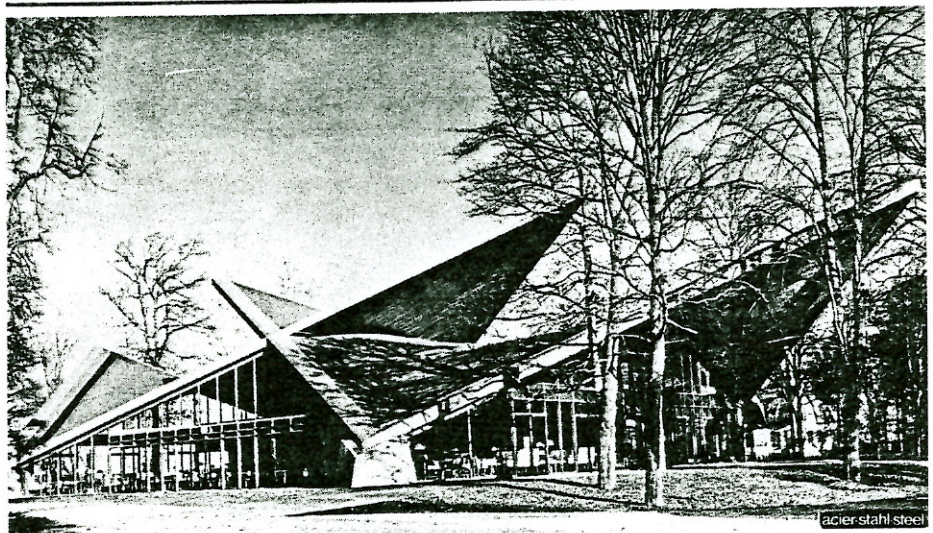- The options of modifying, converting or taking down and reus-

Fig. 3. Brunnsparken Restaurant, Orebro, Sweden. Designed by Svenska Riksbyggen, Architects. Structures: System Jawerth.
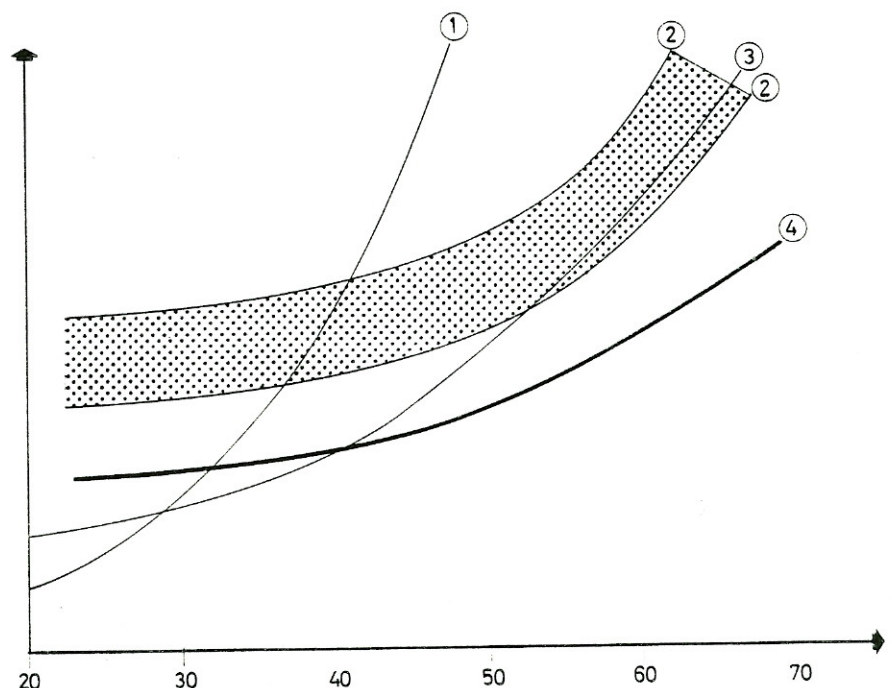

Fig. 4. Diagram giving Comparative Costs. 1. Steel Beams. 2. Curved rib members. 3. Arched structures. 4. Suspension Structures, Jawerth System.

ing are inherent properties of steel structures.

- Better site organisation and reduction of essential plant (appliances, scaffolding, etc.).
- Closer matching of contract costs to estimated costs with the added help of optimum structural efficiency.

Economic Aspects

The most effective exploitation of the properties of special high-strength steel, within the context of a structural system which is stressed throughout by direct tensile forces, leads us naturally to consider its possible economies as against structures which are subjected to bending moments or are stressed by axial forces, either tensile or compressive, as is the case with framed structures. In the case of bending and up to the elastic limit, the material near the neutral axis of the section is not stressed to the limit of its capacity. Only those parts of the sectional area remote from the neutral axis are stressed to the effective limit set by the strength of the material.

In framed structures, the bars in compression which have to be dimensioned to prevent their failure by buckling also tend to add considerably to the weight of material used.

These points are clearly illustrated by Diagram A, where for various clear spans we give specific costs for conventional structures and those for structures on the Jawerth System (Fig. 4).

Curve (1) gives the costs for beams with solid webs and framed steelwork. The curve has a very steep slope, because structures which are basically stressed only within the elastic limit utilise only at a few points the full strength of the material up to the permissible limit. Other parts of the structure, which are not made to play their full part in contributing to the overall strength of the structure, increase unnecessarily its weight and therefore the cost.

Curves (2) indicate the range of cost of curved rib members stressed either in bending or as parts of surface (membrane) structures.

The cost of these structures arises principally from technical factors, such as site assembly and erection, expensive formwork, scaffolding, pouring of concrete at high levels, etc.

Curve (3) represents arched structures, which are considerably cheaper to construct than any of the foregoing examples, because the problems of prefabrication and erection are easier than is the case with shells in reinforced concrete or in steel. Nevertheless, if a certain span is exceeded, costs again become prohibitive.
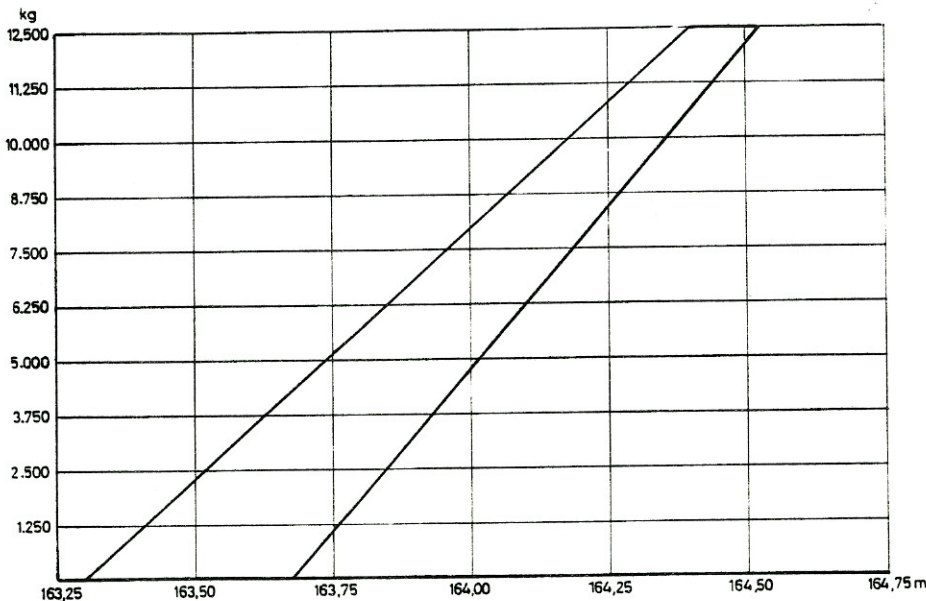
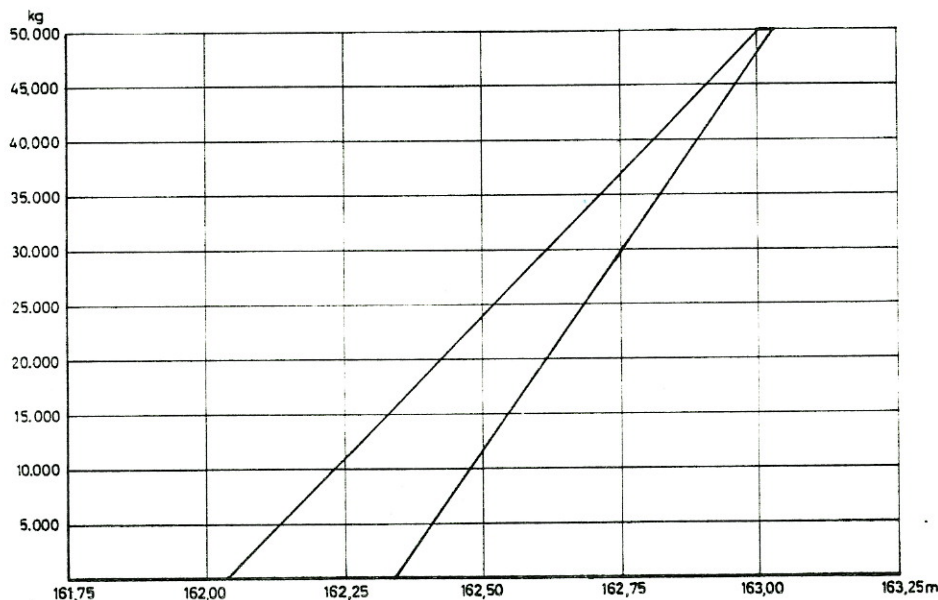Fig. 5a. Diagrams of Pretensioin Effects. (a) Behaviour of rope with spiral lay.

Fig. 5b. Diagrams of Pretension Effects. (b) Behaviour of locked-coil rope.

Curve (4) is typical for suspension structures and gives costs for the Jawerth System.

Obviously the drawback presented by the high cost of the high-tensile steels and of the constructional accessories renders the system not acceptable in all respects for small spans. As the span increases we note that the cost does not increase proportionally, also that for spans beyond the intersection of curves 3 and 4, where the costs are equal, the tension structure is proved to be the most economical by any reckoning. Other thechnical merits of these structures, such as their demountable character, possibility of reuse, the architectural opportunities they afford, and so on, have made them acceptable even for small spans.

Moreover, Table I shows the quantity of steel required for the suspension structures of some buildings on the Jawerth System.

Other factors which have a considerable bearing on the overall profitability of wide-span structures are the following:—

Transport of the structural units

Conventional wide-span structure must for obvious reasons be hauled in sections to the building site. In the case of prestressed concrete construction, off-site fabrication presents many difficulties and for two-dimensional or spatial reticulated structures, precast to modular dimensions, the low ratio of self-weight to bulk can make transport charges a not inconsiderable item in the global cost of the structure.

Tension structures, however, consist of steel cables which span the clear space without any discontinuity of their material. Thus we can have structural units of more than 656 ft (200 m) in length, which, thanks to their flexible character, can be wound on drums for easy transport. The weight of tension structures lies between 0.82 and 1.02 lb per sq.ft (4-5 kg/m²), which means that it is possible to transport the structural materials for 21,500 to 32,300 ft super (2,000-3,000 m²) of roof area quite comfortably in a single lorry.

Erection

The structure is assembled at ground level. — The cables are unrolled. The supporting and the staying cables have previously been marked ou under tension to indicate the exact positions for the friction-type aluminium fastenings (patented). When these grip fittings have been fixed in position,

Table I. — *Approximate weight of structures suspended on steel wire ropes, in kg/m²* (*multiply by 0.205 to give lb per ft super*).

	Clear Span (metres)	Ropes	Fittings	Diagonal Bars	Junctions	Total
Sports Palace (Sweden)	49.5	3.6	0.1	0.9	0.2	4.8
Works Building Lesjofors (Sweden)	5×16	1.3	0.1	0.9	0.2	2.5
Supermarket Athis Mons (France)	43	2.8	0.1	0.8	0.2	3.9
Goods Station Depot Calberson (France)	6×32	1.3	0.1	0.6	0.1	2.1
Sports Palace Sala (Sweden)	45	4.9	0.1	0.6	0.2	5.8
Exhibition Hall Poznan (Poland)	57	2.6	0.1	0.4	0.1	3.2
Sports Hall Kerkrade (Germany)	61	3.0	0.1	0.3	0.1	3.5
Goods Depot, Schiphol (Netherlands)	77	3.4	0.2	0.4	0.1	4.1
Edeka Store, Karlsruhe (Germany)	2×32	1.5	0.1	0.4	0.2	2.2
Sports Palace, Helsinki (Finland)	93	5.2	0.3	0.5	0.2	6.2
Sports Stadium, Johanneshov (Sweden)	83	6.1	0.5	0.5	0.2	7.3
Industrial Building, Pomezia (Italy)	45	2.7	0.1	0.4	0.1	3.3

Time taken for erection in single bays: about 10 min. per sq.yd (0.2 h/m² approx.)

the two main cables are tied one to the other with diagonal braces, generally of drawn steel rod. After assembly at ground level, the cables are hoisted and anchored to structures already in place. With the help of a hydraulic jack and special measuring appliances, a predetermined degree of tension is applied to the system. The average time for the complete erection operations is 10 min per sq.yd (0.2 h/m²).

Programming

Because it requires neither bulky formwork nor propping of spans, this method of construction does not retard other building work which may be going achead at the same time. So it can be adopted in conjunction with totally prefabricated methods and effectively accelerate site operations.

In Table II is given a typical programme of operations for a structure of medium size. It will be observed that the date for handing-over the building depends chiefly on the date on which the cables are delivered by the suppliers.

Materials

The main component of tension structures is, of course, wire rope in high-tensile steel (114 t.s.i. or 180 kg/mm²). These cables are formed, to suit the diameters and sectional areas of steel required, of individual wires, varying in number, and arranged or laid up to produce a specific type of wire rope.

Usually in the manufacture of such ropes, spirally-laid or locked or half-locked types are odopted. The first, which is the most commonly used type, are given a coating of 99.9 % pure zinc, electrolyti-

cally deposited on the individual wires at the rate of 0.041 lb per sq.ft (200 kg/m²) of surface area.

The second (and third) types, for use in corrosive atmospheres (chemical works, for example) or where the cables come above the roof sheeting as external members, are so shaped that the cable forms a closed section, capable in itself of preserving its interior from rust. In general, the cables have a modulus of elasticity 'E' of between 8,890 and 12,050 t.s.i. (1.4-1.90 × 10⁶ kg/cm²), depending on the way in which they are laid up and the point to which they are stressed. To rule out the latter source of uncertainty, the cables have to be brought to as stable a state as possible by pretensioning, so that, as shown diagrammatically, the strain produced under tension (positive) is, as nearly as possible, equalled by the recoil observed on removing

Table II. — *Programming for Suspension Structures.*

Serial No.	Time	1st month	2nd month	3rd month	4th month	5th month	6th month
1	Structural calculation and working drwgs.	▰▱					
2	Provision of aluminium sections for cable terminal fittings	▰					
3	Preparation of aluminium sheet templates .		▰▰	▰			
4	Fitting of cable terminals			▱▱▰			
5	Making up diagonal bars		▰				
6	Deliveries of cables	▰					
7	Work to cables		▰▰▰▰▰				
8	Organising erection work for suspended structure			▱▱▱▱▱			
9	Erection of suspended structure						▰

the tension (negative) in Fig. 5a, we illustrate the behaviour of a spirally laid cable of 5/8″ (16 mm) diam., containing 37 wires, laid up 1 + 6 + 12 + 18, and in Fig. 5b, that of a locked-coil cable, 1 3/8″ (36 mm) diam. with 34 round wires, laod 1 + 9 + 9 + 15, and 43 shaped wires, laid 19 + 24.

Projects on the Drawing Board

At the present time, Jawerth Interstatik, in association with Prof. Paul Hedquist as architect, is designing for the department responsible for sport and recreation in Stockholm a new covered football ground (Fig. 6).

Suspension roofs with clear spans that are repeated at the ends make it feasible to design a stand for a football field, roofed in and with only the end walls glazed. A good example of this is the icehockey stadium at Johanneshov, Stockholm.

Also in this category of sports buildings, a scheme for a convertible swimming pool is also being worked out. This comprises two distinct structures, namely, that for the bath itself, which can be opened up completely in about two minutes, and the attached accommodation for 850 bathers, which can stretch along two sides of the building. The roof consists of a PVC membrane, 0.035″ (0.9 mm) thick, reinforced with polyester fibre. It is estimated that this will remain weathertight for some 10 years. At the centre it is supported by a steel rope principal, designed on the Jawerth System and spanning 249 ft (76 m). The roof slides along three tracks, one in the middle and one at each end, all equipped with electrical gear.

Stability is ensured by pretensioning and by the geometric double curvature of the surface, which is established by specific settingout lines of the tracks. The design of this scheme lends itself readily to complete off-site fabrication of the various parts of the structure, leaving only foundations and floors to be executed on site (Fig. 7).
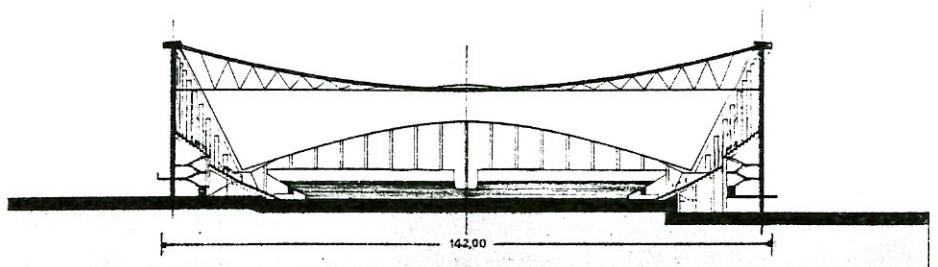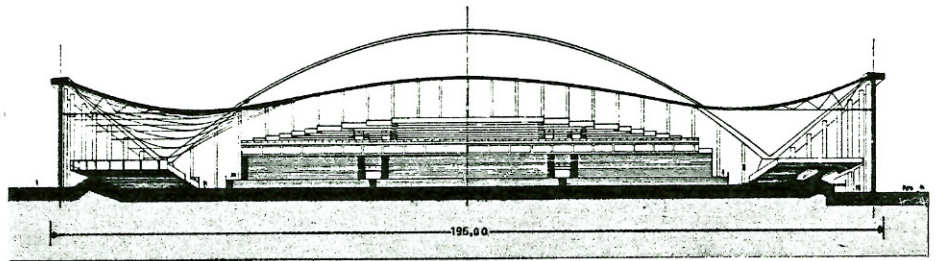

Fig. 6. South Stadium in Stockholm. Designed by Prof. Paul Hedquist. Structures by System Jawerth.
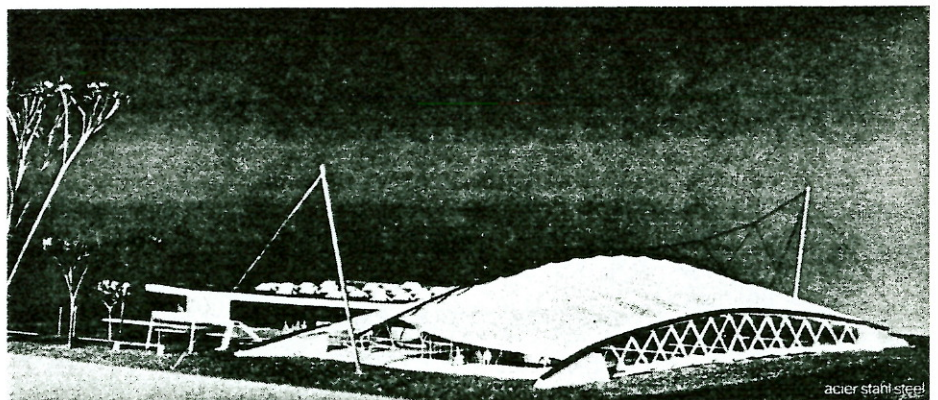

Fig. 7. Design for Convertible (indoor, open-air) Swimming Bath. Architects: Y. Carduner and A. Ghiulamila.
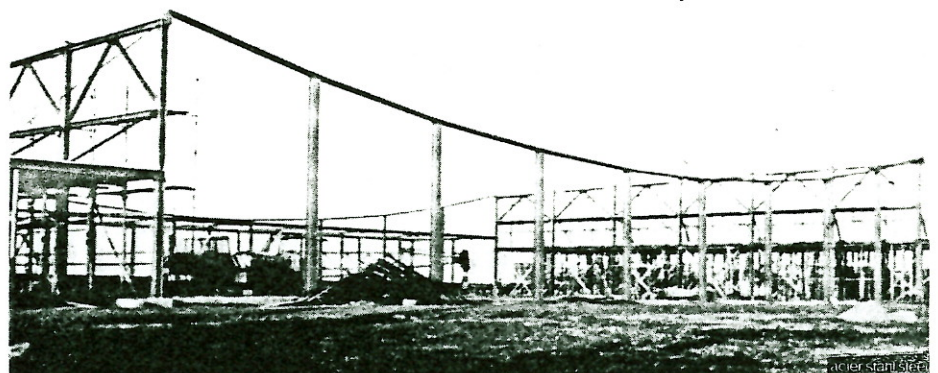

Fig. 8. Italwig Works Building at Pomezia. Steel structure.
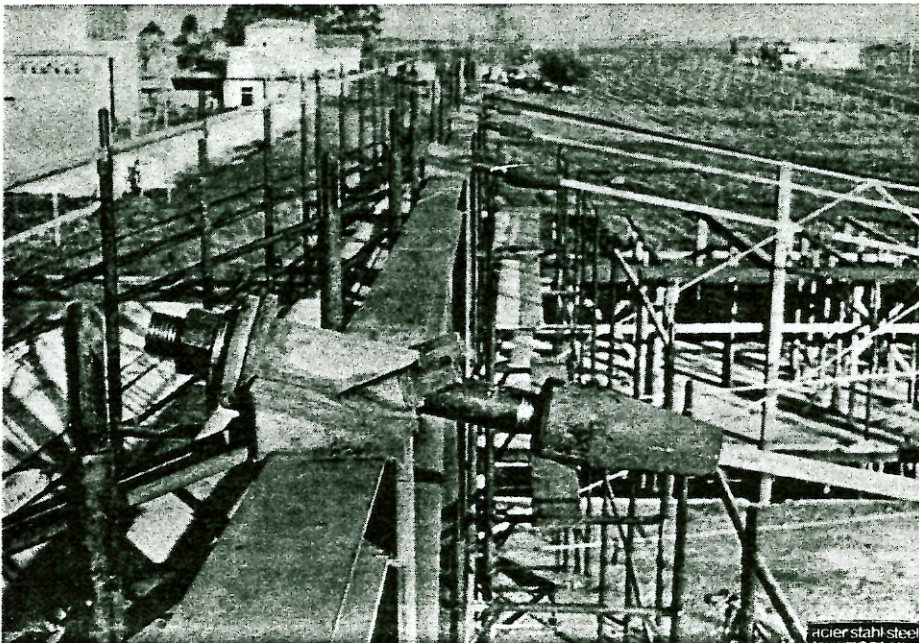
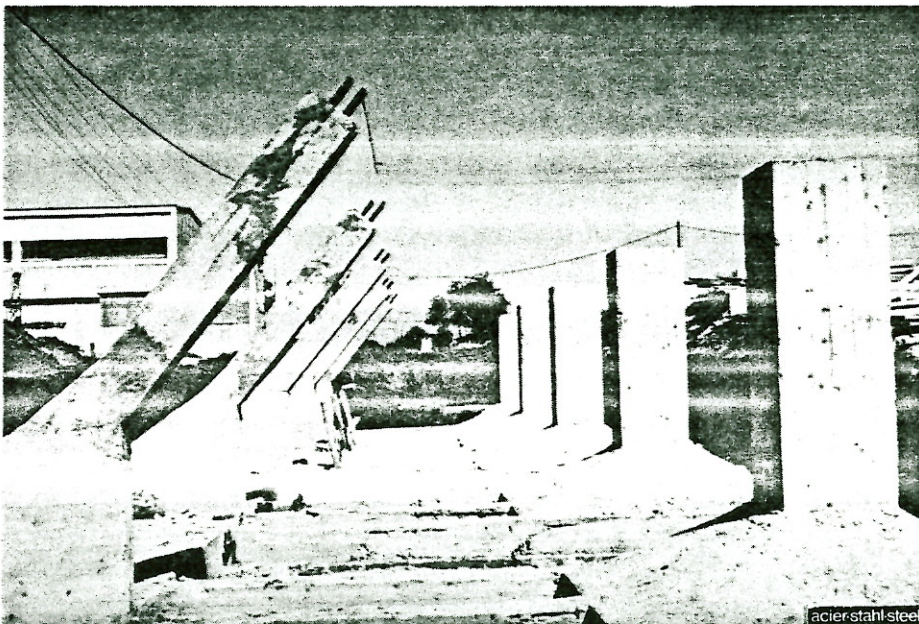Fig. 9. Italwig Works Building, Pomezia. Detail of fastenings for ropes.

Fig. 10. Italwig Works Building at Pomezia. Mass concrete foundations for transverse guy ropes.

Industrial Building at Pomezia

The new works building of *Società Italwig,* at Pomezia, is the first building in Italy to use a Jawerth structure for its roof.

This project, worked out in the Italian office of Jawerth Interstatik, gives a clear span of 147′8″ (45 m) with two annexed blocks, each of 32′9″ (10 m) span (Fig. 8).

The spacing of the main steel principals, carefully fixed to suit the roofing material, is 16′5″ (5 m). At the front, the office block connects with the tension structure by means of a wall in blockwork filling which has a matching parabolic contour. Both roof carrying cables and staying cables are of spiral lay and are fitted with terminal steel caps of Italian Type 2 for diameters of 1 3/8″ and 1 1/2″ (36 and 38 mm), respectively (Fig. 9).

The diagonal ties are in drawn rods of Type 1 steel, 5/8″ (16 mm) in diameter. The vertical supporting structures are built in 9″ × 9 1/2″ light-weight beam sections (European Type HEA 240). The pull from the upper cables which are anchored to the tops of the columns is resisted by five 1″ (26 m) diam. tie rods in bright, hard-drawn, steel rod. Three of these are anchored to the structure of the auxiliary service rooms, which abut either flank, while the other stay rods carry the roof deck of these structures, so that a clear span of 32′9″ is obtained at very low cost. The pull of the lower cable, anchored directly to the framework of the service buildings, and that from the combination of the other horizontal forces produced by the lateral guy ropes are finally transmitted to the subsoil by four more tie rods in bright-drawn steel via massive concrete foundation blocks (Fig. 10). The tension structure is erected in two stages.

First, the structure is put together at ground level to reproduce the geometric shape apposite to the initial state of loading. As the second stage, this assembled structure is raised and fixed to the structures which have to anchor it (Fig. 11). This operation, undertaken by four workmen with no previous experience of this kind of work, is effected within an average period of 90 minutes for each main tension-structure principal. As soon as all these principals have been set up, the whole system is subjected to tension by hydraulic jacks. This pretensioning force, applied to the stay ropes, varies as between one principal and another, from 25 to 34 metric tons. This represents the tensions in the external structures. The final adjustment of the tension and geometric form, applied by working on the diagonal bars with the aid of special measuring devices, is done after fixing the roof covering, which weighs 6.14 lb per sq.ft (30 kg/m²). The application of this covering will have changed to profile of the principals from its state when first erected and will produce an increase of something like 3 1/2" (90 mm) in the sag of the supporting ropes and increase the tension in these to about 30 metric tons.
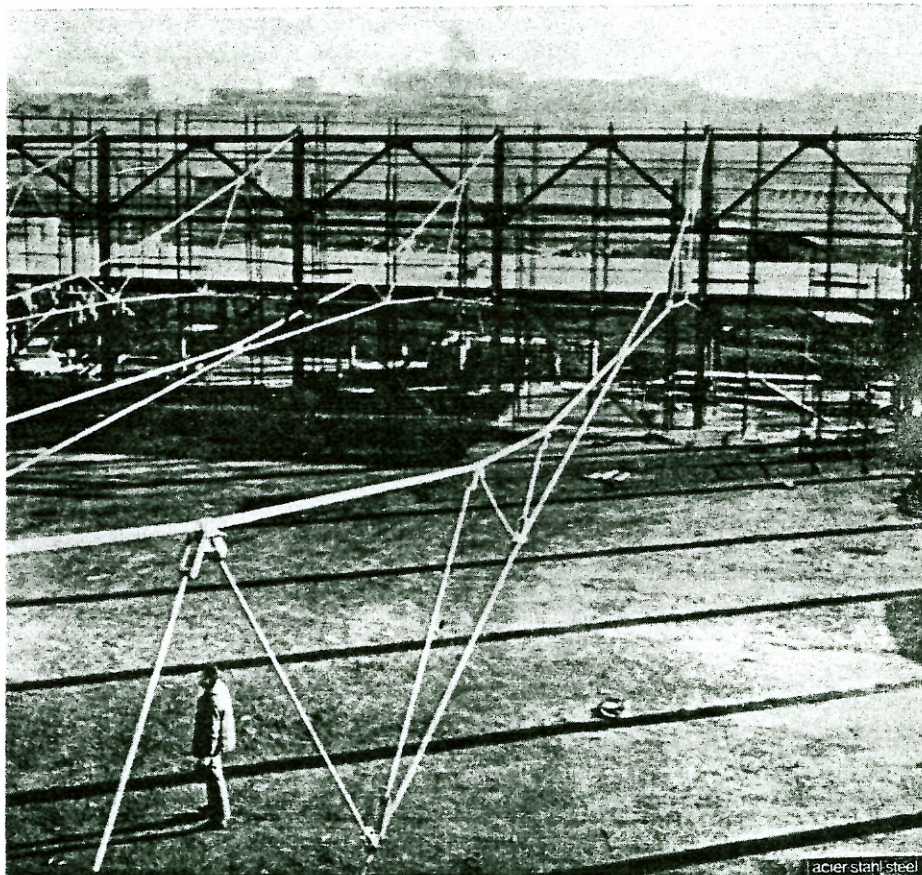

Fig. 11. Rigging up the tension structures for the Italwig works building at Pomezia.

With the allowance for snow loading, the tensile forces in these supporting ropes would reach 46 metric tons, while, under suction caused by wind, such forces may drop to 18 metric tons. The longitudinal slope of 1 in 50, required for shedding rainwater, is obtained by adjusting the heights of the external masts and the sag of the guy ropes.

Design and Construction

Owner: Italwig S.r.l., Pomezia.
Design, Calculations for the solid and tension structures: Jawerth Italiana, Bologna.
Roof Sheeting: Robertson Italiana.