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Bridges - Construction techniques and methods (concrete and steel)

Ponts - Procédés de construction (béton et acier)

Brücken - Bauverfahren (Beton und Stahl)

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SUMMARY

The object of a good construction method should be to build a bridge in the safest possible way for the least possible expenditure. As in general the construction costs determine the cost of a structure, the construction methods used can become of importance and together with a reduction in labour costs, can make the old priority "lowest materials expenditure" of secondary importance.

RÉSUMÉ

Le but d'une bonne méthode de construction devrait être de construire un pont dans des conditions de sécurité maximum pour des frais de construction minimum. Etant donné qu'en général, les frais de construction sont décisifs pour la réalisation d'une construction, la méthode de construction peut prendre une importance capitale: l'ancienne condition «réduction au minimum des quantités de matériaux nécessaires» peut devenir d'importance secondaire.

ZUSAMMENFASSUNG

Das Ziel eines guten Bauverfahrens sollte sein, eine Brücke mit möglichst niedrigen Baukosten bei grösstmöglicher Sicherheit im Bauzustand zu errichten. Da die Baukosten im allgemeinen über die Realisierung einer Konstruktion entscheiden, kann das Bauverfahren dominante Bedeutung gewinnen und im Zusammenhang mit einem verringerten Arbeitsaufwand die alte Priorität des „geringsten Materialsverbrauchs" zweitrangig werden lassen.

The structural design of bridges used to be governed mainly by the final load-carrying capacity, but behaviour during construction is now gaining increasingly in importance.

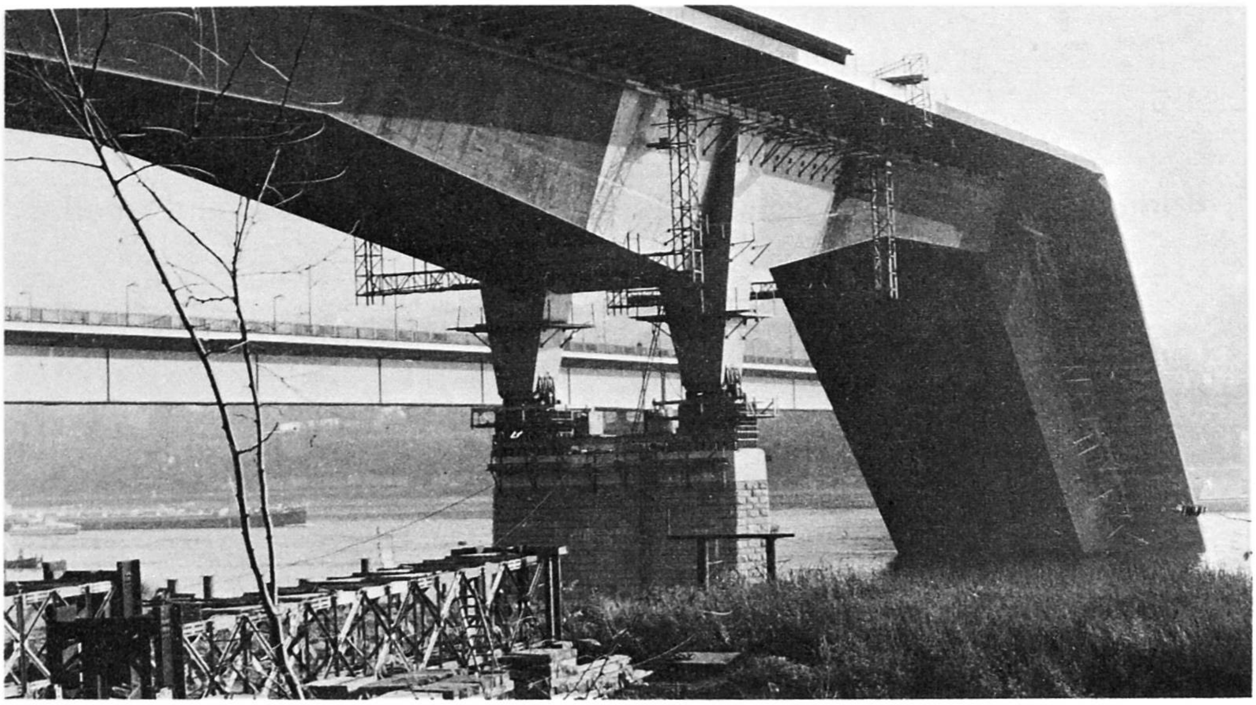

Fig. 1

Many bridges are subjected to their maximum loads during construction and this is the time where the risk of collapse is at its greatest (Fig. 1, 2). So, due to above, construction methods exercise a great influence.

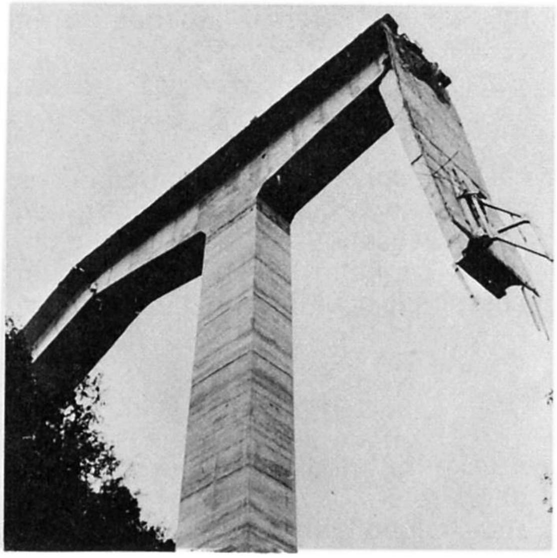

Fig. 2

Generally, construction costs play a decisive role and the construction method which also for example requires a minimum of labour may be given priority over the old principle of "saving, whereever possible, on materials".
More material may contribute a higher stability during and after construction and reduce the susceptibility to repairs.

Steel bridge construction is about 50 years older than the construction of reinforced concrete bridges and it was another 100 years before these were revolutionized by prestressing. Concrete without tensile stresses has characteristics which are more similar to steel than those of concrete with mild steel reinforcement. New developments in steel bridge construction still exercise a useful influence on the design and construction of concrete bridges (Fig. 3, 4).

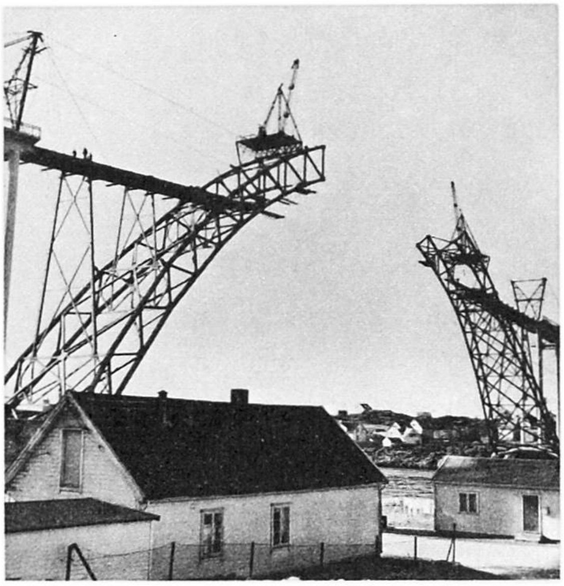

Fig. 3

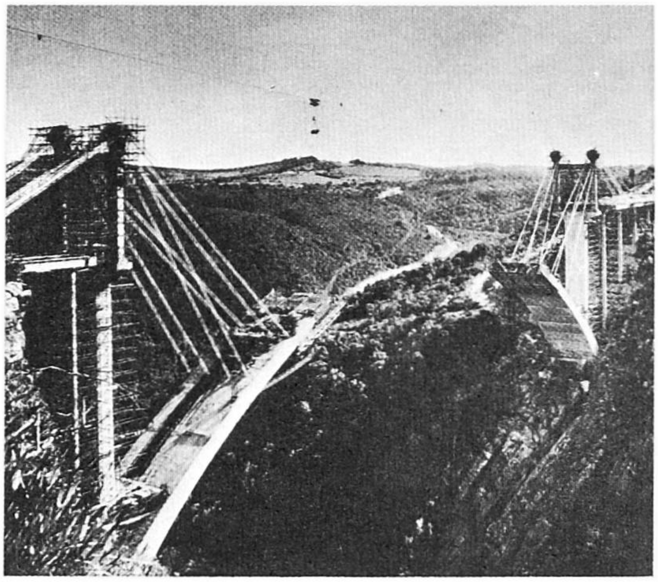

Fig. 4

Less weight and easier control of steel in statics and structural design made steel bridges superior to concrete bridges for large spans. Strong competition from prestressed concrete contributed on the other hand also to the efficiency of the structural design and construction of steel bridges, in the realization that structural design and construction method are closely connected.
Economical fabrication in steel bridge construction is based on fabrication of continuous girders having the same cross-section regardless of the distance at which they are supported or suspended. Already a small number of these "longitudinal systems" covers the most interesting range of spans for steel bridges from about 100 metres to 3,000 metres, the maximum span considered possible in the light of present day knowledge and techniques. These systems mean an independence of normal factory production from the bridge load-bearing system.
Girder bridges, multiple-cable stay bridges, cable stay bridges and suspension bridges are suitable for such normal factory production, whereas load-bearing systems with concentrated induction of forces, as frame bridges, tied and cantilever bridges and self-anchored suspension bridges are not or not easily suitable for normal factory production. Arches and, to some extent, very wide-spanned girders are likewise not suitable for this. Thus, the cable stay bridge, which in regard to span, is between the girder bridge and the suspension bridge, benefits largely from this development of longitudinal girder systems by decreasing the economical span of girder bridges and increasing those of the suspension bridges (Fig. 5).

The solid web main girder is now given nearly universal preference over the trussed beam, even for wide-span suspension bridges (Fig. 6). The main reasons for this, some of them independent from others, are:

- Developments in the fabrication of large plates,
- theoretical knowledge in the field of "continuum-orientated" stability problems with specific continuity
- developments in structural design incorporating the carriageway into the main load-bearing system,
- welding in lieu of riveting,
- possibility of hauling large units, and efficient means of erection.

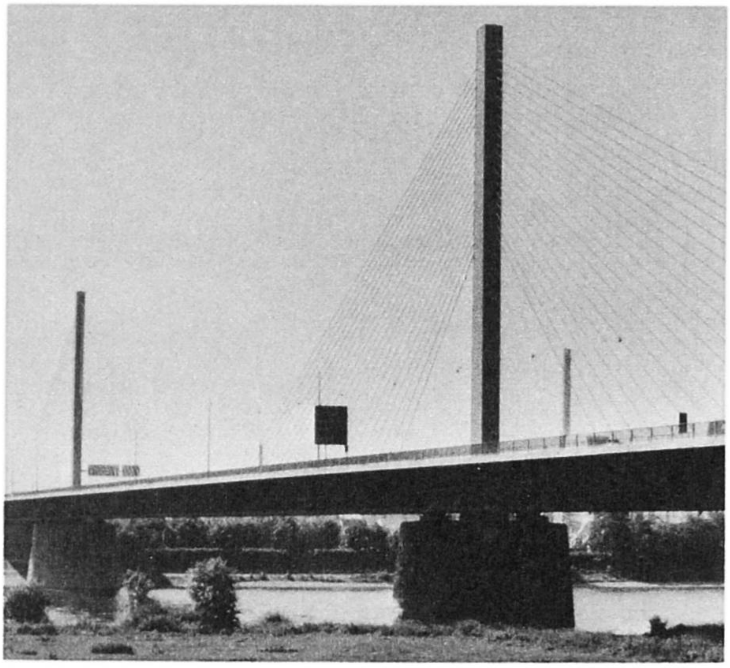

Fig. 5

An analysis of the bridge cross-sections preferred in the last thirty years reveals, broadly speaking, that for large bridges the basic cross sections in relation to the square metre of bridge area, were used in the order as shown in Fig. 7. Today it is generally agreed on that the number of different cross sections can be limited and that mixed systems can to a large extent be dispensed with. About fifty per cent of all bridges could economically be

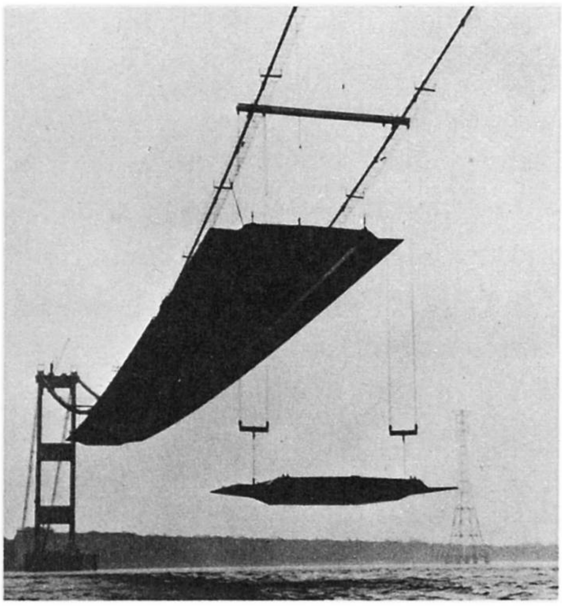

Fig. 6

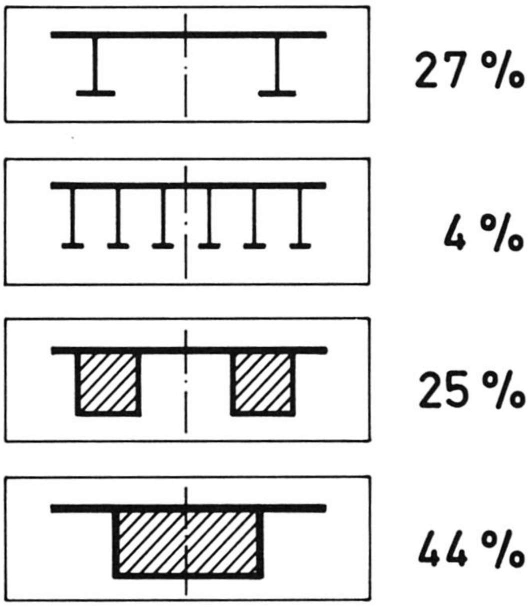

Fig. 7

constructed today with open cross sections, whereas the other half could economically be constructed with plain box main girders with torsional rigidity. This statement is, however, only true for bridges with an orthotropic decking. Wide-span suspension bridges with main trussed beams and separate carriageway are not considered in this analysis. According to present knowledge, they would be designed anyway as wind-slippery main plain box girders, unless a double-deck design with main trussed beams is specified for traffic reasons. This preference for the plain main girder does not, however, mean the end of the trussed beam, but it is hardly conceivable that it will regain its former importance under present circumstances.

The statical analysis and structural design of the orthotropic bridge decking have always been considered highly important. But the vast expense still required for orthotropic plate design bears no relation to economical success. Three proven designs for fine meshed carriageway grids are shown in Fig. 8. The hollow longitudinal ribs require the least number of cross beams and intersection, whereas the most number are required by the simple solid longitudinal ribs as solid webs.

The development of the so-called "structural continuum" is of the greatest importance. This means skillfully combining "factory-grown" planar cross sectional units as large as possible with a minimum of on-site erection efforts in the construction of the bridge cross-section. Two trend-setting examples for an open and a closed cross section are given in Fig. 9.

Skillful combination of economical standardized systems resulted in the past and still results today in cross sections satis-

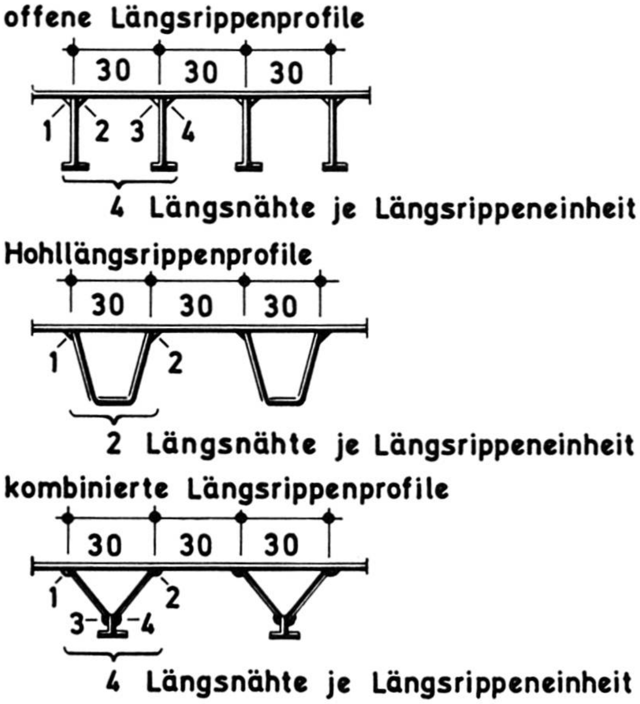

Fig. 8

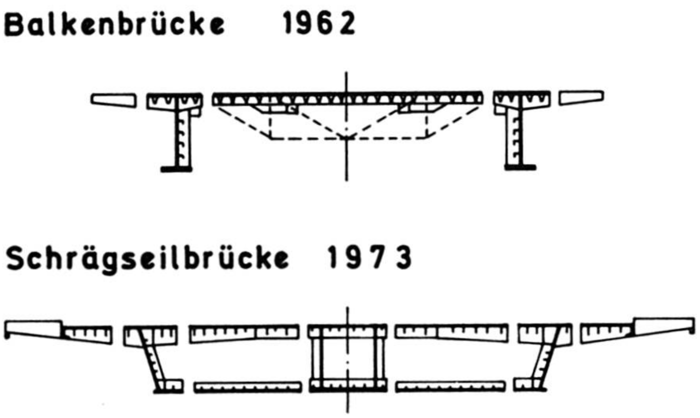

Fig. 9

fying various longitudinal systems so that advantages in fabrication are achieved by limiting the number of systems. Advantages for design and construction are obvious, if a longitudinal system could be designed which can be based on proven basic systems. This rationalization trend stems from the fact that up to sixty per cent of bridge costs are incurred by labour in planning, shop fabrication and erection. The need for rationalization has been underlined by a study of a ten-year period, which shows an increase in materials prices of about 20 %, but about 150 % for wages. The costs triangle "materials, wages and equipment" must therefore considerably be improved on the wage side. This, however, requires investments on the equipment side for both shop fabrication and erection. The efficiency of the means of erection decisively influences erection wages and it is, in combination with shop and transport capacities, very often the decisive factor in governing the degree of prefabrication and erection progress (Fig. 10, 11).

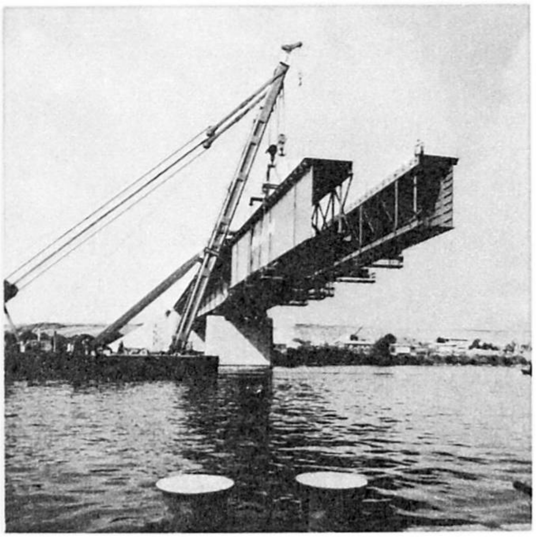

Fig. 10

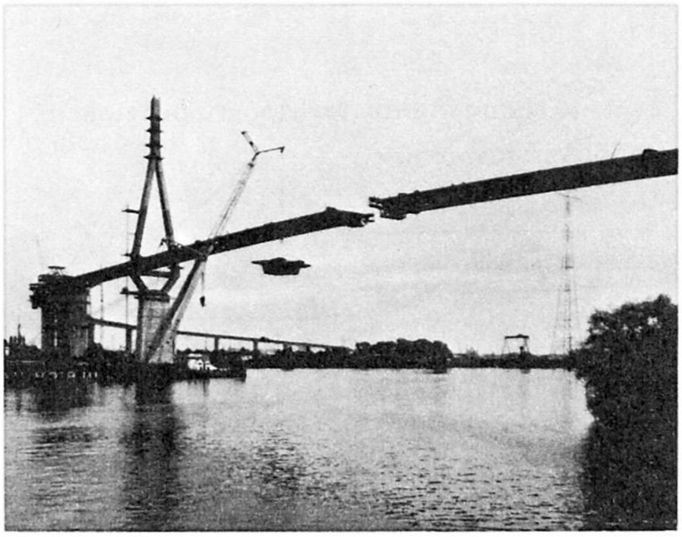

Fig. 11

The number of field joints should be kept as low as possible. This is also favourable to the structural design, because the number of disturbance points is reduced. The hours required in the shop and in the field as mean values obtained from numerous large bridge constructions of different types in recent years are shown below:

- Shop	-- Preliminary drawings	3.3 %	
	-- Machining operations	7.7 %	
	-- Assembly	24.8 %	55 %
	-- Welding and riveting	14.8 %	
	-- Shop erection	4.4 %	
- Field	-- Site installations, means of erection	8.0 %	
	-- Erection	31.0 %	45 %
	-- Supervision, miscellaneous works	6.0 %	

Longitudinal systems, which do not depend on the load-carrying system, are highly conducive to fully automatic fabrication because the units are uniform and can be shipped to the site in accordance with the speed of erection, eliminating interruptions of the work (Fig. 12).

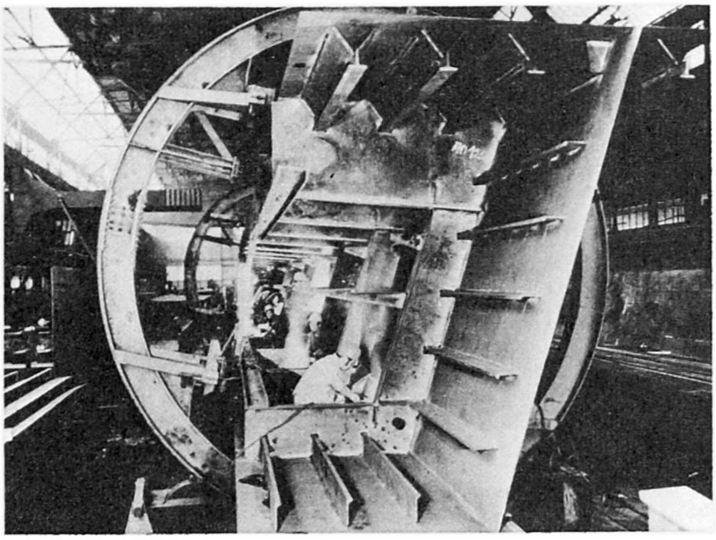

Fig. 12

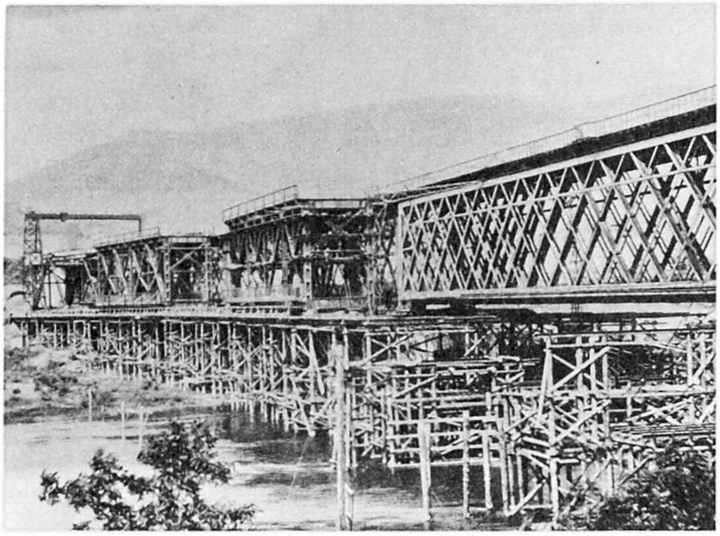

Fig. 13

The principle of erecting the load-carrying system free of stresses and strains, and subjecting only the completed bridge to loads, has long since been abandoned because the supports required are uneconomical and very often not feasible from technical points of view (Fig. 13).

The erection methods used today utilize the load-carrying capacity of the intermediate erection systems and the erection joints in cantilevering construction are connected continuously to the beams with or without ground supports or stay cables (Fig. 14, 15). Complicated intermediate loadcarrying systems, which do not correspond to the final load-carrying systems, are very often necessary during erection. High stresses and strains generally result from this and the accumulated erection stresses are superpositioned on the final stresses of the bridge. The additional material needed is, however, in no proportion to the advantages of cantilever construction.

Cable stay bridges are highly suitable for erection of wide-span beams, above all multiple cable structures, because they allow favourable intermediate erection systems by the intermediate stay cables which harmonize well with the final system by correcting the cable forces, if required. Since this type of bridge also allows the use of "factory-grown" beams of uniform cross sections, it is quite understandable that it is increasingly resorted to in steel bridge construction.

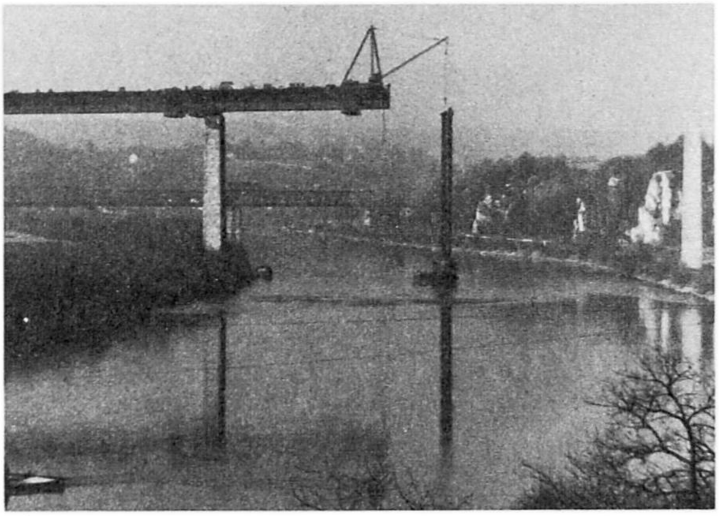
Fig. 14

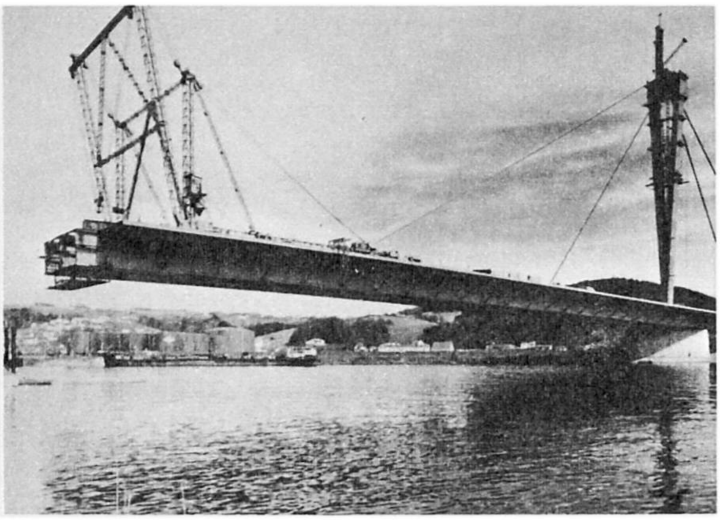
Fig. 15

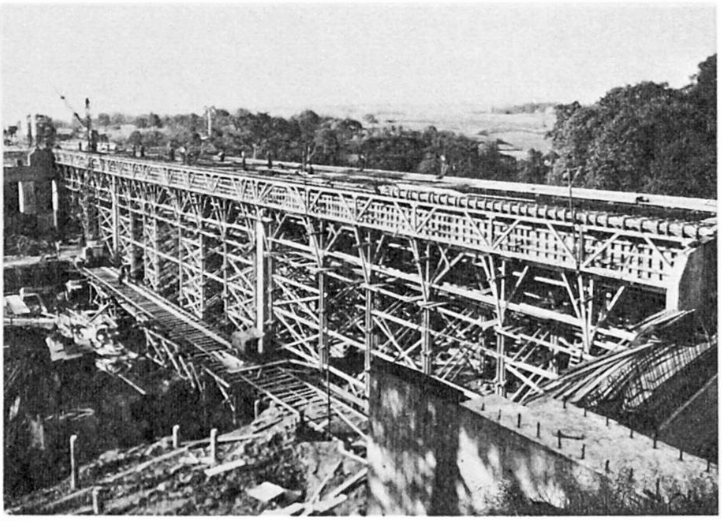
Fig. 16

Formwork and scaffoldings are considerable cost factors in reinforced concrete bridge constructions (Fig. 16, 17) and in order rationalization is here of primary importance. Following the lines of steel bridge erection, the prefab beam method and, for long spans, the cantilevering construction method using in-situ concrete are resorted to. In the latter method, the beam is built as a cantilevered member with stepping formwork (Fig. 18, 19).
Normally, cantilevered construction is carried out from the piers as symetrically as possible and the cantilever arms join in the centre of the span where the centre joint is made by an articulated coupling or a continuity connection with continuous tendons.
In order to eliminate difficulties arising when cantilever construction starts from slender and high piers, the method of working in one direction only is useful, but it requires auxiliary pylons with cable stays in order to support the beam during erection (Fig. 20). The speed of erection is, however, considerably less, since there is only <u>one</u> working platform to proceed.
At first, re-bars in the main load-carrying direction were used in cantilever construction. They were lengthened section-wise by couplings with the joints preferably arranged alternating at every other section joint (Fig. 21). About

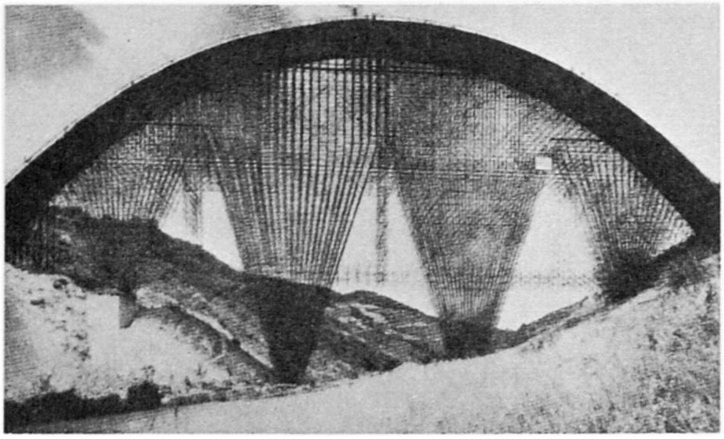

Fig. 17

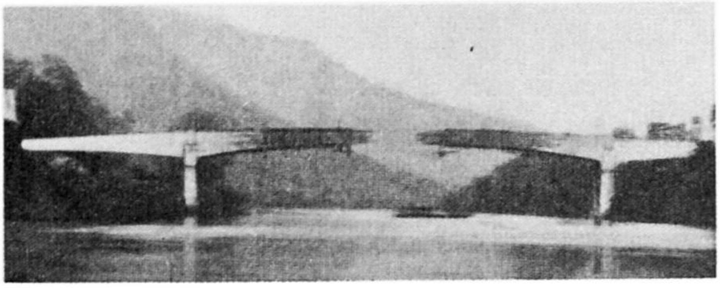

Fig. 18

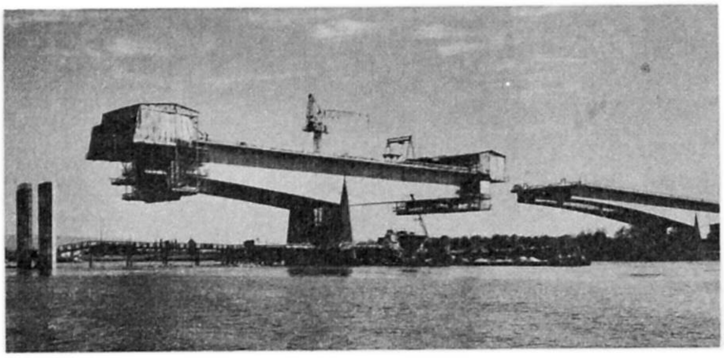

Fig. 19

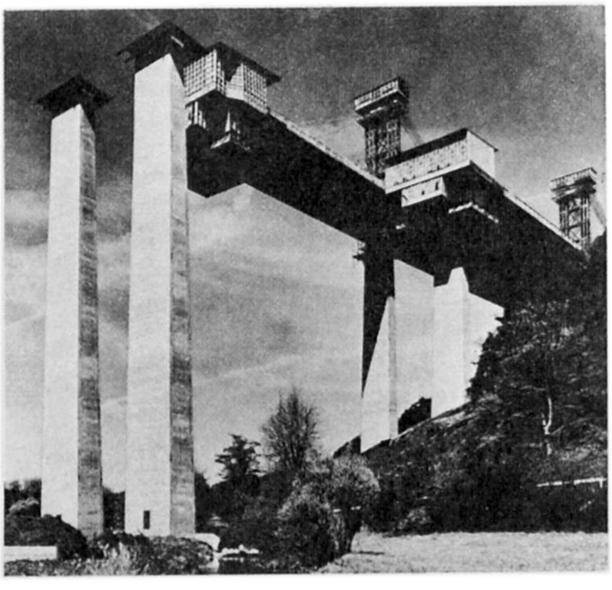

Fig. 20

twenty five years ago it was discovered, however, that continuous wire cables without joints can easily be used, if the sheathes can reliably be laid section-wise at the same time by using stiffeners (Fig. 22). Since then, the use of wire cables for prestressed concrete bridges built by the cantilever method has increased throughout the world.

Stepping formwork equipment was used for the first time about twenty years ago. This equipment bridges the ground between piers and allows in-situ concrete bridges to be constructed spanwise by repetitive operations (Fig. 23, 24). Since construction operations do not proceed on the ground but at bridge deck level, any lengths, even with changing locations, can easily be built. In the case of large spans, it is advisable to combine section-wise and spanwise construction (Fig. 25, 26). In this case the cantilever span and the back span are built out from the pier at an equal rate with the stepping formwork equipment providing a link for men and materials. It is also possible to increase the sections and the speed of construction, since the dead loads of these sections are temporarily fully or partially absorbed by the stepping girder prior to prestressing. The lengths of the sections

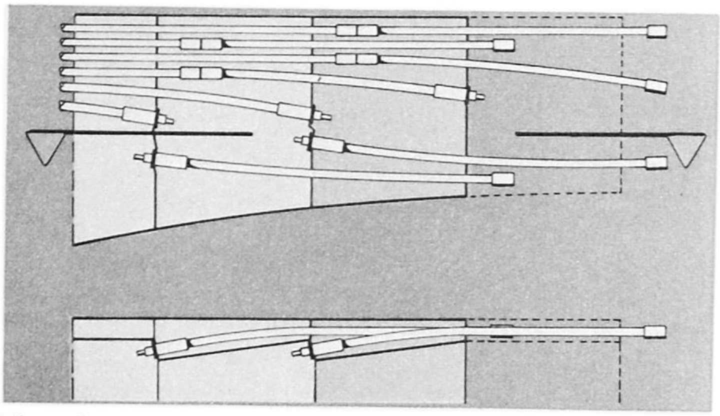

Fig. 21

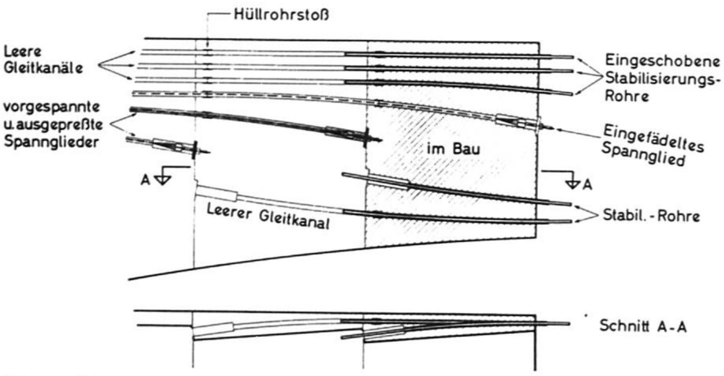

Fig. 22

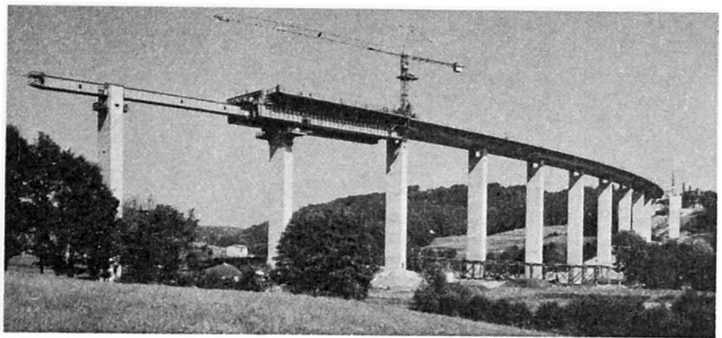

Fig. 23

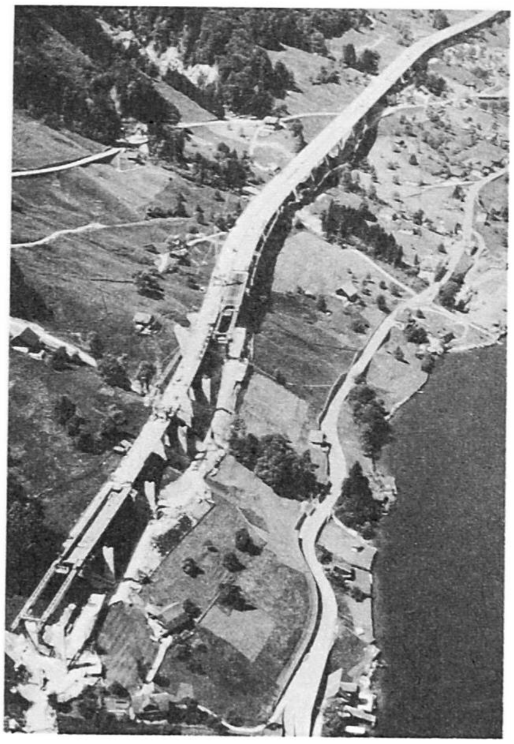

Fig. 24

should be adapted to the spans and the required speed of construction. It can be calculated, and local conditions, especially the number of repetitive spans, decide on how much steel should be used and invested for the stepping formwork equipment. This method has also been reversed by setting up stationary

Fig. 25

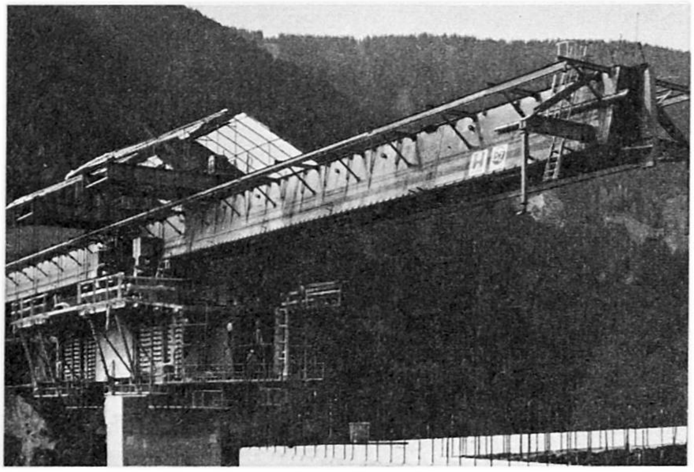

Fig. 26

facilities at the end of the bridge and building the superstructure from there piece by piece. This is an improvement to the method to cast the superstructure in one section after another, stressed together, and the entire structure inserted lengthwise. But since space behind a bridge abutment is normally restricted, it is much better to move the superstructure sectionwise in accordance with the concrete pouring length (Fig. 27). Steel cantilever erection girders limit the cantilever moments in the beams resulting from stepping. A fine example of this type of construction is the recently completed 760-metre long bridge over the Shatt al Arab at Basrah. The superstructure of the prestressed concrete swing bridge was arranged in such a way that it could not be released from the erection joint until the beam, inserted from one side, had reached its final position (Fig. 28).

Fig. 27

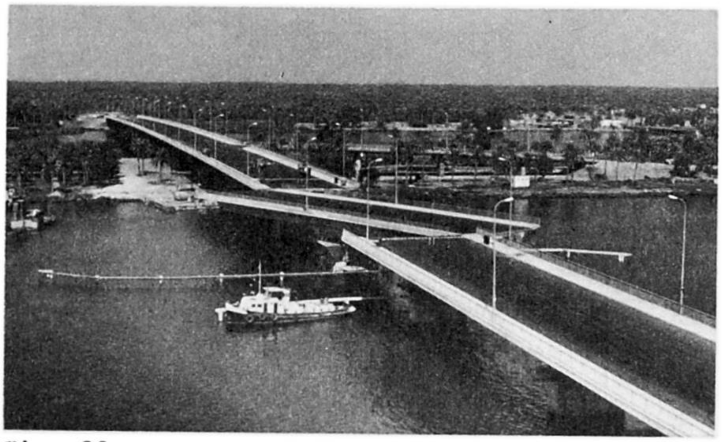

Fig. 28

Steel bridge construction ideas where always in mind when trying to increase the spans of concrete bridges. In both cases there is the same aim of reducing construction costs and time, while increasing quality. None of the methods mentioned here use any stationary falsework and this minimizes the technical risks involved in using this equipment, which are difficult to assess anyway. Repetitive operations reduce labour costs, which is of great importance in view of the constant rise in wages and the shortage of skilled men. Efficient utilization of materials also requires unsophisticated and easily

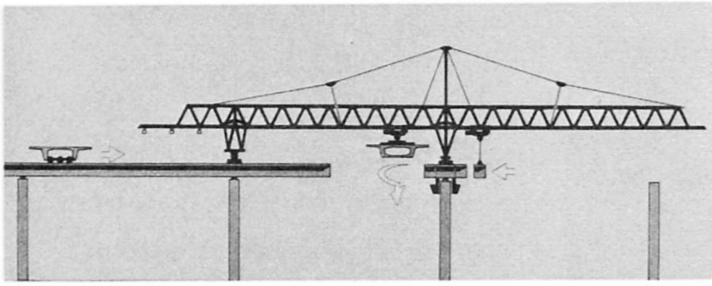

Fig. 29

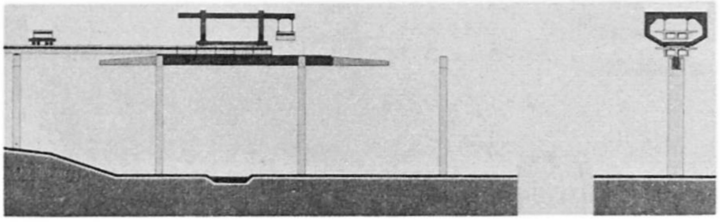

Fig. 30

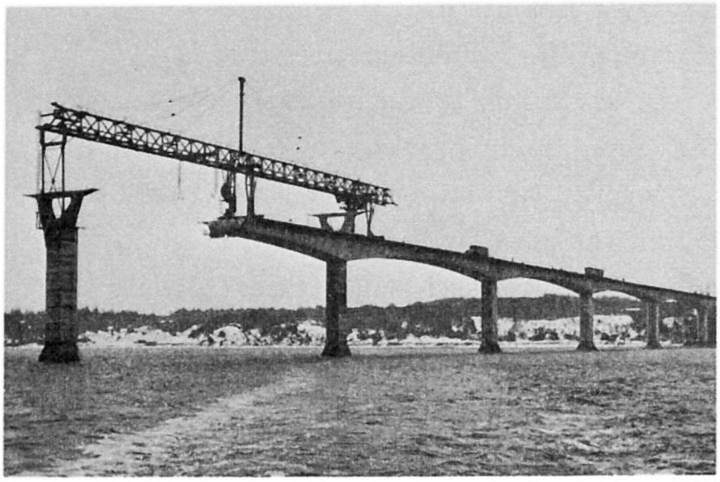

Fig. 31

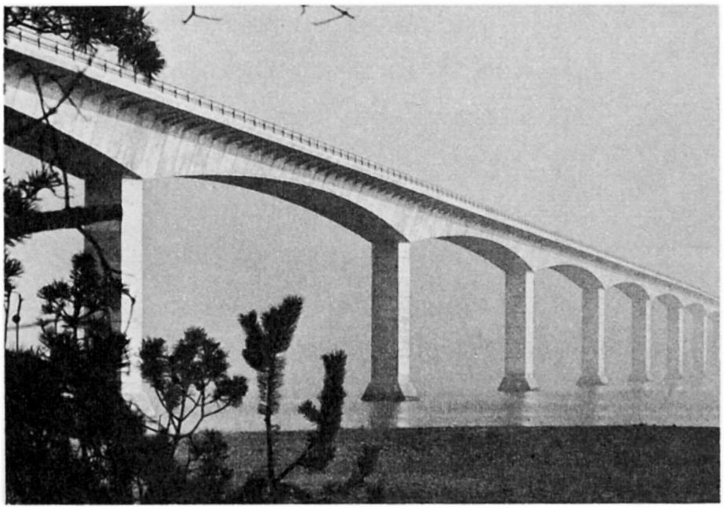

Fig. 32

controllable operations resulting in high quality of the final structure; (not only the quality of material).
Therefore, prefabrication of boxes and span-wise construction with stepping formwork equipment especially (but not only) for large spans is growing increasingly important (Fig. 29, 30).
In this case, however, no attempt is made to interlock fabrication and erection as in steel bridge construction. Here fabrication and erection are intentionally separated in order to eliminate weekly repetitive cycles and allow fabrication to continue under cover even in bad weather so as to achieve a higher rate of progress of the erection work.
The question of whether it is sufficient only to stress the bridge deck together with tendons and to fill the joints with adhesive, for example epoxy, without continuous mild steel reinforcement has not yet been sufficiently answered.
As is generally known there are the Germanic and the Romance point of view; and it will definitely take some time until an understanding is reached. The crucial question is whether advantages for the life of the bridges outweigh the disadvantages if its quality is better controlled by using prefabri-

Fig. 33

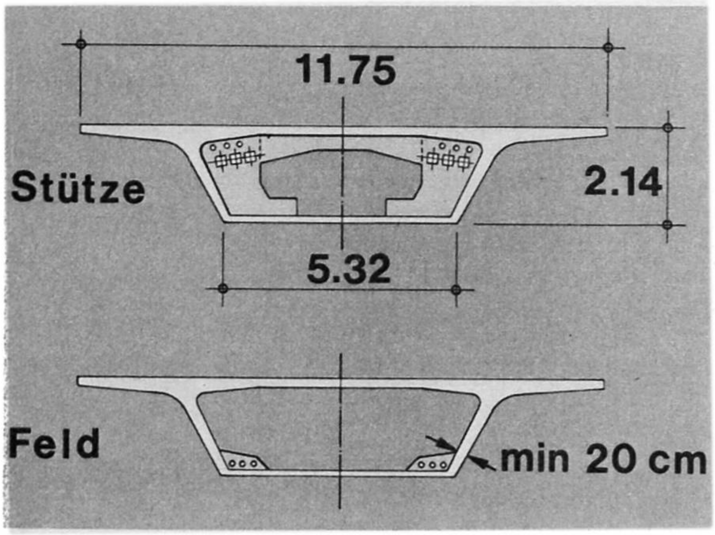

Fig. 34

cated boxes and the risk of cracking is concentrated in the joints. A clean joint seal without reinforcement and sufficient prestress in the compression zone are decisive factors for the life of a bridge. No disadvantages were found in this respect in recent investigations on the Sallingsund Bridge in Denmark (Fig. 31, 32). The maximum standard span feasible with span-wise stepping formwork equipment constructed sectionwise is ~ 150 m.

For spans up to about 50 metres, where the prefab boxes lined up on a stepping girder, connected and stressed together span-by-span, there are new examples in which the reinforcement joint overlaps on the support (Fig. 33, 34). This allows the tendons to be installed independently span by span within the box girder. The tendons running beside the webs in polygonal pattern are only connected point-wise to the system. This simple method of installation speeds up and provides easy access for checking and replacing tendons. It was found about thirty years ago that a continuous bond between tendons and the surrounding concrete is indispensable to prevent relative movement between them. Large relative movements between tendonds and surrounding concrete can lead to cracking, necking of the compression zone and collapse due to compression failure. The magnitude of tendons is important if failure strength is to be proved in respect of a system of suspended cables or (and) the bonded cables and reinforcement in the slabs. This is perhaps another divergence of opinion between Germanic and Romance countries in the structural field, but a final clarification to this problem has an important bearing on the choice of this construction method.

The aim of completing two spans in a week could, however, also be achieved by just prefabricating the outer skin (including accurate placing of the outer reinforcement), placing the load-carrying tendons (Fig. 35) (including the continuous mild steel reinforcement) in large units in the webs, placing the trans-

Fig. 35

verse reinforcement in the form of mesh and cages for the slabs and cross beams and pouring all the concrete. This would reduce working time on the stepping girder to such an extent so that two cast-in-place concrete spans could be completed within a week.

Individual solutions in the construction of concrete bridges are only useful if standard solutions cannot fully be applied or are excluded by local site conditions. Thus, the tied cantilever bridges and the cable stay bridges were followed by the multiple-cable stay bridges which allow a continuous construction of the beam in cantilevered section-wise construction using in-situ concrete or prefabricated cross-sectional boxes (Fig. 36, 37). Whereas in the construction of a tied cantilever bridge, temporary cable stays are required to hold the large cantilevered arms until the final cable stays take over the load, the multiple-cable system allows the use of final cable stays during the actual construction. In this case, one final stay after another is placed as work progresses.

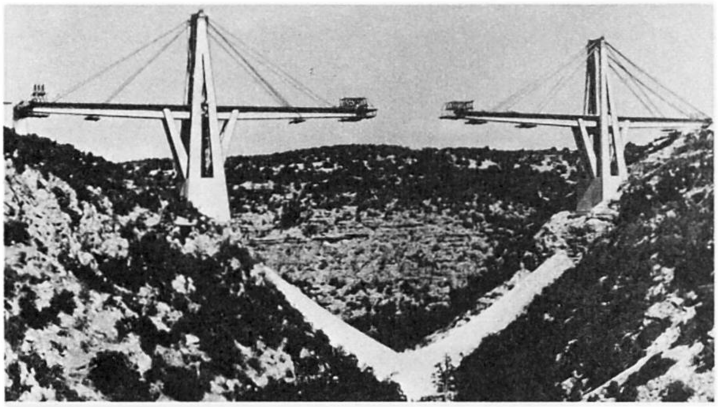

Fig. 36

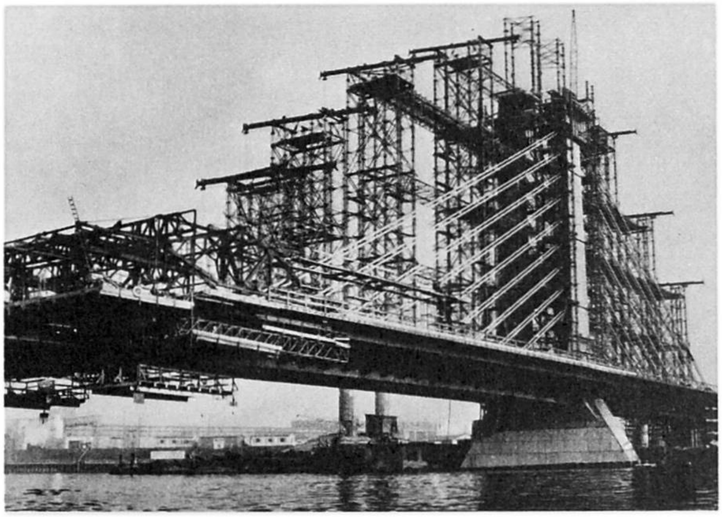

Fig. 37

If a cable stay bridge is flanked on one or both sides by long approach bridges, it is advisable to run the bridge beam through the main opening in one size (Fig. 38). It would even be possible in such case to proceed cycle-wise from one side or both sides by using temporary supports or cable stays and provide final suspension at a later stage.
Stepping in a bridge beam in an arch has already been done successfully (Fig. 39). The final arch was used as an erection aid. In the case of cable stay bridges, it should also be possible to use only a limited number of temporary supports or to do without them when stepping, if the pylon with the cable stays could be

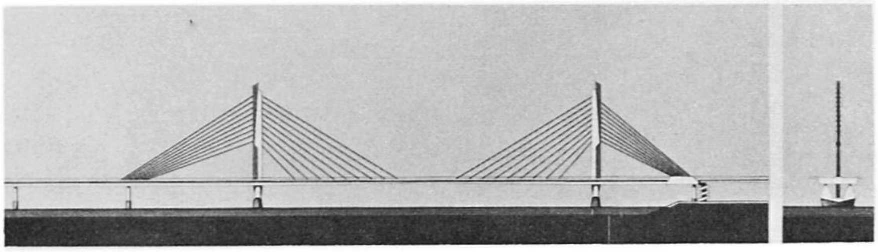

Fig. 38

erected before the beam reaches the larger spans during stepping. The final cable stays could then hold the cantilevering beam during stepping. This, however, means that the load of the pylon must be supported by the beam in the extreme spans using erection aids, if necessary, such as cables temporarily placed in or outside the beam. This method could be used for a single pylon in the centre line with a central curtain of ropes. It might also be used for an A-pylon if, during stepping in, a simple temporary pylon would be used which, in final position, transfers the head and the cable guides to the final A-pylon (Figs. 40, 41).

Interchangeability of all cables preferable made on the site is a prerequisite for cable stay bridges. On this basis, multiple-cable stay bridges, on which individual cables are most easily replaced without seriously interrupting traffic, are the most favourable.

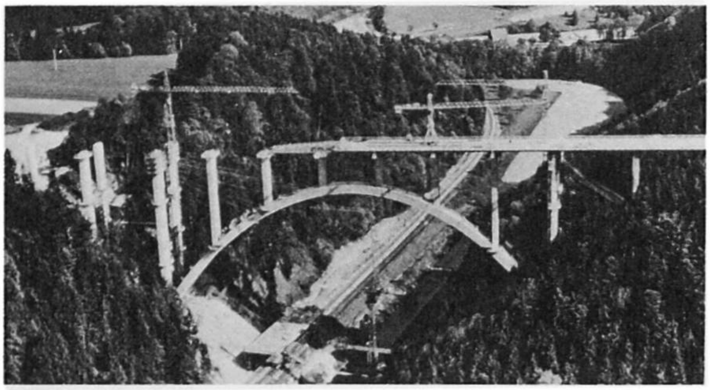

Fig. 39

As it is now possible to haul large units weighting about 40 tons, shop fabrication of cables could again be used whereever possible, under prevailing conditions. It is quite possible to reel cable lengths of 1'000 metres. The locked wire strand cables, which have proved their worth in the past, could again be used, if the difference of deformation is insignificant in view of the reduced modulus of elasticity and if they are competitive in price. It is generally known that big cable packages of sufficient rigidity are less susceptible to vibrations induced by the wind than the nonrigid cables of multiple-cable systems. If the advantages of the multiple-cable system are to be utilized fully, the vibrational behaviour of the cables should be carefully studied and controlled, if required, by vibration damping measures.

The high dead loads of concrete bridges for which they are very often criticized, can thus be used to good purpose on cable stay bridges. Oscillating loads resulting from traffic are opposed by larger cable cross sections which reduce the amplitude of vibrations. This is a defi-

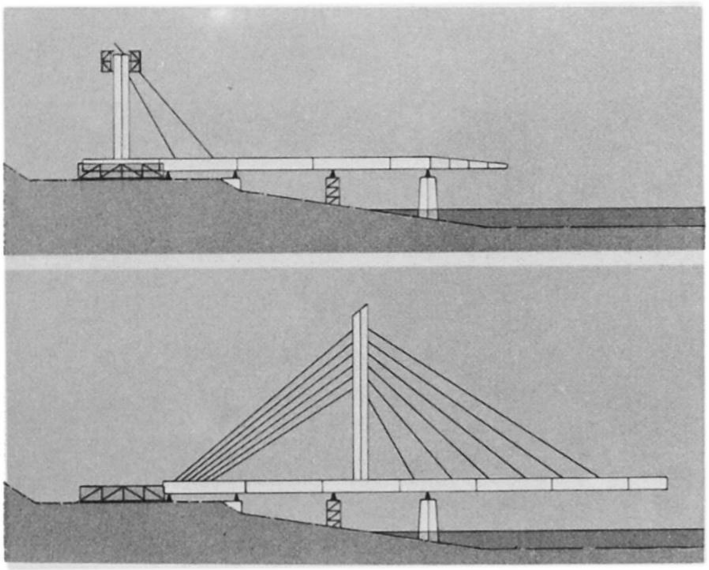

Fig. 40

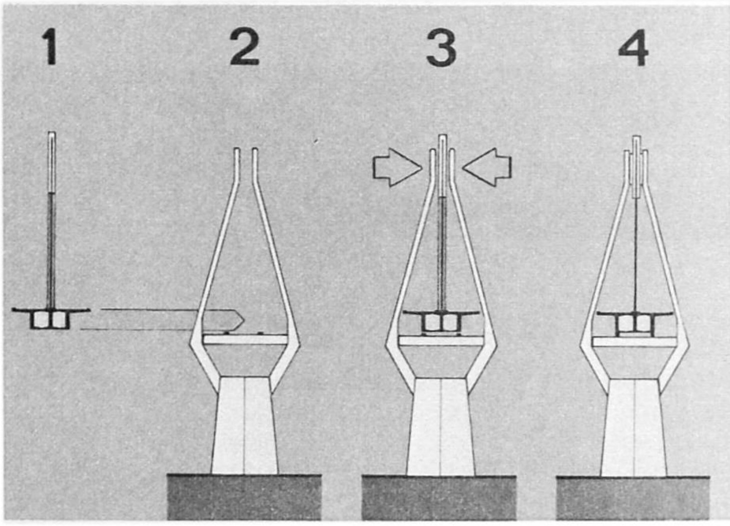

Fig. 41

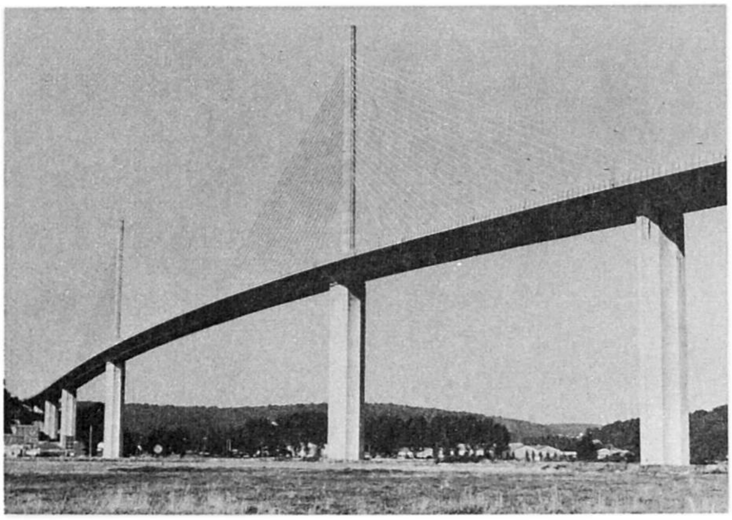

Fig. 42

nite advantage if high traffic loads prevail. Nevertheless a reduction in weight is desirable for large spans. It is held that spans of 600 to 1'000 metres are possible on symmetrical prestressed concrete cable stay bridges. 320 metres have been achieved on the Brotonne Bridge (Fig. 42). Highgrade light-weight concrete, which can also be used for wide-span beams like those on the new Rhine Bridge Köln-Deutz, could gain more importance in the future. It is useful, above all, when load multiplied by lever arm is most efficient and the longitudinal compression stresses are minimized.

In spite of some examples and interesting ideas, prestressed concrete has not yet become an established feature of suspension bridges, perhaps because even in steel bridge construction suspension bridges are still only used for the very large spans. There are more promising prospects for the use of prestressed concrete on cable stay bridges.

Steel bridge construction and concrete bridge construction will continue keeping a close eye on each other in the future in order to learn from each other and build more durable bridges quicker and at a lower cost. From time to time, they will also cooperate to use both material to the best possible advantage in steel/concrete structures.

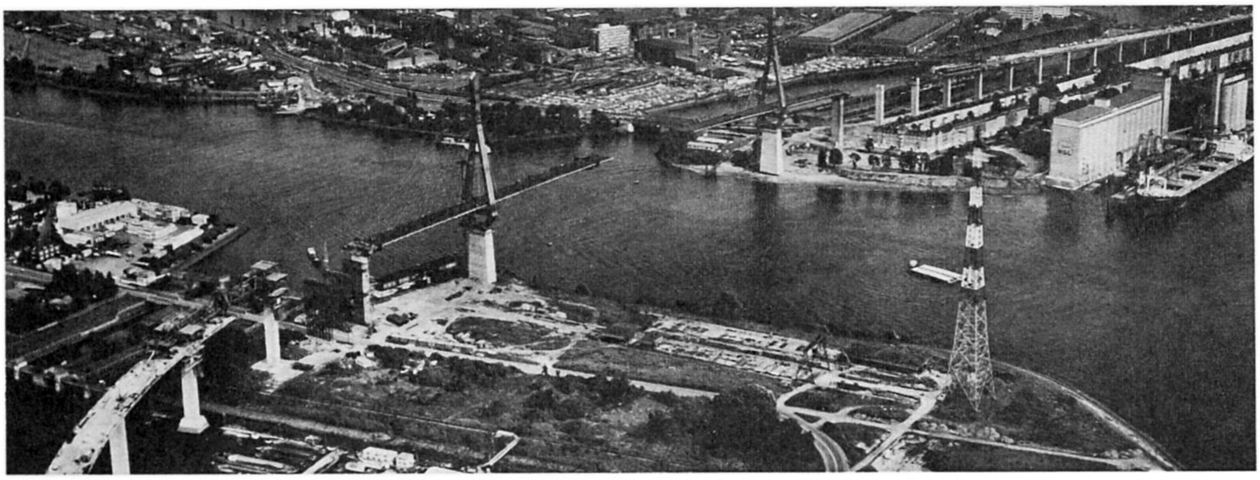

Fig. 43