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Triangular Concrete Trusses

Structures triangulées en béton

Dreieck- Fachwerke aus Beton

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SUMMARY

Although the idea of triangular concrete trusses is not a new one, such structures have now been recognized for the savings afforded by prestressing techniques. This article summarizes the theoretical advantages of triangular trusses, and includes arguments in favor of their quality and durability characteristics.

RÉSUMÉ

Les structures triangulées en béton ne sont pas une idée nouvelle mais sont aujourd'hui économiques par les avantages d'assemblage donnés par la précontrainte. Quelques chiffres montrent les avantages théoriques de telles structures, et des arguments sont énumérés pour prouver que ces structures offrent toutes les garanties de qualité et de durabilité.

ZUSAMMENFASSUNG

Die Idee der aus Dreieck-Fachwerkträgern zusammengesetzten Betonkonstruktion ist nicht neu. Das Konstruktionssystem ist jetzt jedoch preislich interessant geworden, da der Spannbeton neue Möglichkeiten beim Zusammenfügen bietet. Einige Zahlenangaben zeigen die theoretischen Vorteile dieser Konstruktionsart und es werden Argumente aufgeführt, die beweisen, dass die Konstruktionen alle Garantien für Qualität und Dauerhaftigkeit bieten.

*Translated into English by Ms. A. Frank

The design principle of triangular trusses is not a new one. Indeed, Albert CAQUOT implemented structures of this type for the Gare de l'Est station and a bridge over the Seine, in Paris.

The technique was soon abandoned, having met with considerable practical difficulties which seemed to outweigh its theoretical advantages, namely high density of reinforcement. At that time reinforcement consisted of smooth bars entailing substantial staggered overlapping, resulting in complex reinforcement patterns, full propping of structures and extremely intricate formwork. Concreting was a laborious operation and compaction techniques were inadequate.

Since then, construction difficulties have often given rise to the opinion that the basic principles of triangular concrete frames were analogous to those of structural steel, but that concrete structures should be based on simpler designs, specifically suited to the nature of the technique. The recognized disadvantage of the simpler designs is that they entail a significant increase in the deadweight of a structure.

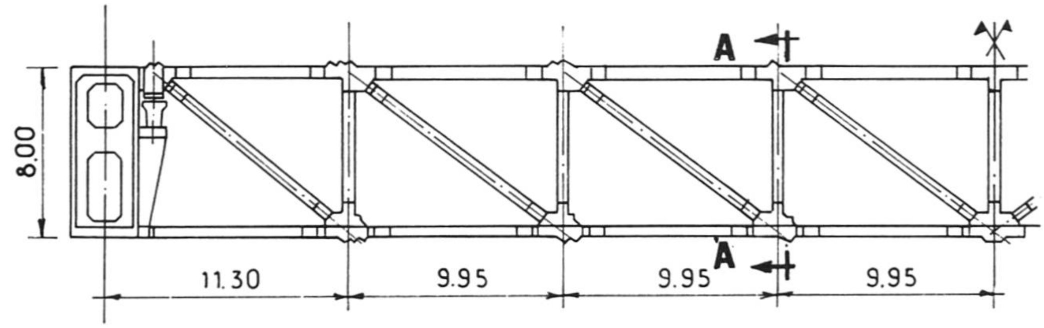
The development of prestressing shed new light on the problem of construction. Prestressing facilitates assembly of individual precast elements ; without such techniques, cantilever bridge construction methods would not be realistic.

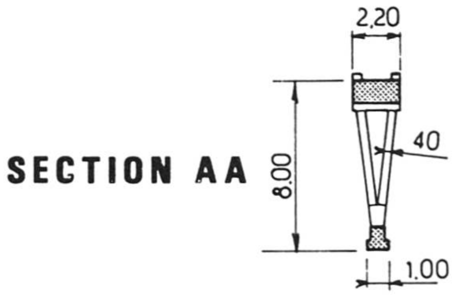
In 1972, we were faced with the unique construction challenge of roofing for the omnisport facilities of the Tehran Olympic Complex, which led us to take a closer look at simple design principles. In fact, the economic situation of Iran, the need for completion in record time which required simultaneous execution of seating and playing fields or of pools and their roofing, the seismic history of the country, which made lightweight roofing a necessity, all contributed to our decision to build triangular-truss girders of 80-meter span.

The implementation of triangular trusses becomes economically feasible when the structure is broken down into smaller, simpler elements which are subsequently assembled by prestressing.

Hence, in this case, we cast the vertical members complete with starter bars for the diagonal members, that is, the upper flange of the tie rods. Then, the diagonals themselves, of simple geometry, are precast. All of these elements are cast in "prone" position, which simplifies both formwork and concreting operations. Of the above-mentioned members, only the vertical elements are of complex geometry. Elements are assembled on a good quality surface, by first positioning the vertical members at their final location in the soon-to-be-completed girder. Starter bars are equipped with steel elements designed to bear the horizontal and diagonal bars, as well as the joint shuttering and the starter bars built right into the vertical members. When joints are set, prestressing provides for final assembly of the various elements composing the triangular-truss girder.

Although this technique requires a well-organized jobsite, the economic and technical results have proved highly satisfactory. The following statements explain why we waited ten years before applying this technique a second time.





Figures 1 and 2 : Simplified drawing of Tehran stadium truss girder :
half-span — cross section — photo

Until recently, the idea of external prestressing was only acceptable in structural repair operations. The fact that tendons had to be installed in the space occupied by the concrete itself led to large-scale elements and girders generally too tall for use in bridge decks. Finally, we wanted to apply segmental precasting techniques which had already yielded satisfactory technical and economic results.

In 1980, thanks to a new outlook on external prestressing and a series of exceptional circumstances, we were able to design a triangular truss for an important project in KUWAIT. In conjunction with this contract, we implemented industrial-scale production methods, thus taking full advantage of the theoretical aspects of this technique.

1. THEORETICAL ADVANTAGES OF PRESTRESSED TRIANGULAR FRAMES

As we know, the efficiency factor of a section is expressed by :

$$\rho = \frac{I}{Svv'}$$

This is the fraction of the height of a section, within which the resultant compression can move without resulting in the decompression of the extreme fibers of the section. Therefore, the prestressing force required must be inversely proportional to the value in order for the section to withstand a variation in moment, Δ M. It is easy enough to verify that the value ρ is higher for a triangular-frame structure than for a solid-web structure, allowing for a savings in prestressing. Moreover, since the triangular frame results in a better distribution of tangential stress, it can be built lighter than solid-web structures, thereby reducing dead loads.

Efficiency factor calculations for the main span of a structure with an infinite number of 40-meter spans and a section height of 3.00 meters yield the following values :

Concrete box-girder with solid web and internal tendons : $\rho = 0.582$
Concrete box-girder with solid web and external tendons : $\rho = 0.614$
Triangular truss : $\rho = 0.722$.

These basic theoretical aspects explain the savings obtained in construction materials. Likewise, average concrete thicknesses for the cases cited in value calculations are : 0.53 m, 0.49 m and 0.39 m, respectively. The quantities of prestressing per square meter are, respectively 14 kg, 11.3 kg and 8.9 kg.

Substantial savings in construction materials is not the only advantage of triangular trusses : this technique also results in improved structural quality, as explained below.

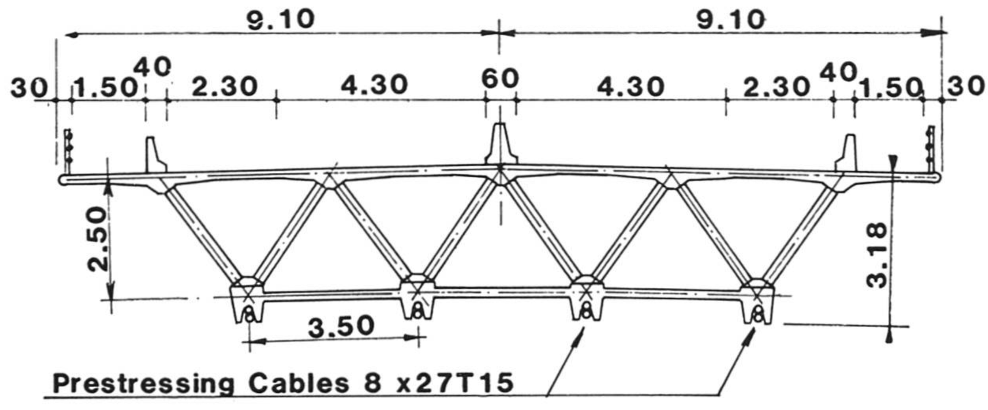


Figure 3

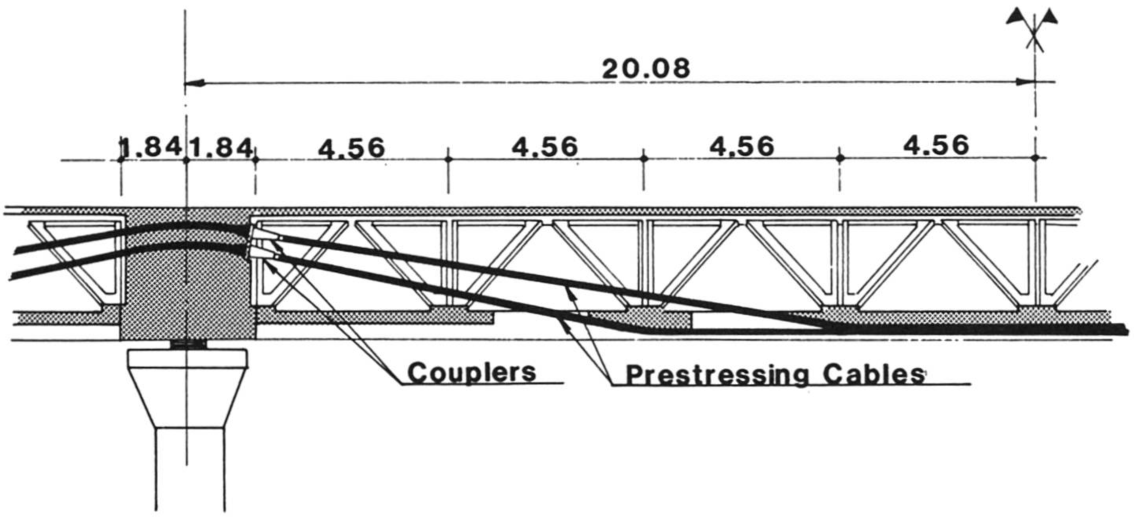


Figure 4 : Longitudinal section of typical half-span

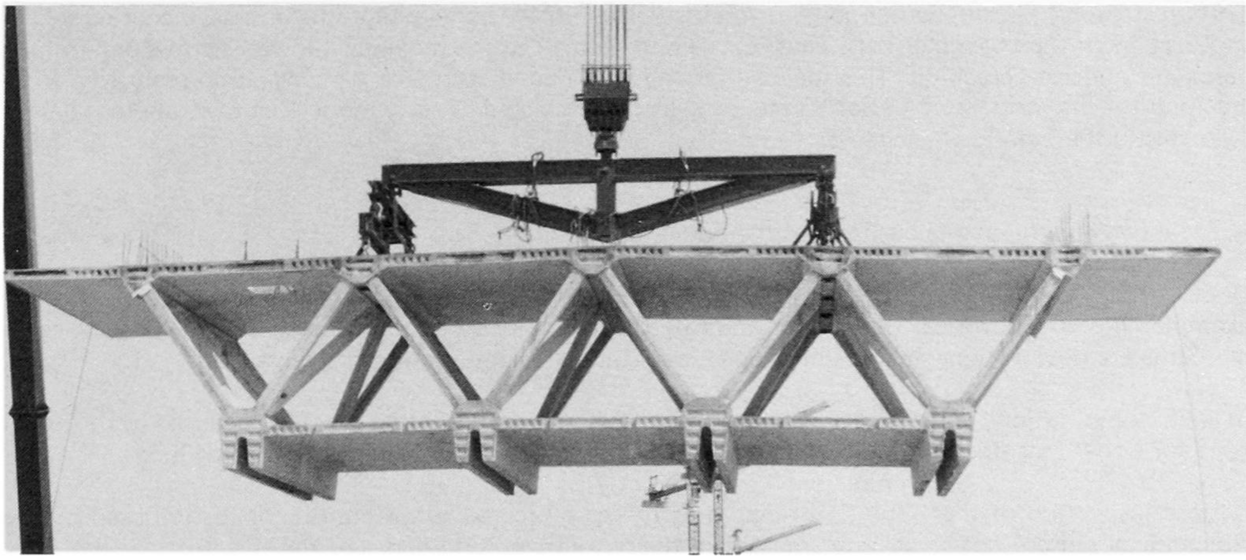


Figure 5 : Photo of triangular truss of Bubiyan Bridge

Traditional solid-web box-girders have the lowest possible number of webs –– usually two or three. These restrictions are imposed essentially for reasons of cost, formwork complexity and dead load limitations.

However, the resulting configuration leads to compressive stresses in the upper and lower flanges of the girders, which can be susbstantially higher than the average design values traditionally used, as we learned long ago from precise elastic design. Other factors are also involved. For instance, limiting the number of webs in a girder has the direct effect of increasing the thickness of the existing webs, and it is not uncommon to see thicknesses of 0.60 m, 0.80 m or even 1.00 meter. Shrinkage occurs more slowly in these elements, namely at the node joint between web and slab, than in the deck slabs themselves. It would seem logical that stress becomes concentrated in the webs. Measurements tend to confirm this hypothesis.

The triangular truss designed for the Bubiyan Bridge in Kuwait accommodates a greater number of webs for a given section of box-girder.

It is thus clear that elastic design leads to an improved distribution of normal stresses in the slabs. Since elements are of almost uniform thickness, stress patterns are not aggravated by the phenomenon of differential shrinkage.

Finally, bending strain in the cross section is greatly reduced. It thus appears justified to consider a simplified triangular truss section (fig. 3). On the other hand, computations currently performed on traditional wide or extra-wide box girders with two webs must be deemed erroneous, since actual working stress values are quite different from those obtained through this simplification.

2. FREQUENT OBJECTIONS TO TRIANGULAR TRUSSES

– Tensioned bars in triangular structures

We have used reinforcement bars made of high-tensile steel, where allowable stress values are limited by concrete cracking conditions.

We believe, and experience has shown, that cracks whose width does not exceed 0.1 or 0.2 mm have no deleterious effect on the durability of reinforcing steel. The main determinant is the degree of concrete compaction.

The prestressing pattern is defined in non-loaded conditions, such that the stresses occuring in the various bars of the triangular truss never exceed one-fourth of the maximal allowable stress determined based on concrete cracking. This means that the non-loaded structure remains completely free from cracking for a considerable period. Tests now in progress on a life-size model demonstrate that cracks close back up in non-loaded conditions.

– Second-degree moments occuring at the nodes

Under dead weight and prestressing, deflection of the structures is slight. The Bubiyan Bridge, for example, has a theoretical deflection value of 0.8 cm. Since deflection is so slight, second-degree moments are obviously negligible under dead loads, and are only produced by live loads.

In fact, computations and testing performed on the model show that no cracking occured in the nodal zone for either tensioned or compressed bars, until well beyond the maximum working load.

A close inspection of the Bubiyan Bridge after it was subjected to exceptional loads imposed by the launching girder did not reveal any cracking in the more than 8000 nodes of the structure.

– Calculation difficulties

We performed both simple and sophisticated calculations, as well as test model measurements. The experiments conducted justify basing computations on a simplified model.

Calculations of overall stresses can be performed as for a traditional box-girder, but with more accurate results. Stresses in the diagonals can then be defined by Cremona's method, with deviations of less than 20 % and on the safe side. With a little bit of practice and a few basic rules, design of triangular-truss structures does not entail any exceptional research investment.