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Considérations économiques sur le béton précontraint

Die Wirtschaftlichkeit von vorgespanntem Beton

The economy of prestressed concrete

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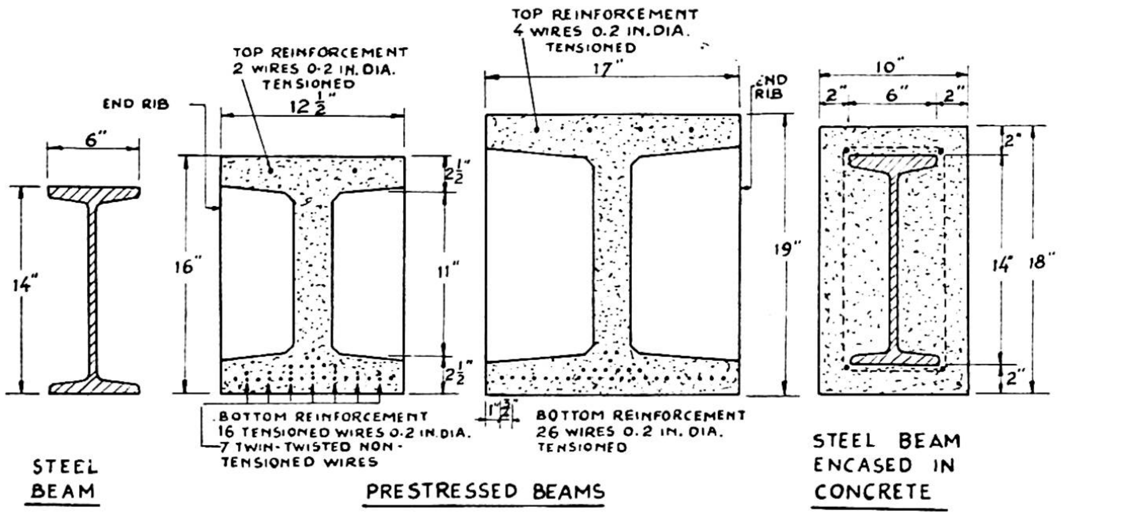
The cost of prestressed concrete work is made up very differently in the cases of pre-tensioning (when the prestress is transferred to the concrete by bonded wires which were tensioned previous to casting) and post-tensioning (i.e. when the prestress is obtained by reaction against the hardened concrete, the steel being non-bonded at tensioning).

Pre-tensioning relates particularly to precast reinforced concrete; consequently, the main consideration for pricing is that of precast concrete work. The cost per unit volume of precast concrete depends particularly on the amount of steel required (e.g. 6 lb per cu. ft corresponding to 100 kg/m^3) and on the amount of depreciation of the mould taken into account. Thus, the price of precast reinforced concrete placed in position varies, within a wide range, for various products, if in addition to differences in steel quantities, shape and depreciation of mould, also different distances for carriage are taken into account.

On the whole, the steel consumption of prestressed concrete per unit of concrete is much less than that of ordinary precast reinforced concrete, even if in view of the higher permissible stresses, the concrete section is reduced. On the other hand, the price of high strength wire is considerably higher than that of mild steel, and the cost of tensioning must also be taken into account. Considering these points, it can be said that the unit price of prestressed concrete should not greatly exceed that of ordinary reinforced concrete (say up to 20 per cent). This depends mainly on an economical use of moulds and on a suitable arrangement for tensioning. It must be borne in mind that the price depends greatly upon the output, which, in turn, is dependent on the demand.

In fig. 1, a steel joist $14'' \times 16'' \times 46$ lbs is compared with two prestressed concrete members, one designed as a partially and the other as a fully prestressed beam. The stresses and material consumptions are seen



DEAD WEIGHT	46	90	120	210	LB. PER FOOT
STEEL WEIGHT	46	3.2	3.0	APPROX. 50	
Pt + Pt'	—	APPROX. 80,000	APPROX. 120,000	—	LB.
STRESS-DIAGRAMS	18,000 (+); -18,000 (−)	-170, +1940 (AT TRANSFER); 1500, 0 (AT 0.57W); 2,725 (+), -1220 (AT W)	0, 2000 (AT TRANSFER); 1,700 (+), 0 (AT WORKING LOAD W)	STEEL: 18,000 (+), -18,000 (−); CONCRETE: 1,550 (+), -1,550 (−)	LB. PER SQ. IN.

Fig. 1. Comparison of stresses and material consumptions.

in fig. 1. The fourth member is a steel joist embedded in concrete wherein the additional carrying capacity of the concrete is neglected as is usual in railway design.

If a price of £ 40 per ton steel and 18/— per cu. ft precast concrete is taken into account, including transport and placing, then the following comparative costs per ft run are obtained; Steel Beam — 16/6 d. Partially Prestressed Beam 11/7 d. and Fully Prestressed Beam 15/3 d., the fourth member being obviously much dearer than the steel joist itself. It is seen that a fully prestressed member is cheaper than a steel joist, but the construction depth is increased. On the other hand, with a partially prestressed member both the depth and the costs are further reduced. However, this construction is unsuitable for certain purposes where permanent freedom from fine cracks must be ensured, but could readily be employed, for, example for roofs, floor, or transmission poles in which the maximum load occurs only occasionally, any fine hair cracks closing up in this special instance if the load is reduced to 57 per cent of the entire working load, when only compressive stresses occur in the section (1).

In the case of post-tensioning, the cost can be more clearly assessed than with pre-tensioning, since the main items for stretching the wires are represented by the end anchorages, the preparation of the cable and the hole or groove (afterwards to be filled with cement mortar) and the tensioning operation itself, the cost varying only slightly with the

(1) See the author's contribution : *The behaviour of prestressed concrete at cracking. Conclusions for Design.*

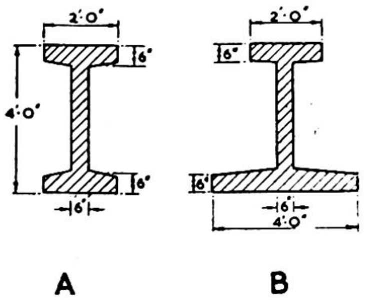


Fig. 2. Girders of types A (partially prestressed) and B (fully prestressed).

Girder " A "	£ s. d.	Girder " B "	£ s. d.
Concrete 320 cu. ft **a** 5 s.	80 0 0	430 cu. ft **a** 5 s. . .	107 10 0
Wire 0.55 tons **a** £ 80.—	44 0 0	0.6 tons **a** £ 80.— .	48 0 0
Tensioning, etc. 88 wires **a** 11 s. 3 d. (including anchorages)	49 10 0	138 wires **a** 11 s. 3 d.	77 12 6
Mould, used for 10 girders, say . . .	20 0 0	Mould, say . . .	23 0 0
Hoisting of girder 20 ft, say	30 0 0	Hoisting, say . . .	35 0 0
Total £	223 10 0	Total £	291 2 6

TABLE I. *Cost per girder.*

length of construction. Generally, the following costs apply for a group of wires, be it a round cable of the Freyssinet pattern or the Magnel-Blaton sandwich cable.

$$\text{Cost of prestressing} = C + H + A + J + T = a + b\,L.$$

C is the cost of the cable excluding the tensioned wires, but including spacers and placing, H the cost for preparing the hole or groove, and later filling it with cement mortar, A represents the cost for anchorage for the groups of wires at both ends, J is the cost for supplying the jack for the duration of tensioning the group of wires and T is the labour cost for tensioning. The entire costs are to a certain extent dependent on the length L of the member, a and b being constant values, in which a is normally of much greater importance than b L. Obviously, these values will differ for different type of cables and anchorages and may vary for different jobs, dependent on the influence of transport cost, travelling expenses, and the extent of the work. On the whole, post-tensioning will be economical for relatively long members which are produced near the site and hoisted into position.

Fig. 2 is a comparative example of girders of 80 ft span capable of carrying a load of 1 200 lb per ft, 40 per cent of which is live load, the depth being limited to 4 ft. A steel truss complying with these conditions would require a cross-sectional area at the top and bottom of approx. 16 sq ft resulting in a steel requirement of approx. 6 tons; this would cost say £ 360 per girder placed in position based on a steel price of £ 60 per ton, it being assumed that no lateral bracing is required (which would mean an increase in cost).

Table I gives details of cost of a partially prestressed girder A in which only compressive stresses occur under dead weight and of a fully prestressed girder B on the assumption that at least 10 girders are built. The cost of prestressing is taken rather high with 11/3 d. per tensioned wire of 0,2 in dia.

From Table I it is seen that a prestressed concrete girder is much cheaper than a steel truss of the same limited depth. Even in the event of some additional mild steel reinforcement being provided, the cost would be increased only by say 10-15 per cent, if approximately the same quantity of mild steel as wire were used.

The position becomes, however entirely different if the depth of the girder is not limited. Assuming for example the depth may be doubled, then the cost of the steel truss would be almost halved, to say £ 200 per girder. However, it is rather doubtful whether the costs of the prestressed beams could be appreciably reduced by increasing the depth. While the cost of the wire and that for tensioning, including anchorage, would be reduced, that for the concrete, mould and hoisting would be increased. Thus, a reduction of more than, say, 15 per cent, could hardly be expected for a girder of unlimited depth, resulting in £ 190 and £ 257 respectively for designs A and B.

It should be noted that in this special case, design A is still competitive and could be employed without hesitation in countries in which the full live load (snow) only seldom occurs.

From the foregoing it is seen that greater economy will be obtained by using prestressed concrete in cases of limited depth. This is of particular importance for floor constructions and road bridges over railways (in order to reduce the approach roads to a minimum). Fig. 3 shows two designs of road bridges which are being built in Great Britain to replace stone arches in order to provide clearance for an overhead collector wire in connection with the electrification of a railway line. A slab construction has been found most suitable to reduce the depth to a minimum and a combined construction has been chosen, as shown in design 1 in which the precast prestressed component with bonded wires represents the permanent shuttering of the slab. It is designed to carry the dead weight of the entire slab without any support and, in conjunction with the in-situ concrete of the slab, the dead weight of the deck construction and the live load. Under dead weight no tensile stresses occur in the prestressed members even after the greatest possible losses of the initial prestress have taken place; whereas under maximum live load (which however occurs in a road bridge very seldom) tensile stresses are permitted in accordance with the recommendation given in (1).

In this case the prestressed component is approx. 1/3 of the entire concrete consumption. An alternative design for encased steel joists was prepared in which the joists had to be reduced to 14 in (i.e. the same depth as the prestressed beams) in order to allow sufficient concrete cover. However, the additional carrying capacity of the concrete encasing has not been taken into account as is the practice in railway design. According to the lowest tender, the encased steel construction of one bridge would have been approx. 50 per cent dearer than the design 1 (fig. 3) taking into account only the concrete slab; and approx. 30 per cent, taking into account the whole bridge superstructure including parapet and deck.

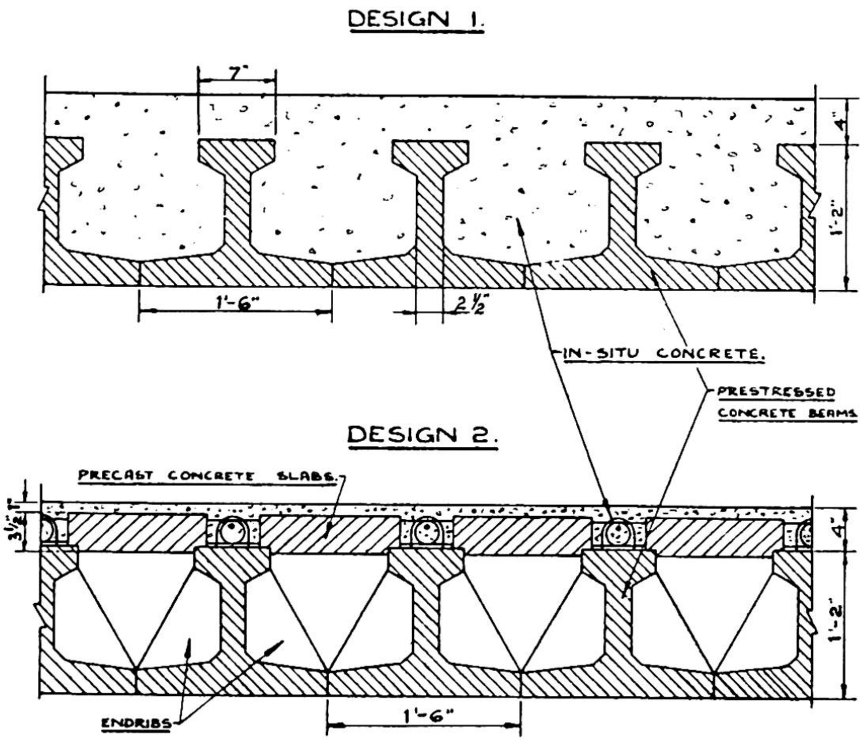


Fig. 3. Cross sections of two bridge designs.

Instead of 14 1/2 tons mild steel (13 3/4 tons joists and 3/4 ton steel bars) only 3 tons (1/2 ton hard drawn wire plus 2 1/2 tons mild steel bars) are required for the superstructure of the bridge in question. Thus, both reduction of cost and considerable saving of steel have been attained.

Design 2 of fig. 3 shows a cross-section of another solution, using the same type of prestressed beam in combination with precast slabs. Co-operation is ensured by a strip of in-situ concrete provided over the top of the joists into which links protrude from the individual precast elements, in addition to a continuous in-situ topping. This design is employed for bridges for which a lesser carrying capacity is required and a reduction of the in-situ concrete to a minimum is desirable in view of their isolated location. The saving in weight and cost is even greater in this case if compared with the conventional solution of a solid slab containing encased steel joists. (Acknowledgment : Fig. 3 is published with permission of the Civil Engineer, of the Eastern Region, British Railways, Kings Cross, London.)

In connection with the question of economy, fig. 4 may serve to discuss the development of a prestressed concrete floor construction. The Norwegian J. G. F. Lund's suggestion of 1907 was not successful similar to all other proposals of prestressing of that time, because the initial tensioning stress was too low and soon became ineffective. However, even if an effective prestress had been obtainable, this solution would not have been very suitable or economical.

Though the prestress is transmitted at post-tensioning by washers (as seen in the fig.) it would not be possible to prefabricate individual members but necessary to place the blocks on a centering, since the bars are located in holes formed by interlocking grooves of adjacent parts. Morever, it would be impossible to obtain an additional bond, since the mortar filler

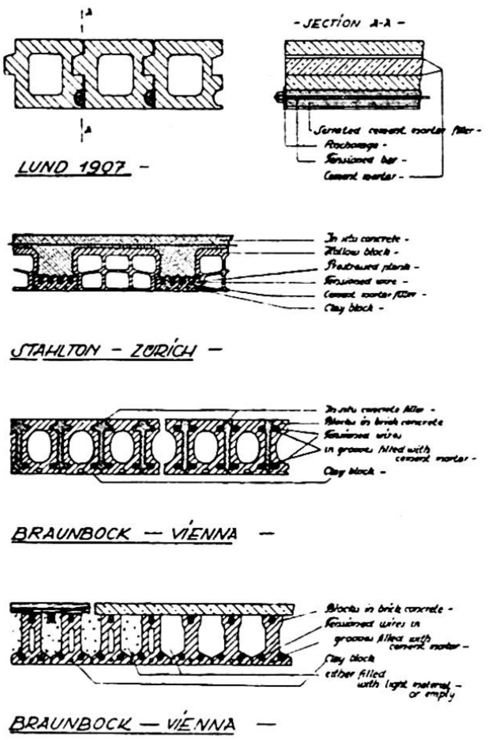


Fig. 4. Development of a prestressed concrete floor construction.

would have to be inserted into the hollows, before tensioning and the bond between mortar and bar would be broken at tensioning.

Compared with the proposal by Lund, the "Stahlton" floor, using prestressed planks, represents a great technical and economical improvement, the prestressed precast component being reduced to a small proportion. These planks can be produced in a small factory in which wires are tensioned over a long length and severed at the ends of the individual planks, after a mortar filler inserted in the individual grooves of clay blocks containing the wires, has hardened. The " Stahlton " floor has proved to be competitive with other non-prestressed floors apart from saving steel.

Though the manufacture of the " Stahlton " plank is highly economical and suitable for cheap mass production in a small factory, a certain plant is required. Mr. E.Braunbock of Vienna has developed a method for which no plant is required. Blocks of clay or brick concrete are prestressed at the site by means of a simple screw jack. Either they are only temporarily post-tensioned and the endplates are removed after the cement mortar filler (which completely surrounds the tensioned wires placed in grooves) has hardened; or relatively cheap anchor means are provided which remain permanently. The grooves may be filled before placing the individual member or afterwards, when the interspaces between adjacent members, together with the grooves are filled with cement mortar. These solutions allow the prestressing to be carried out at the site without requiring a factory. Thus, the extent of transport and handling is reduced, but the precast component is rather large which may offset the saving due to this reduction. It will therefore depend on certain circumstances whether this solution is really cheaper than the " Stahlton " floor. However, both these proposals illustrate the development of an economical floor construction.

When summing up, it can be stated that prestressed concrete is especially competitive when of limited depth. Precast members should be rather light in view of cost of transport and handling; thus, combined sections are always more economical. Of particular importance is an economical use of moulds. Post-tensioning allows new applications of concrete in cases in which ordinary reinforced concrete is unsuitable.

Résumé

L'auteur distingue deux cas : *Pré-tension* (lorsque les fils sont tendus avant le bétonnage) et *Post-tension* (lorsque les fils sont tendus après durcissement du béton). La pré-tension est en général limitée sur des éléments de construction alors que la post-tension est applicable sur des grandes constructions, à exécuter sur le lieu d'érection où a lieu leur mise en place par des engins de grande puissance. L'auteur donne des exemples comparatifs pour les deux modes de construction et montre les avantages économiques d'éléments partiellement précontraints.

L'auteur décrit ensuite deux types de passages supérieurs de ponts-routes construits en Angleterre. Pour terminer il donne le développement des planchers en béton précontraint.

Zusammenfassung

Zwei Fälle werden unterschieden; *Vorheriges Spannen* (wenn die Drähte gespannt werden, bevor der Beton gegossen wird) und *Nachträgliches Spannen* (wenn die Drähte gegen den erhärteten Beton gespannt werden). Vorheriges Spannen ist im wesentlichen beschränkt auf Eisenbeton-Fertigteile, während ein nachträgliches Spannen auf grosse Konstruktionen angewendet werden kann, die am Ort oder ganz in der Nähe der Baustelle ausgeführt und mit Hebezeugen in die endgültige Lage gebracht werden. Der Verfasser bringt vergleichende Beispiele für beide Arten und weist auf die grossen wirtschaftlichen Vorteile von teilweise vorgespannten Gliedern hin.

Dann bespricht der Verfasser zwei Ueberbautypen von Strassenbrücken, die in Grossbritannien über einige Eisenbahnlinien gebaut werden. Schliesslich wird noch die Entwicklung der Decken aus vorgespanntem Beton beschrieben.

Summary

Two cases are distinguished : pre-tensioning (when the wires are tensioned before the concrete is cast) and post-tensioning (when the wires are tensioned against the hardened concrete). Pre-tensioning is mainly limited to precast concrete, whereas post-tensioning is suitable for large constructions manufactured in place or near the site and boisted into position. Comparative examples for both cases are presented and the great economy of partially prestressed members is seen.

Two general designs of superstructures of road bridges are shown, which are being built over certain railways in Great Britain; also, the development of prestressed floor construction is illustrated.

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