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IIb 1

The Elimination of Tension in Concrete, and the Use of High Tensile Steel by the Freyssinet Method.

Der Ausschluß von Betonzugspannungen und die Verwendung hochwertigen Stahles durch das Freyssinet-Verfahren.

L'élimination de la traction dans le béton et l'application de l'acier à haute résistance suivant la méthode Freyssinet.

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Knowledge as to the causes and importance of crack formation in reinforced concrete has made great progress. Precautions against cracking extend both to the choice of suitable material and to proper constructional procedure, but so far it does not appear that advances made in producing cements of higher tensile strength will play an important part in these precautions; nor does attention to the choice of aggregates and of the water-cement ratio, and to the after-treatment of the concrete, offer more than partial guarantees of succes; and these controls are not practicable in all circumstances. The adoption of specially shaped reinforcing bars, which has become customary in conjunction with the higher stresses in certain kinds of steel (Isteg and other types of deformed bars) indeed offers some improvement from the point of view of bond, and therefore some reduction in the risk of the steel slipping and giving rise to large cracks; but the greater part of the advantage so gained is discounted by the heavier permissible stresses in such steel, which are attended by heavier than normal stresses in the concrete. The fact that the unavoidable shrinkage is in itself sufficient to cause tensile stresses without any load being on the structure when (as is most often the case) the reinforcing bars are placed eccentrically, and that the calculated values of such stresses may be up to the limit of the available tensile strength, is only slightly mitigated by plastic tensile strain; for such strain can be significant only in cases where the concrete is relatively weak, and this in turn implies that the tensile strength is low.

The possibility of improving matters by suitable choice of materials would appear, therefore, to have reached its limit. As a rule the criterion for distinguishing between dangerous and harmless cracks is taken to be that the width of the crack shall not exceed an amount variously given as 0.2 to 2/3 rds mm. In principle it may be laid down that such cracks as cannot be prevented from arising when the permissible stresses in the concrete and steel are attained (the maximum elongation at fracture of the concrete, under bending, being approximately 0.3 mm per metre) are not to be regarded as dangerous. The distinction between harmless and dangerous cracks is however, very vague, being influenced by the situation of the job and by the effects of weathering, and above all by the effects of repeated stressing and impact.

In view of this fact the regulations which are operative in various countries continue to fix limits for the tensile stresses, although it is known that these limitation are of little value for the reason that the initial stresses cannot be estimated. In the German regulations for reinforced concrete bridges, for instance, the tensile stress is limited to $^1/_5{}^{\text{th}}$ of the cube strength, and the French regulations of 1934 are similar in their implication, though applicable only to oblique principal stresses.

It is therefore an advance, the importance of which it would be impossible to exaggerate, that a reliable means altogether different from those suggested above has now been found for eliminating all tensile stresses (including those which are not dangerous), and of doing this without exceeding the limits of what is economically feasible. The methods proposed by *M. Freyssinet* in the Preliminary Publication combine the following advantages:

1) Certainty of eliminating all tensile stresses in a member exposed to bending or to eccentric pressure, with consequent elimination of all risk of cracking.

2) Apart from the matter of freedom from cracking, which is germane to the present report, there is the circumstance that the whole of the cross section of the concrete can be utilised for compression so that a member is made to resist bending to the full extent of its cross section and resisting moment, and can be calculated as if it were a homogeneous body.

3) This makes it possible for the same compressive stresses in the concrete to take up much heavier bending moments, or alternatively, if higher permissible stresses can be accepted in the concrete, it is possible considerably to reduce the size of cross section and therefore the amount of material required.

4) Variations and repeated alternations in load no longer play any appreciable part in determining the risk of cracking, and variations in stress in the reinforcing bars are minimised by contrast with what is true of structures designed in accordance with Stage IIb.

As is well known, *M. Freyssinet* has obtained these revolutionary advantages in reïnforced concrete construction mainly through the adoption of pre-stressing both of the longitudinal steel and of the stirrups. This principle has long been understood, but earlier applications, as for instance those attempted by *Koenen* and *Lund*, have been defeated by two difficulties:

1) The pre-stressing was so light that the whole of its effect was lost by shrinkage, plastic deformation and drop in temperature.

2) It was not possible for the engineers concerned in these attempts, and for those who later took up the problem, to devise practical means of pre-stressing which would be certain in their effect and at the same time economical.

Freyssinet himself succeeded not by developing the idea of pre-stressing by itself, but by combining it intimately with the following measures:

1) By making the amount of pre-stressing very heavy, somewhere between 4000 and 7000 kg/cm², and by the use of steels with yield points of 8000 to 12 000 kg/cm².

2) By adopting a constructional arrangement so designed as to ensure uniform pre-stressing of the steel reinforcements, the necessary anchorages being connected either to the shuttering or to its sub-structure in such a way that the pre-stressing operation would be perfectly carried out and the apparatus afterwards disconnected by simple means.

3) Neither of these two conditions could be fulfilled without radical improvement in the production of the concrete itself. It would be both difficult and uneconomic to maintain these heavy pre-imposed stresses in the steel long enough for the concrete to harden sufficiently to pick up the stresses. *Freyssinet*, therefore, devised a means of making concrete of medium and high compressive strength in less time than ever before, using a process which he has described as "virtually instantaneous hardening" *(endurcissement quasi instantané)*; a process which offers the further advantage that concrete beams, posts, piles and pipes can be formed in short lamellar layers, whereby the expense of complicated shuttering is reduced to a fraction. The principle of this "virtually instantaneous hardening" has been described in the Preliminary Report, and depends on subjecting the concrete to vibration, compression and heat; the practical significance of these treatments has been discussed in detail in the Publications of the I.A.B.S.E., Vol. IV, and here it need merely be stated that vibration has the effect of so arranging the small particles of aggregate as to reduce the voids; the effect of pressure is further to reduce these voids; and after both these processes have been carried out it is permissible to apply heat, since the capillarity of the voids effectively reduces the loss of moisture by evaporation.

It is to be noticed that none of these three processes by itself gives the desired result. It is known, for instance, from the vibration tests carried out by *Graf* and *Walz* at Stuttgart, that the vibration of plastic watery mixtures such as are used in reinforced concrete work, containing large quantities of sand, does not by itself cause any reduction in the time required for hardening nor any improvement in quality. It is only applying pressure to increase the density, that the limited void content resulting from the packing of the small particles makes it possible to apply heat. This additional heat considerably increases the total present due to the setting of the cement.

This process has been carried out not only in the laboratory, but also on actual work for making masts, solid and hollow piles, pressure pipes and beams of large dimensions. The results vary according to the shape of cross section; with closed and compact sections strengths corresponding to those obtained after 28 days in ordinary reinforced concrete work, or even considerably higher, are obtained in a very short time. With other forms of cross section, as for instance I-beams, the shuttering is removed after a few hours and an initial strength of 150 to 200 kg/cm² is secured, which is enough to allow either of another piece being begun or of the pre-stress being transferred into the concrete.

Owing to the fact that longitudinal tensile stresses are entirely eliminated it becomes possible by suitably pre-stressing the stirrups to render the principal stresses entirely compressive, and the question of permissible compressive stresses for concrete made on the site assures a fundamentally new aspect.

In the customary form of reinforced concrete design, assuming the presence of a tensile zone, the permissible compressive stress in the concrete is quite properly based upon a higher factor of safety than that which governs the steel stress referred to the elastic limit. As a rule this implies a considerably higher factor of safety as regards the permissible compressive stress in the concrete; a differentiation which is justified only by the greater uncertainty which attends the production of concrete by comparison with that of steel in the steel works, but also, more pertinently, by the question of freedom from cracking. If, then, the compressive stress in the concrete is notably increased, the calculated tensile stress in the concrete will likewise be increased, and the limitation of cracks will become more difficult. Apart from this, in T-beams an increase in the compressive stress in the concrete is associated with a crowding together of the steel bars, which may itself tend to cause cracking. Both these components of safety as affecting concrete compressive stresses are eliminated by the *Freyssinet* system, and the only remaining reason for the concrete being made subject to a somewhat higher factor of safety than is possessed by the steel referred to its elastic limit lies in the different conditions of their manufacture; not on any effect of the increased concrete compressive stress on the design. There is, therefore, no point in fixing the permissible compressive stress in the concrete at about $^{1}/_{3}{}^{rd}$ of the 28-day cube strength, because when the *Freyssinet* system is applied compressive stresses in the concrete of 150 kg/cm^2 are obtained even in unfavourable cases, and these may straight away be looked upon as permissible values.

As regards alterations occurring in the steel stresses under live load (particularly under moving loads) it is to be remembered that since the neutral axis lies approximately at the lower edge of the beam the whole cross section cooperates, so that variations in the steel stress will amount only to n times the variations in the concrete compressive stress. This is relatively quite a small fraction of the initial stress, contrasting in this respect with reinforced concrete construction with a tension zone.

The use of high elastic limit steels, without pre-stressing, as hitherto practised, is known to have resulted in increased safety against breakage but not in any increase in safety against cracking, though deformed bars have been proved efficacious with regard to bond and to sub-division of the cracks. The increased steel stresses adopted with these kinds of steel, with correspondingly greater elongation, increase the danger of crack formation, thus contrasting with the effect described above. With the *Freyssinet* system the high tensile steel which is pre-stressed no longer performs the same function as is performed by reinforcement in ordinary construction; it merely serves to take up the heavy eccentric pre-imposed stress, and contrary to what happens with high tensile steel used without pre-stress it results in an avoidance of cracks. Hence all the arguments against the adoption of high tensile steel become invalid, and this applies particularly to the objections which have been raised to the use of coldstretched steels. Any apprehension is easily overcome by the fact that these qualities of steel may be produced by suitable alloying without cold stretching. By reason of the high stress in the steel it is not necessary to make use of exceptionally large diameters; hence anchorage by the usual form of hooks involves no risk.

The application of the method extends to a great many types of construction. It is already well known how hollow piles of almost unlimited length have been made in this way, an operation of which *M. Freyssinet* has given an account in the literature (see also the Preliminary Report of the Congress), in the reconstruction of the marine station at Le Havre. In addition, the production of thin walled high tension pylons for power transmission has been practised for some years. Quite recently two applications of the method have been developed both in the laboratory and on actual work which deserves special attention here, namely (1) the production of long span beams, and (2) the production of high pressure pipes of large diameter for heavy pressures both in service and under test.

There is neither space nor occasion here to give details of the constructional arrangements adopted for producing pre-stress, or of the qualities of the "virtually instantaneous hardened" concrete; these matters must be left for later description. The underlying principle of the system may, however, be briefly mentioned: the pre-stressing is carried out either with the aid of the shuttering itself or with that of its supporting structure, and usually by means of hydraulic jacks. Contrary to what was found in the earlier experiments by other workers, it is possible with safety to make use of pre-stressing loads as high as 1000 tonnes. Another method, which is particularly interesting, is to make use of the concrete itself for pre-stressing the steel reinforcement. This method is quite new and is being widely adopted. The idea of using the concrete itself to pre-stress the steel bars may at first sight appear difficult to understand, but it may be readily understood by recalling the heavy shear and compressive resistance offered by concrete which has been placed while in a fluid condition, and has been systematically dewatered and subjected to heavy pressure on all sides. Here, as a rule, such pressure is imposed by means of tight inflatable rubber sheaths connected to the shuttering. The theoretical principle underlying this process (which has met with great succes in practice) have been explained by *Freyssinet* by reference to considerations recently put forward by Caquot in his *Equilibre des Massifs à Frottement Interne* (Paris, 1934).

A brief outline of the stress conditions obtaining in long span beams will now be given, reference being made to the treatment of the subject of "Long Span Girder Bridges" at the Paris Congress in 1932 in which the economical constructional limits of span were found to be determined by the tensile stress of the concrete and the space taken up by the reinforcing bars. In this consideration of long span beam bridges the unfavourably small ratio between live load and dead load moments plays a vital part, and the ratio in question is one which becomes smaller still in proportion as the span increases. At the same time it is proper to observe that this circumstance, unfavourable as it is from an economic point of view, has frequently been put forward as an advantage of reinforced concrete construction, by reason of the fact that variations in load and in the stress of the reinforcing bars are in this way reduced. In the case of beams constructed by the pre-stressing method much more favourable (that is to say much greater) ratios between the live load and dead load moments are obtained, while at the same time the advantage of limited variation in stress under repeated fluctuations of load is ensured, because — as explained above — the whole cross section collaborates.

Fig. 1 shows an experimental beam constructed in Germany on the *Freyssinet* system, in which all the dimensions of the steel reinforcing bars and of the

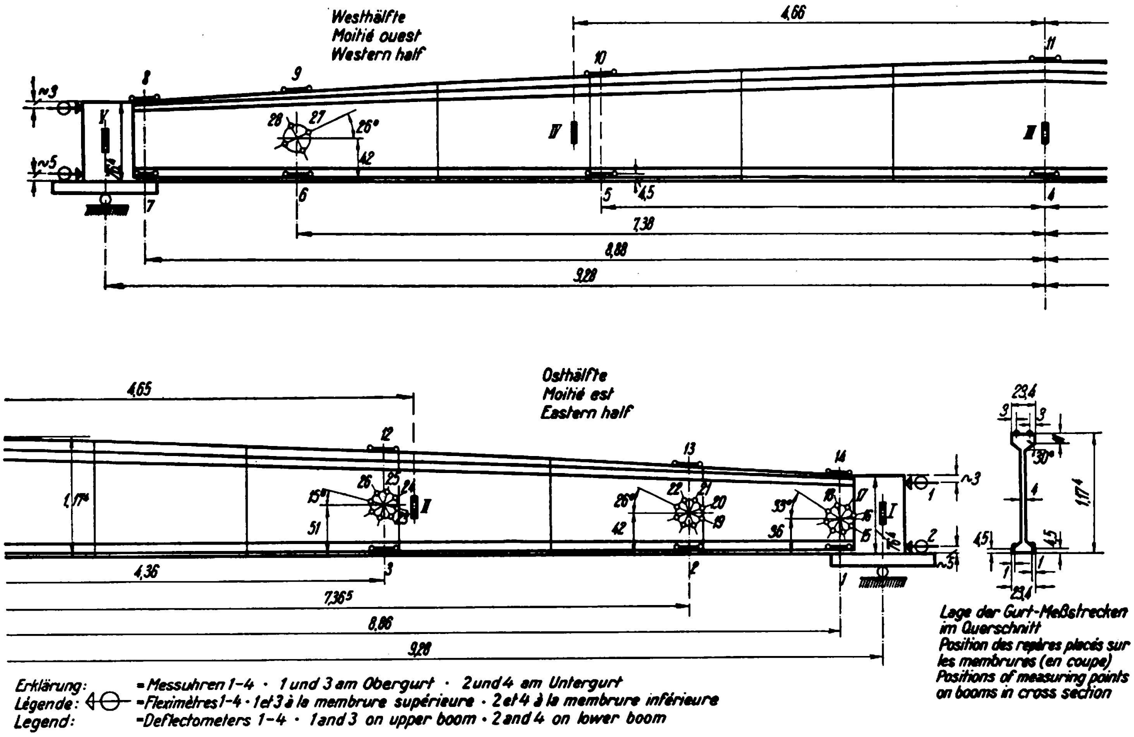

Fig. 1.

Arrangement of measuring points.

spaces between are made exactly to a scale of 1:3, representing a roof girder over a hall of 60 m span. The model reinforced concrete beam has, therefore, a span of approximately 20 m; the pre-imposed stress in the reinforcing bars is 5500 kg/cm², which gives the following moments at the central section:

From own weight, and loading frame .	9.67	m-tonnes
From live load	59.5	m-tonnes
Total, approximately	69,2	m-tonnes.

The maximum concrete stress due to own weight plus maximum live load plus loading frame amounts to:

In the upper flange	143.7 kg/cm²	compression
In the lower flange	18.9 kg/cm²	compression.

The neutral axis thus falls below the lower edge of the beam. With a pre-stress of only 3500 kg/cm² the stress in the upper flange amounts to 160 kg/cm² and that in the lower flange to 40 kg tension. With a pre-stress of about 5000 kg/cm² the lower flange stress at the soffit of the girder is exactly zero; the total compression in the lower flange amounts to 205 kg/cm² due to the pre-stress alone without counting the "own weight".

The girder has a cross section of 1008 cm² at the centre, and its lower boom is reinforced with 64 round bars of 5.4 mm dia., corresponding in scale to bars of 16 mm dia. in the full sized construction. As already mentioned above, the girder was constructed in lamellar stages in such a way that altogether twelve pieces are arranged in sequence along the length. The construction and hardening of such a member required only a few hours. Before the pre-imposed stress was transferred onto the concrete shrinkage cracks appeared at the horizontal boundaries between the lamellae, the width of which was estimated at 1/20th mm. After the transfer of the pre-imposed stress these shrinkage cracks closed up so that they could no longer be detected with the naked eye, and the lime wash which had been painted over for purposes of measurement was observed to flake off. Measurements of elongation in the flanges, made in the direction of the principal stresses and in that of the bisectors between the principal stresses and the axes, were carried out by the Materials Testing Laboratory of the Technische Hochschule at Stuttgart, and these showed that *all the principal stresses were compressive.*

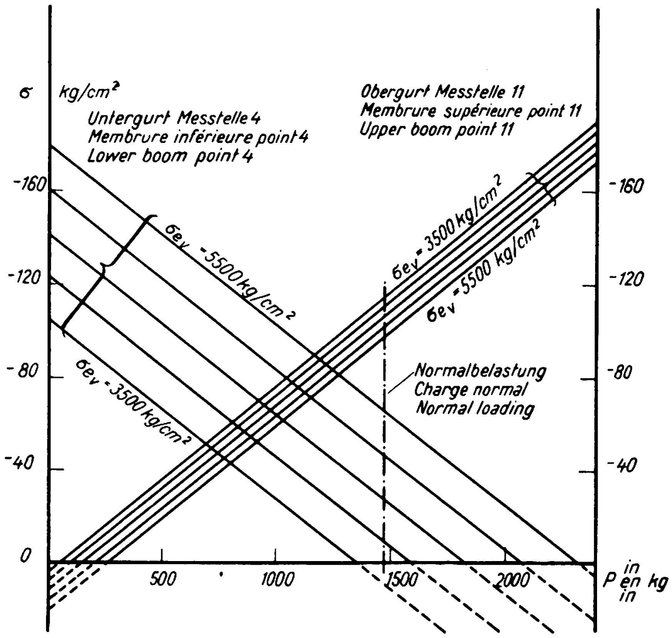

Fig. 2.
Section on centre line.

The following observations may be recorded (Fig. 3). With a pre-imposed stress of 5500 kg/cm² the girder acted under full load like a homogeneous girder, the whole cross section co-operating to provide resisting moment against bending. No tensile stresses arose either in the lower boom or in the directions of the principal stresses, nor in any other direction. The deflection of the girder was relatively very small as a result of the large resisting moment; it amounted to only 1:750, corresponding to that of a steel girder of similar cross section stressed to only 500 kg/cm².

The explanation of this exceptionally favourable distribution of stress is to be found in the pre-stressing of the longitudinal bars and stirrups. As is well known, the principal stresses corresponding to the stresses σ_x and σ_y are given by

$$\sigma_{I,\,II} = \frac{1}{2}(\sigma_x + \sigma_y) \pm \frac{1}{2}\sqrt{(\sigma_x - \sigma_y)^2 + 4\tau^2}\,; \qquad \operatorname{tg} 2\varphi = \frac{2\tau}{\sigma_y - \sigma_x}$$

With ordinary reinforced concrete construction at the neutral axis $\sigma_x = \sigma_y = 0$; hence the inclined principal stress $\sigma_{II} = -\tau$ is at an angle of $\varphi = 45^0$. It is clear that the effect of the normal stress σ_x (pre-imposed compression) is to diminish the principal tensile stress. If Mohr's diagram be drawn (Fig. 4) with $\sigma_x = \tau$ there is obtained a principal tensile stress of

$$\sigma_{II} = \frac{\tau}{2}(1 - \sqrt{5}) = -0.618\,\tau$$

If $\sigma_x = 2\,\tau$ the maximum principal tensile stress becomes $\sigma_{II} = -0.414$. If, finally, besides $\sigma_x = \tau$ a vertical pre-stress is imposed by means of stirrups, the principal tensile stress becomes $\sigma''_{II} = 0$ and the principal compressive stress $\sigma''_I = 2\,\tau$. This condition can easily be obtained by stressing the stirrups, as was done in the present case. As regards shear effect, tensile stresses are entirely eliminated and the shear stress may therefore be brought up to one half of the permissible compressive stress.

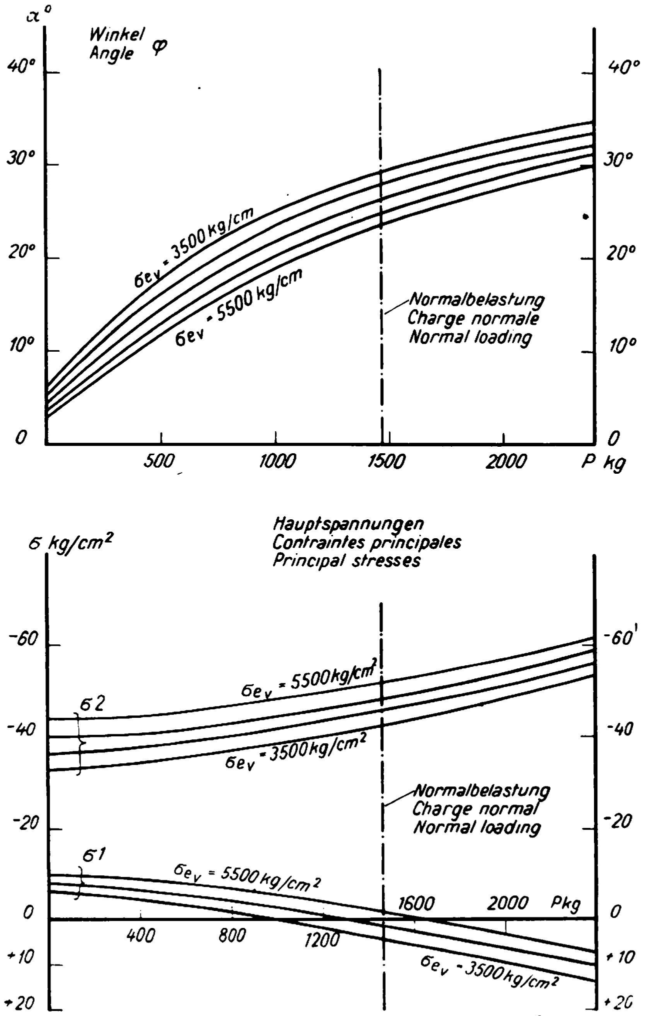

Fig. 3.

Section 1—14.

With concrete compressive stresses of approximately 145 kg/cm² as already stated, the girder suffices to carry a live load amounting to seven times its own weight.

The girder to be actually constructed would have a cross section of 0.84 m² at the centre, and the total moment at the centre of the span would then amount to about 2000 m-tonnes, the ratio between the live load moment and the dead load moment being approximately 1.2. If these spans, not hitherto realised with solid webbed girders, are compared with those of existing bridges, the very favourable relationship of live load to dead load moment will become evident.

A girder of 100 m span subject to the same stresses would have an average "own weight" of 5 tonnes per m run, and would be able to carry a live load of 3 tonnes per metre run, it being assumed that the permissible compressive stresses are kept suitably low.

High pressure pipes have been constructed on the same principle, the steel reinforcing bars being pre-stressed by compression of the concrete itself while supported all round and subjected to an increase of internal pressure. The following results were obtained:

Small test pipes of 440 mm internal dia., and 37 mm thickness of wall, were exposed to a test pressure of 90 atmospheres without any detectable loss of water. By contrast with this a pipe of the same dimensions and containing the same amount of reinforcement, but not pre-stressed, was unable to withstand a pressure in excess of 6 atmospheres without loss of water-tightness. It is particularly notable that the empty pipe had to withstand a compression of 550 kg/cm² due to the pre-stressing at the instant of its removal from the forms, and this happened within a few hours of its manufacture.

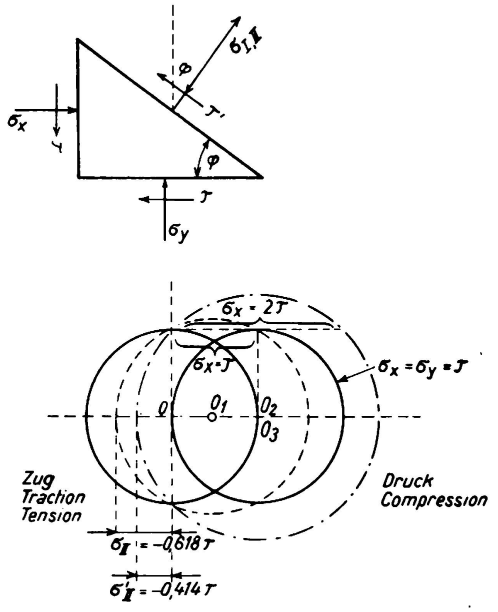

Fig. 4.

The same principle is now being applied, in actual practice, to the continuous production of high pressure pipes of large diameters. Thus pipes of 800 mm dia., with walls 5 cm thick, for test pressures up to 16 atmospheres, have been produced without any defects, and are removed from their shuttering a few hours after the beginning of the process of manufacture. Under these conditions the concrete when removed from the moulds is subject to a compressive stress of 140 kg/cm² about three hours after it has been deposited. It is particularly notable that if such pipes are purposely exposed to pressure in excess of the usual test pressure, so as to cause them to sweat, they again become perfectly water-tight after the pressure has been relieved, and remain so when the pressure is again increased up to the permissible amount. This shows that the effect of pre-stressing is completely to close up any cracks that may have been formed by statical effects; a result which is of great importance as regards resistance to impact effect (from water hammer).