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REENFORCED CONCRETE STRUCTURAL
MEMBER

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This invention relates to a method of reenforcing concrete structural members and the product thereof, and more particularly to the construction of a reenforced concrete beam having new and useful properties.

Reenforced concrete construction is in widespread use to-day utilizing two totally different structural materials; namely, concrete and steel. It is a well known fact that the modulus of elasticity of steel is approximately 30,000,000 and that of concrete, while not a constant, may usually be found between 3,000,000 and 4,000,000, so that the modulus ratio, commonly called "n", varies around 6, 8 or 10 according to the quality of the concrete. Furthermore, steel in tension can support between 30,000 and 60,000 pounds per square inch before reaching its yield point, while the ultimate strength of concrete is usually between 300 pounds and 500 pounds per square inch in tension. In other words, concrete must be expected to stretch but 1/10,000 of its length before cracking, whereas steel will stretch more than 1/1000 of its length and recover without injury or permanent set. The difference between these two deformation characteristics causes much trouble in practice.

Especially is this true in the design of a reenforced concrete structural member such as a simple beam in which the theory is that only the concrete above the neutral axis or surface may be depended upon to resist the effects of bending by the compressive stresses found therein and that the steel reinforcement, usually placed near the bottom of the beam, carries all the tensile stresses. Of course, the stress in the matrix below the neutral axis is tensile in character and actually does assist the steel by furnishing a small part of the tensile component in the resisting moment couple. Furthermore, the usual procedure did not stress the reinforcement in any way during the formation of the beam, and because of the shrinkage of the matrix and difference in elasticity of the two materials the bonding between the steel and concrete tended to form incipient cracks in the bottom of the matrix and put the reinforcement in compression prior to loading.

It is also necessary that a good bond be had between the concrete and steel in order that the beam may act as one homogeneous material, and an entire design practice has grown up around the straight line variation between stress and deformation and upon the theory that only a small part of the plane cross-sectional area in a beam takes the compressive stresses. This area is that

above the neutral axis, which is relatively high up in the body of the beam. The portion below the neutral axis is not considered to be safely dependable in resisting bending moment. Speaking loosely, the compression stresses forming the compressive component of the resisting moment couple in the present day beam are confined to only a small part of the matrix such as the upper half. This invention purposes, for one thing, a larger part of such matrix in use to resist this type of stress.

In the design of these beams, which will be referred to as old type beams, use is made of the formulas to be found in any concrete handbook or textbook, often supplemented by actual test results and guided in many instances by building codes, so that the entire science is far from being an exact one because of the number of variables to be found in daily practice. A concise list of the formulas which are commonly used in prior practice and which will serve as the standard for prior practice whenever such practice is mentioned in this specification, is to be found in sections 49 and 50 of the textbook by Prof. George A. Hool, entitled "Reinforced Concrete Construction" volume 1, Fundamental Principles, 3d edition, 1927.

That there are limitations and disadvantages to be found in the old practice is readily apparent from the fact that the deformation characteristics are so different that defects appear not only during the formation of the beam, but during the loading thereof. Furthermore, since in the old type beam only those stresses that lie above a relatively high neutral axis can safely be considered to resist bending, in that sense it is inefficient. Again, when all the stress requirements have been satisfied, the deflection or sagging of a beam can readily be so great as to impair its usefulness as a structural member and some other design must be chosen and followed. Then, of course, there are always the unavoidable conditions in the beam itself, such as the concrete in the lower surface being in tension prior to any loading thereon.

There has been quite some attempt to remedy the major defects in the old construction, some of which consist in ramming the concrete in the form to increase the bond, or in stretching the reinforcement where such reinforcements as heavy wires are used to take bends. In an attempt to prevent the incipient cracking due to the bonding during the setting and hardening of the matrix, attempts have been made to prevent bonding and then to supply co-ordination be-

tween the two materials by means of abutment plates. The use of these plates places large injurious stresses on small areas of concrete where they press.

Further, following these attempts, the usual amount of reinforcement was put under considerable tension in some cases and under lesser tension in others and the relative unit stresses thrown out of balance under greater load. But such a practice merely had the effect of lowering the neutral axis, with the result that the moment resisting couple arm was shorter and the beam more readily failed when tested to destruction.

The old type beams were also designed with an eye to economy and balance, that is, the concrete proportions and the steel proportions were such that there was, theoretically, at least, neither an excess of one material nor of the other, and no benefit was obtained in increasing either the amount of steel or the size of the matrix because in such case the one material would fail in advance of the other and unnecessary expense and waste would be entailed.

It is a primary object of this invention to avoid the difficulties and disadvantages of the old practice and to produce a reinforced concrete structural member which shall be more efficient in practice and which shall have new and extraordinary properties. At the same time, the purposes of the invention include the substitution of a new design theory for the old, the production of a totally new beam and a method of producing such beam which will involve means which are practical and simple.

Advantages of the new beam are greater length of span permissible for a given depth, greater resistance to bending stresses, less deflection under all loads within the range permissible for the given allowable concrete unit stress, and ease and convenience of construction.

Basically, the invention in its relation to beams, slabs or other structural members subject to bending, consists of the conception that by utilizing a part varying between the major portion and the entire cross-sectional area of the concrete matrix to withstand safe and efficient compressive stresses, a new and useful structural member of reinforced concrete is achieved. Certainly, this method of reinforcement is the first capable of utilizing the entire cross-sectional area of the beam as forming the compressive component of the resisting moment couple with a permissible stress that is great enough to be practical as a suitable unit stress. The practice of that conception consists in making such a beam or other structural member with substantially more steel therein than the old formulas permitted or warranted, such reinforcement being in a state of predetermined tension in the unloaded beam or structural member referred to.

To prevent waste in the exploitation of this invention and uneconomical design, hereinafter in this specification a guide will be set down disclosing the proper approach to prepare such a member involving or employing the invention. On the other hand, however, no theory of design set out, nor beliefs as to the workings of the beam, are to be taken in any limiting way to obscure the concrete results which have been arrived at under this invention because it is thought that an understanding that a simple beam having substantially more steel than the old practice and with such steel under predetermined tension in the unloaded beam will enable any de-

signer to work out his own construction practice.

Preferably, when the concrete matrix has been poured and during the setting and hardening or prior thereto and before any bonding takes place, the reinforcement, the amount of which is computed as will be explained later, is placed under great and approximately determinable tension and the beam left to harden before the restraints are released. Upon the release of the steel from its outside restraints forming the total tension initially placed in the reinforcement, a portion may be lost, owing to the shrinkage of the beam, and another portion in compressing the matrix leaving a residual portion exactly balanced by the resultant compressive stresses built up by it in the matrix prior to any loading on the beam. This operation has several effects. In the first place, it changes the behavior of the neutral axis in such a way that it is impracticable to locate in the new beam any such fixed surface or axis and so that the beam tends to bow upwardly deflecting more or less in the opposite manner from that caused by load. Secondly, the new design and application has the effect of causing the entire cross-sectional area of the concrete matrix to bear resultant compressive stresses prior to and during the loading thereof.

While it is true that the moment resisting couple arm in any section of a new type beam may be shorter than the corresponding couple arm of an old type beam, the extensive increase in the moment resisting area of matrix and steel annuls any loss from this cause. Needless to say, this conception results in a radical departure from accepted practice of design for making safe use of only those stresses in the matrix above a relatively high neutral axis. It has led to the new beam of this invention and with slight modification in construction details new slabs that may be analyzed in strips precisely like beams. It has led also to new design for columns, arches and other structural members, thus revising design practice in all fields.

The new design departs from the old type design in increasing the amount of reinforcement (merely increasing the amount of reinforcement would be of relatively little avail) and at the same time tensioning such steel. The stretching alone that was sometimes used, as pointed out above, did not result in the increased benefits that result from the practice of this invention.

It is necessary in order to arrive at the benefits outlined above to properly proportion both the amount of the reinforcement used and the amount of tension applied to it prior to the setting of the matrix around the reinforcement according to the structural qualities of the matrix to be made and the reinforcement used. Such proportions require, however, no greater accuracy or precision than is to be found in the present practice in order to achieve radical changes from and advantages over such prior practice.

In connection with the new design, there are assumptions which are made like some of the assumptions made under the old practice, the first one and most important being that there is a straight line variation between stress and deformation. But there no longer is a fixed neutral axis intercepted by a line at the point of maximum bending stress to make an origin on which to build a stress diagram. A new mode of procedure and attack of the new problems must be substituted. Looked at from the basis of a work theory, it is entirely proper that more

concrete area, taking more stress as a whole, should require more steel, but without the suitable tensioning of such steel the invention was not achieved.

Whereas in ordinary practice the sectional area of the longitudinal reinforcements, on the tensile side of a beam at critical points, usually constitutes between seven-tenths of one percent (.007), and one percent (.01) of the sectional area of the beam at such points, in the new practice such reinforcements are used under like conditions running up to six percent (.06) and usually between two (.02) and three (.03) percent of such sectional area. These percentages may be increased still further by the introduction of longitudinal steel in the upper or compressive area of the beam. In stressing this steel, it is preferable to place the reinforcement under its full working tension plus an amount to take care of stress in the matrix filaments adjacent the steel, plus a small indeterminate amount to be lost because of the shrinkage in the matrix. Then, after the beam has set and hardened and the restraints on the reinforcement are released, a portion of this full working stress will be lost in compressing the matrix, thus starting in an unloaded condition with the beam matrix in the plane of the reinforcements in compression and the steel in tension.

If it is possible or practicable to release a small amount of the tension imposed on the reinforcement during the setting and hardening of the matrix so that resultant contraction of the steel approximates the shrinkage in the concrete, then a still more perfect bond may be found, but for practical purposes the restraint can be released after the beam has set and hardened particularly if cured with considerable water.

With the new unloaded beam there are several tendencies present which will be explained. With the steel in tension and the restraints released, the concrete matrix, because of the fact that the steel is placed nearer the lowest surface thereof, tends to bow upwards usually to the extent of creating a little tension in the top surfaces of the beam. It may possibly be that such stress found in the steel may cause any tensile forces in the top layers of the concrete to become unsafe to the existence of the same as a whole, in which case suitable top reinforcing bars of the kind which are known in the old practice may be placed along the top of the beam prior to the pouring. This top reinforcement may be used unstressed or it may be tensilely stressed, but usually to a less degree than the bottom steel.

Thus, with a large compressive force in the bottom of the beam and a small compressive or tensile force in the top, and a straight line diagram before loading, it is obvious that the same bounding line for the stress diagram is going to swing through a more extensive area than was found in the old beam since now the forces on the bottom of the beam under full loading become zero, small compressive or even small tensile forces while the upper surface assumes a compressive stress preferably equal to the full working strength of concrete in compression. At the same time, the steel will increase from its residual stress to its full working stress, which is usually around 16,000 lbs. per square inch.

There is, however, an interesting surface to be found in the beam of this invention, the trace of which on a transverse section we shall call the gravity axis of the transformed section. This transformed section is arrived at by placing in

the plane of the steel reinforcement the same volume of concrete multiplied by the ratio of the moduli of elasticity of the two materials. It is believed that this surface has a constant longitudinal compressive stress component from the beginning of loading to the point where the beam is fully loaded, or, in other words, that the bounding line of the stress-diagram for any beam section swings about this point as a center and serves to permit some definite design procedure to be used with these new beams, so that tests and experiments will not be the only data to be relied upon to enable the proper structure embodying this invention to be used in whatever particular circumstances may be present.

A measure of the relative strength between the new and old beams, assuming the conditions of size and span are the same, which is to be found in a comparison of their elements K which is familiar to the designer under the old practice and equals pfs_j , and although j is somewhat shorter, the quantity p of the new beam is several times larger than the p of the old construction, so that K will bear practically a corresponding ratio, and it is not at all unusual to find the new beam with a bending strength two or three times that of the old beam. But the only way to put this new p to work to obtain the valued results of this invention is to stress it to a relatively high degree, otherwise one would have the old type with a greater unstressed p of little avail because it could not be fully used without causing the matrix stress to exceed that permissible. The shear and diagonal tension stresses have been found to compare favorably and proportionately with the analogous stresses to be met with in the old type.

Before attempting to start upon a discussion of the design application of these new beams, reference will be made to the figures in the accompanying sheet of drawing, which are not necessarily to scale.

Fig. 1 shows an unloaded beam of the new type;

Fig. 2 is a cross-section of the beam shown in Fig. 1 with dotted line indications of the transformed section of the same;

Fig. 3 discloses the stress diagram of the unloaded beam in Fig. 1;

Figs. 4, 5 and 6 show the three types of stress deformation diagrams which can result at the section of maximum bending moment when the beam is fully loaded.

The gravity axis of a transformed section lies at a distance

$$\frac{1+2pr(n-1)}{1+p(n-1)} \cdot \frac{d}{2}$$

from the bottom of the beam in which p denotes the ratio of the sectional area of the reinforcements to the product $b \cdot d$, and n equals the modulus of elasticity of steel over the modulus of elasticity of concrete

$$\left(\frac{E_s}{E_c} \right)$$

and r equals the distance from the bottom of the beam to the reinforcement over the total depth of the beam. This axis is in fact the gravity axis of a section such as shown in Fig. 2, in which the steel is replaced by thin concrete flanges of negligible thickness, such that total replacement equals $n \cdot p \cdot b \cdot d$.

A line $A-A_1$ parallel to and spaced a distance

$$\frac{pF}{1+p(n-1)} = f_A$$

to one side of the axis $C-Y$ of the stress diagram,

intercepts this gravity axis. In the last formula, F equals the initially applied stress less an amount e for shrinkage of the steel reinforcement. The compressive stress f_a is a constant along the gravity axis and bounding line B of the stress diagram swings about the intersection of A—A₁ and the gravity axis. Before loading with a tension T in the steel after the restraints are released, there is a tendency in the concrete beam to bow upwards resulting in compressive force f_2 in the bottom fibre of the beam and in this instance in a small tensile force f_1 in the top fibre of the beam (Fig. 3), depending upon the initial assumptions of design, with straight line variation of stress from f_1 to f_2 .

As load comes on, f_2 will tend to decrease and will assume in succession if the loading is carried far enough, the magnitudes shown in Figs. 4, 5 and 6 respectively and at the same time the top stress f_1 will swing over to attain a magnitude equal to the maximum permissible working stress of concrete in compression.

The matter of a design is a relatively simple one and involves the choice of one of the diagrams shown in Figs. 4, 5 or 6 as the desideratum to end up with when the beam is fully loaded. For purposes of economy and safety perhaps the design in Fig. 4 should be chosen. The steel is placed at a suitable small distance above the bottom of the beam and the percentage thereof is determined in the following manner:

$$p \cdot b \cdot d \cdot F_2 = \frac{1}{2} \cdot b \cdot d \cdot (f_1 + f_2) (1 - p) \quad (\text{numerically})$$

If stresses f_1 and f_2 are opposite in character, they are to be used in these formulas with opposite signs. Practically this last factor $(1 - p)$, which is approximately unity anyway, adds little or nothing to the accuracy of a formula, which is only approximate at best. We shall, therefore, determine p from the formula

$$p = \frac{f_1 + f_2}{2F_2}$$

which is a sufficiently good approximation with which to make the new beam.

It appears from a consideration of the diagrams in Figs. 3, 4, 5 and 6 that the horizontal stress component f_s in those filaments of the concrete matrix in contact with the reinforcements may be expressed in terms of f_1 and f_2 as follows:

$$f_s = f_2 + r(f_1 - f_2) \quad (\text{numerically})$$

Furthermore, there is a relation between f_s and the component F_1 of the stress initially applied to the steel lost in compressing the matrix of the form:

$$n \cdot f_s = F_1 \quad (\text{numerically})$$

The initially applied tension to the steel consists of such a component F_1 plus a suitable working stress F_2 (16,000 to 20,000) plus an amount "e" disappearing on the shrinkage and setting of the matrix so that: F (initially applied tension) = $F_1 + F_2 + e$. In this formula F_2 is known, F_1 is obtained through f_s through f_1 and f_2 (depending on the diagram chosen) and "e" is determined independently to fit the practice since it will have many values according to the manner of making and curing the concrete.

As an example, let us assume that we wish to design a beam ending with the stress-diagram shown in Fig. 5 and assign a maximum value of 800 pounds to f_1 and a working stress in the steel equal to F_2 equal to 16,000 lbs. per square inch. The steel is placed $\frac{1}{8}$ of the way up from the

bottom fibre so that the quantity r equals $\frac{1}{8}$ and the ratio of the moduli of elasticity equals 10. Substituting in the formula

$$p = \frac{f_1 + f_2}{2F_2}$$

we find a p equalling

$$\frac{800}{32,000}$$

or .025. Then, regardless of the width and depth of the beam, .025 $b \cdot d$ is the amount of steel used and the concrete poured. Before the pouring, however, the steel is placed under an initial tension equal to the working stress of 16,000 lbs. per square inch plus a small amount "e" for shrinkage, plus $(n \cdot f_s)$. [$f_s = r \cdot f_1 - 80$] and n times 80 equals 800, so that the initial stress imposed on the steel will be around 17,500 lbs. assigning an arbitrary value of 700 lbs. to "e".

At the proper time the restraints on the steel are released and a portion of the working stress is used up in compressing the concrete matrix. At this point the load is put on and when fully stressed, a beam is obtained having a maximum bending stress-diagram like Fig. 5. In the event that the approximations are slightly off to some extent, the diagram shown in either Fig. 4 or Fig. 6 will be produced instead and is perfectly satisfactory for use in the same premises.

Throughout this specification the work has been made simpler by referring to one specific type of reinforced concrete structural member; namely, the simple beam and slab. The advantages of the invention accrue just as well to the other types such as foundations, footings, walls, continuous beams, arches and columns.

With respect to columns, if the vertical reinforcements are stressed then as the concrete shrinks and sets there is no compression of the steel to tend to produce an unstable compressive condition in the reinforcement because when the load comes on and the matrix is working upward toward its maximum compressive stress the tension will be but dying out of the reinforcement. Furthermore, it does not in any sense or to any degree affect the value of this invention whether or not the structures are used in monolithic construction or by themselves and whether or not they are precast or poured in place. If they are precast, there may be some advantage derived by the more easily realizable partial release of the restraints to keep the steel shrinking in step with the concrete shrinkage in the interest of bond. In this new design as in the old design the use of hoops and stirrups preferably stressed, where necessary to combat shear and diagonal tension stresses may just as well be used and will suggest themselves at once to the designer.

The practice of to-day in bending the reinforcement over the supports can still be adhered to in this invention if due precaution is taken not to make the bends too abrupt which might otherwise injure the matrix. Such bent reinforcement could be suitably tensioned by a device such as a tie rod connected in an offset manner to the lower part of the bend in the steel and taking up on the rod a proper amount to stretch the steel.

The invention is entitled to a broad construction and is not to be limited except as may be done by the appended claims since various changes may be made in the details of the invention without departing therefrom or sacrificing any of its advantages.

I claim:

1. The method of making a structural member of reinforced concrete comprising using an amount of steel reinforcement substantially in excess of that warranted by prior practice, tensioning said steel, pouring the matrix and after the matrix shall have sufficiently set and hardened to effect a bond with said steel releasing said steel to compress the matrix throughout its bonded connection with the steel.

2. The method of making a structural member of reinforced concrete comprising using an amount of reinforcement substantially in excess of that warranted by prior practice, employing outside restraints to tension said steel, pouring the matrix, releasing said restraints a small amount during the setting of the matrix, and completing the release after the beam has set.

3. The method of strengthening the bond during the formation of a reinforced concrete structural member employing tensioned steel comprising placing the steel under great tension beyond the working limit thereof, permitting the steel to be partially released to decrease in length an amount equal to the matrix shrinkage during setting and hardening, and thereafter completing the release of said steel.

4. A method of constructing a reinforced concrete beam comprising tensioning an amount of steel substantially in excess of that warranted by prior practice to a degree in excess of the working limit, pouring the concrete matrix over said steel, partially releasing said steel as soon as said matrix can stand the resulting compressive stress without injuring the bond, completing the release after the beam has set and hardened so that a considerable portion of the tension is left in the steel even after the matrix has been compressed, and permitting the matrix to contract upon total release of the steel.

5. A structural member of reinforced concrete in which, at any critical point, the reinforcement, prestressed and bonded to the concrete matrix in its prestressed condition, has been increased to such an extent over the amount of unprestressed reinforcement now prescribed under standard practice for a member of like dimensions, to compensate for the larger compressive component built up in the concrete matrix under loading by reason of the prestress in the reinforcement, that the intensity of unit stress permissible under standard practice either in the reinforcement or in the concrete matrix will not be exceeded.

6. A structural member of reinforced concrete in which the reinforcement, prestressed to an extent bearing a predetermined relation to the load to which said member is to be subjected and bonded to the concrete matrix in its prestressed condition, is of an amount greater than the unprestressed reinforcement required by standard practice, to compensate for the reduction of the residual permissible tension caused by the prestressing, to the degree that the total residual permissible tension of the prestressed reinforcement is sufficient to prevent the intensity of unit stress under loading, which is permissible under standard practice either in the reinforcement or in the concrete matrix, from being exceeded.

7. A structural member according to claim 5, in which the steel reinforcement constitutes between .01 and .06 of its sectional area.

8. A structural member according to claim 5, in which the matrix holds the reinforcement at

a tension of several thousand pounds per square inch in its unloaded condition.

9. A structural member according to claim 5, in which the reinforcement is so located in the member and is prestressed to such an extent that the structure, in its unloaded condition, tends to show deflections and/or deformations opposite to those appearing as load is applied.

10. A structural member according to claim 5, in which the reinforcement is so located and the prestressing is of such an amount that, under full load, the maximum permissible stresses will occur both in the reinforcement and in the concrete.

11. A structural member according to claim 5, in which, under unloaded conditions, the matrix is under compression at and adjacent to that face which is subject to tension under loaded conditions and is under tension at and adjacent to that face which is subject to compression under loaded conditions.

12. The process of making a structural member of reinforced concrete, having prestressed reinforcements maintained under a tensile stress which is predetermined for varying conditions of loading, and is greater than zero for zero loading, and in which the concrete matrix, bonded to the reinforcements in their prestressed condition, is under a desired intensity of compressive stress under the same unloaded condition, which comprises employing an amount of steel reinforcement greater than the unprestressed reinforcement required by standard practice, to compensate for the reduction of the residual permissible tension caused by the prestressing, to the degree that said residual permissible tension of the prestressed reinforcement is sufficient to prevent the intensity of unit stress under loading, which is permissible under standard practice either in the reinforcement or in the concrete matrix, from being exceeded, putting upon said steel, before the setting of the concrete, an amount of prestress equal to the tension desired in said steel in the finished beam in its unloaded condition, plus an amount required by its resilience to put the desired compression in the matrix bonded to it under the same conditions of loading, plus an amount sufficient to stretch the steel to permit compensation for shrinkage of the concrete in setting or drying out or otherwise, and allowing and providing for the setting and hardening of said concrete about the reinforcements in the desired form into a substantial bond with the steel reinforcements so prestressed.

13. The process of making a structural member of reinforced concrete according to claim 12 in which a suitable amount of the prestress provided is gradually released as the concrete matrix sets, hardens and, as a consequence, tends to shrink, in order to permit the reinforcements to gradually to contract along with the shrinkage of the concrete matrix in contact with them.

14. The process of making a structural member of reinforced concrete according to claim 12 in which the concrete matrix, after being placed about the reinforcements, is so cured during its setting and hardening that its contraction is negligible until it has acquired sufficient strength to withstand the compression caused by the release of the steel reinforcements from their prestressing restraints and then removing the restraints from the prestressed reinforcements as completely as desired.

15. A structural member according to claim 5, in which prestressed transverse reinforcement

is also provided and held by the matrix under a predetermined tension.

16. A structural member according to claim 5, in which the steel reinforcement is located near a face thereof which is subject to tension under loaded conditions, said reinforcement having been prestressed to such an extent that the member, in its unloaded condition, is characterized by large compression stresses in the concrete matrix near the face above referred to, decreasing in intensity towards the opposite face of the member which is also provided with reinforcement near that face which is subject to compression.

17. A structural member of reinforced concrete in which the reinforcement, prestressed and bonded in its prestressed condition to the concrete matrix, is of an amount greater than the unprestressed reinforcement required by standard practice, to compensate for the reduction of the residual permissible tension caused by the prestressing, to the degree that said residual permissible tension of the prestressed reinforcement at least equals that of said standard unprestressed reinforcement.

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