Aug. 14, 1945. C. P. CUENI 2,382,139

PRESTRESSED COMPOSITE STRUCTURE

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Fig. 1

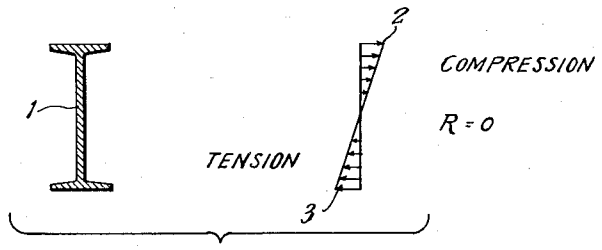


Fig. 2

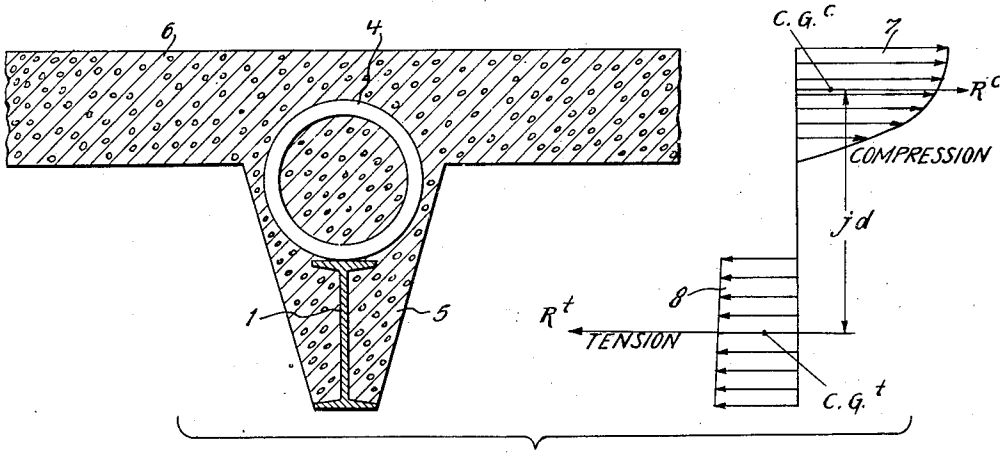


Fig. 3

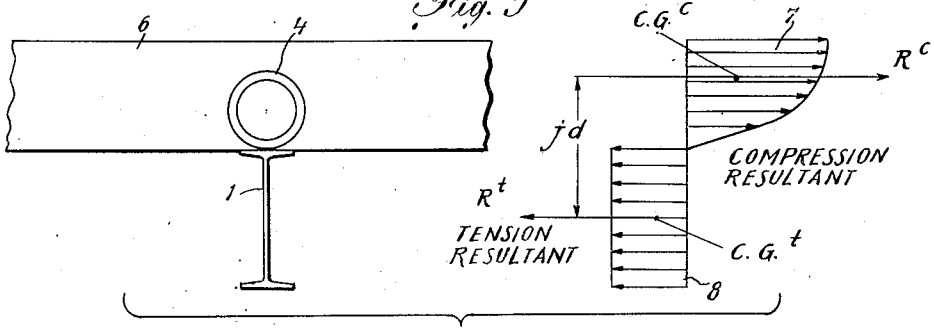
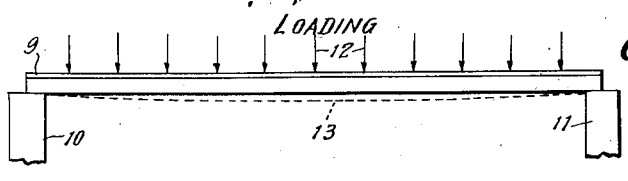


Fig. 4



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PRESTRESSED COMPOSITE STRUCTURE

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Fig. 5

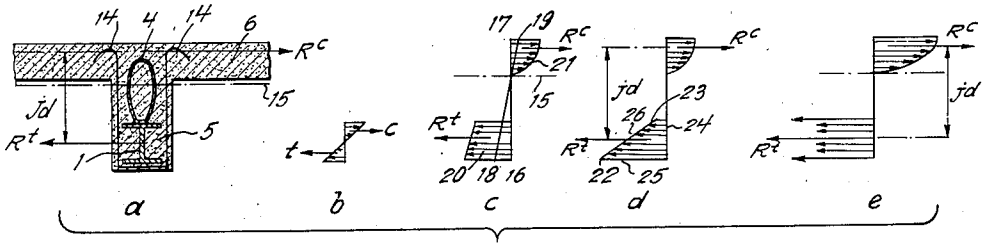


Fig. 6

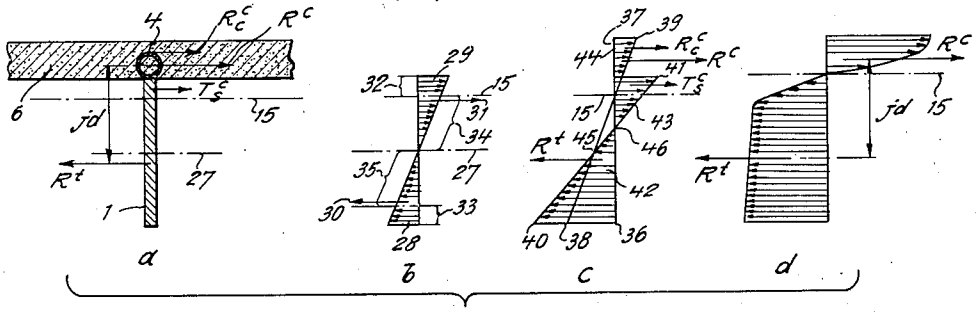


Fig. 7

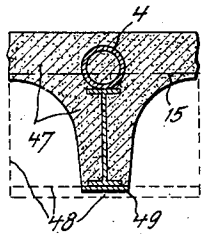


Fig. 8

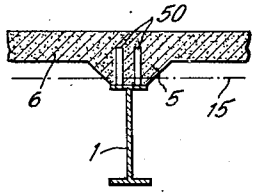


Fig. 9

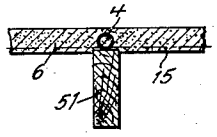
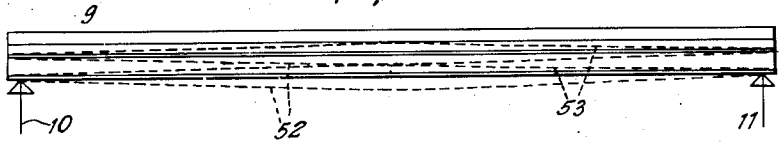


Fig. 10



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UNITED STATES PATENT OFFICE

2,382,139

PRESTRESSED COMPOSITE STRUCTURE

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Application July 16, 1941, Serial No. 402,618

7 Claims. (Cl. 72—71)

The present invention relates to prestressed reinforced concrete and prestressed composite structures wherein steel and concrete members or timber and concrete members are combined into one statical unit, designed to carry predetermined loads.

Composite structures have been known and used for some time, for instance structures like those used in floors for bridges and buildings wherein a series of steel sections, suitably supported by pillars or other permanent members carry a reinforced concrete slab cast on top or around said steel sections, both elements forming one composite beam. To insure the transmission of the horizontal shear between the two materials, and thus make an effective statical unit, metallic members, such as cleats, prongs, rods, or elements of various shapes, are attached to said steel sections and solidly embedded in the concrete slab. If the web of the steel sections is perforated or the upper part of it or the top flange is deformed or stirrups placed around the steel section, this may be sufficient to transmit the horizontal shear and no special shear reinforcement may be required.

Composite structures wherein timber is used as the tension member have also been known and used for a long time, in bridge construction and floors for buildings. The timber joists, suitably supported by pillars or other permanent members, carry a reinforced concrete slab cast on top of them and the two elements, suitably connected, form one statical unit, the timber joists taking care of the tensile stresses and the concrete slab taking care of the compressive stresses of the composite section.

Some structures in which shallow steel sections were used, as the tension reinforcement, and which looked like composite sections in the sense this expression is used here, were in fact nothing else than ordinary reinforced concrete structures and always were designed by using the standard reinforced concrete formulas. Such systems, like the Kis system, the Pohlman system and the M system are more or less accurate in design when the depth of the steel section is only a small part of the total depth of the beam. If the depth of the steel sections is a considerable part of the total depth of the structure, the use of reinforced concrete formulas is not correct even if the beams are temporarily supported.

In using reinforced concrete formulas it was assumed that the tension steel is concentrated in one point and that there is no stress variation in the steel. That this is not correct for a reinforced concrete section with rigid reinforcement at an initial state of load or at the design load is obvious, but, as will be seen later, it is about correct at the ultimate load when the steel section is stressed to the yield point, and if the depth of the steel section is only a small part of the total depth of the beam.

In using composite beam formulas it was assumed that there is a stress variation in the steel, the stress being zero at the neutral axis of the composite section and increasing with the distance, being a maximum at the lowest fibre of the steel section.

Real composite systems like the Alpha System or the Powers System, in the design of which these special formulas for composite sections are used, are applicable to all sections regardless of the ratio of total depth to depth of steel section. In the design of such composite sections it is usually assumed that the composite section carries both dead and live load, provided the steel beam has effective intermediate supports during pouring and setting of the concrete. If such supports are omitted it is assumed that the steel section alone carries the dead load and the composite section the live load only. This assumption is correct, because the concrete cannot participate in carrying load until it has set.

It is obvious that with temporary supports less steel is required because the steel section alone does not have to carry the dead load but is helped in that by the concrete. However, such temporary supports add considerably to the expense of the construction, in that it requires considerable labor for the erection, materials to be used therein and a considerable amount of labor for the removal of such temporary supports. Often temporary supports are undesirable, too expensive or even impossible. Then the steel section alone has to be designed to carry the dead load, in addition to the live load as part of the composite section. This means more steel and steel is expensive. The larger amount of steel of composite beams designed according to previous methods makes them uneconomical in short spans and for light loads as occur in buildings when compared with reinforced concrete beams.

According to a new theory explained in my copending application Serial No. 400,851, filed July 2, 1941, and entitled "Composite beam structure," an unsupported beam under certain conditions has the same ultimate load carrying capacity as a beam which has temporary, intermediate supports during pouring and setting of

the concrete. The disclosure of said application is to be considered as a part hereof.

It is among the objects of the present invention to provide a new and useful design of composite or reinforced concrete structures involving the use of steel beams or timber joists as tension members, effectively connected to a concrete slab, acting as compression member, in which the design for a specific load is derived by the use of factors not heretofore known in the art.

It is among the objects of the present invention to provide a structure of steel and concrete wherein for a predetermined load the steel area and, therefore, the weight of the required steel is reduced substantially without reducing the adequate factor of safety used for conventional designs.

The present invention is based upon the discovery that the prestresses produced in the steel section by the dead load are gradually eliminated by the live load and do not influence the carrying capacity of the composite section, provided that the pre-stressing is pure bending and does not have any horizontal resultant. It has been determined by theoretical investigation and by tests that a well designed composite section may be so computed and built as to reduce the area and therefore the weight of the steel section by a substantial amount without reducing the adequate factor of safety.

This behavior may be partly explained by that in the breaking state at one point of the beam the entire steel cross-section is stressed to the yield point, whereby deformations are produced which are of a higher order of magnitude than the initial deformations caused by the pre-stressing. Pre-stressing, being pure bending, does not produce any resulting horizontal force and therefore cannot influence the resultant tensional force of the composite section at the moment the steel begins to yield.

This established fact holds true for all cases where the yield point of the steel section is the deciding factor for the carrying capacity of the composite section. It is immaterial in this case by what causes the bending stress due to prestressing is produced (load, dead weight, shrinkage or temperature) as long as the pre-stresses are pure bending and do not produce any horizontal resultant. In the design of any composite section which has an effective shear reinforcement, it is therefore safe to assume that the composite section has to carry the live load only, and to disregard all initial stresses in the steel which may be produced by the dead load due to no temporary supports.

It is not new to use pre-stressing of steel in reinforced concrete constructions to change the normal course of the stresses produced by load and bring about a new stress distribution quite different from that of normal reinforced concrete and which may favorably affect the ultimate carrying capacity of the structure. But in all such structures heretofore used, exterior forces had to be supplied to bring about the pre-stresses in the steel.

According to the prior methods, by special machines or apparatus a tensional force is applied to the reinforcing bars before the concrete is poured about them. After the concrete has set, the tensional force is released and the reinforcing bars then bring the concrete on the tension side of the structure under compression, thus changing the statical as well as the physical properties of the section. Advantages result, which, however, do not always compensate for the complicated procedure of such a construction.

In a structure according to the present invention the pre-stressing is effected by the dead load of the structure itself. First, the steel section is stressed by the dead load in pure bending, producing the same amount of tensile stresses in the bottom as compressive stresses in the top of the beam. Then as part of the composite section the entire steel beam is stressed in tension, provided the actual neutral axis of the composite section is above the steel section. The two resultants of the pre-stressing, the tension resultant in the lower part, and the compression resultant in the upper part of the steel section, being two parallel forces of the same magnitude acting in opposite direction, balance each other with respect to the tension resultant of the composite section, which therefore cannot be affected by the pre-stresses in the steel section.

In other words, the dead load of the structure itself is used to pre-stress the steel beam in such a way that these pre-stresses not only have no effect on the tensional stresses of the composite section but are finally eliminated by them. Thus by forcing the live load, applied on the composite section, to eliminate the dead load stresses in the steel section, the amount of steel required is considerably reduced.

In previous designs of composite sections, certain well established formulas have been used. For instance, in computing the tensile stress in steel the following formulas have been used:

a. For composite sections without temporary supports

$$f_s=\frac{M_{D.L.}}{S'_s}+\frac{M_{L.L.}}{S_s} \qquad \text{(No. 1)}$$

b. For composite sections with intermediate temporary supports

$$f_s=\frac{M_{D.L.}+M_{L.L.}}{S_s} \qquad \text{(No. 2)}$$

According to the prior art, the formula used for computing the compressive stresses in the concrete was as follows:

a. For composite sections without temporary supports

$$f_c=\frac{M_{L.L.}}{S_c} \qquad \text{(No. 3)}$$

b. For composite sections with intermediate temporary supports

$$f_c=\frac{M_{D.L.}+M_{L.L.}}{S_c} \qquad \text{(No. 4)}$$

The Formulas 2 and 4 are also applicable to reinforced concrete sections.

In the above formulas the symbol f_s represents the unit tensile stress in the extreme fibre of the steel. $M_{D.L.}$ represents the bending moment due to the dead load. $M_{L.L.}$ represents the bending moment due to the live load. S'_s represents the section modulus of the steel section alone, and S_s the section modulus of the steel of the composite section. f_c represents the unit compressive stress in the extreme fibre of the concrete and S_c the section modulus of the concrete in compression of the composite section. The term "dead load" as used herein includes the weight of the beam plus the first pour of concrete. The term "live

load" as used herein includes the second pour of concrete, such as for example in a bridge, a wearing surface, concrete railings, additional road bed, ballast, rails and the like. The live load also includes the additional dead load such as for example in buildings, floor fill, floor finish, pipes, housings and the like. In other words, any dead load which is not applied to the steel beam before or at the same time the first pour of concrete is made, is included under live load. In addition, the term includes the normal live load, namely the temporary loading of the structure due to traffic in a bridge or due to stored goods in a warehouse and the like, or furniture and people in office or living rooms.

According to the present invention, a different system of computation is used which is based upon the theory that a composite section may be so designed and constructed that the initial stresses in the steel due to the dead load are gradually eliminated as live load is applied to the composite section.

In computing the tensile stress in the steel, the following formula is used in accordance with the present invention:

$$f_s=\frac{M_{L.L.}}{S_s} \qquad \text{(No. 5)}$$

Comparing this formula with Formulas No. 1 and No. 2 as previously used, it will be seen that the bending moment due to dead load has been omitted entirely. However, it is not claimed that at the designed live load the stresses in the extreme fibre of the steel f_s is as given by the above formula. The elimination of the pre-stresses in the steel occurs gradually and may not be fully accomplished until shortly before the ultimate load is reached. The value of f_s is, therefore, more a comparative stress with regard to the factor of safety than an actual stress. Furthermore, the safe use of the above formula is subject to the following restrictions:

1. The actual neutral axis of the composite section must be above the steel beam.

2. Definitely no intermediate temporary supports during the pouring and setting of the concrete. If beams cannot be cambered and total deflection is limited, the dead load deflection may be the determining factor for the design of the steel section. Under no conditions can temporary supports be used to reduce deflection.

3. To keep the same factor of safety as for conventional designs in structures built to carry dynamic loads the pre-stresses in the steel plus the stresses due to the live load should not exceed the fatigue strength of the steel for that particular loading condition.

The stresses in the concrete according to the present invention are computed by the use of the formula

$$f_c=\frac{M_{L.L.}}{S_c} \qquad \text{(No. 6)}$$

Comparing this formula with the previously used Formulas No. 3 and No. 4, it will be seen that the bending moment due to the dead load is omitted as it is in Formula No. 3, used previously for beams without temporary supports. However, due to considerations which have nothing to do with the present invention, and which are explained in my aforesaid copending application, it seems advisable to take into consideration the dead load moment in designing the concrete part of the composite section.

In the accompanying drawings, constituting a part hereof, and in which like reference characters indicate like parts:

Fig. 1 is a cross-sectional view of a steel section showing the stresses therein due to the dead load alone;

Fig. 2 is a cross-sectional view of a composite beam of steel and concrete showing the stresses in said section due to the dead and live loads at the moment of failure;

Fig. 3 is a cross-sectional view of a composite section of steel and concrete, having no concrete around the steel, showing the stresses in steel and concrete due to the dead and live load at the moment of failure;

Fig. 4 is a longitudinal diagrammatic view showing a composite beam suitably supported on permanent supports and subjected to a live load;

Fig. 5 is a cross-sectional view of a reinforced concrete T beam section having a rigid reinforcement in form of an I beam section and showing the compressive and tensional stresses in the steel section and the composite section;

Fig. 6 is a cross-sectional view of a composite section in which the neutral axis of the composite section passes through the steel section;

Fig. 7 is a cross-sectional view of a composite section wherein the concrete encloses the steel section down to the bottom flange, the area of which is increased by attaching a cover plate by welds or rivets;

Fig. 8 is a cross sectional view of a composite section wherein the tension member is a welded or riveted built up steel section;

Fig. 9 is a cross sectional view of a composite section wherein the tension member is a timber joist; and

Fig. 10 is a longitudinal view of a composite beam suitably supported on permanent supports.

There is provided a beam 1 (Fig. 1) which, as shown, is of the standard I-beam type. To the right of the beam 1 is its stress diagram, showing by horizontal arrows the stresses therein due to the dead load. The horizontal arrows 2 represent the compressive stresses therein due to the weight of beam and concrete. The maximum compressive stress is at the top of the I-beam. The arrows 3 show the tension in the lower half of the I-beam due to the dead load, the maximum tensile stress being at the bottom of the I-beam. It will be noted that the magnitude of the compressive and tensile stresses is the same, that their direction is parallel to the longitudinal axis of the beam, but of opposite sign. Therefore, they do not produce any horizontal resultant.

In Fig. 2 is shown the composite section consisting of the I-beam, the spiral shear reinforcing 4 along the top thereof and welded or otherwise secured to the top of beam 1. A concrete section 5 surrounds the reinforcing members and is integral with a slab 6, the weight of which is carried by the steel section 1. To the right thereof is shown the magnitude and character of the compressive stresses in the composite section. It will be noted that the compression is carried by the concrete slab 6. The arrows 8 show the tensile stresses in the composite section, from which it will be seen that the entire tensile stress is carried by the steel beam 1. Long before failure is reached the tensional resistance of the concrete has been overcome and, therefore, is entirely neglected as usually in all reinforced concrete designs.

In Fig. 3 is shown the composite section consisting of the I-beam, the spiral 4 secured to the top of the beam 1, and the concrete slab 6, which is supported by the steel section 1. To the right thereof are shown the stresses in the composite section, due to the dead and live load at the moment the yield point is reached in the steel section. The arrows 7 show the compressive stresses in the concrete, the arrows 8 show the tensile stresses in the steel of the composite section. There is no concrete in the tension part of the composite section.

In Fig. 2 and Fig. 3 is shown the resultant of the compressive stresses in the concrete R^c, passing through the center of action of, and representing all compressive stresses. There also is shown the resultant of the tensional stresses in the steel R^t passing through the center of action of, and representing all tensional stresses. These two resultants with their rectangular distance jd determine the resisting moments of the composite section.

The resisting moment of the concrete is of no interest in the present investigation. The resisting moment of the steel is represented by the formula:

$$M_{R_s}=R^t\times jd$$

wherein M_{R_s} is the resisting moment of the steel (ultimate moment at failure), R^t is the tension resultant, or the tensional force of the composite section. jd is the rectangular distance between the tension resultant and the compression resultant of the composite section. R^t itself is the area of the tension steel multiplied by the ultimate stress the steel can sustain before failing, namely the yield point. The formula for the resisting moment therefore can be written as follows:

$$M_{R_s}=(A_s\times f_{sy})\,jd$$

A_s is the area of the steel section, f_{sy} is the yield point of the steel. $A_s\times f_{sy}=R^t$.

If none of the three factors of the resisting moment or neither R^t nor jd is changed by the initial stresses in the steel, produced by the dead load, then the dead load has no effect on the ultimate resisting moment or the carrying capacity of the composite section and, therefore, can be neglected in designing such a section.

Prestressing due to dead load is pure bending which in any shape of section must produce a compressive force in the upper part of the steel section which is equal to the tensile force at the lower part of the steel section. The two forces are equal in magnitude and parallel but of opposite direction and have no resultant. Therefore, they cannot influence the tensional resultant R^t which is parallel to them. For instance: A steel section is assumed with an area of 10 square inches and a yield point of 40,000 pounds per square inch. Then the tensile force R^t available to the composite section is $10\times40{,}000=400{,}000$ pounds. If the pre-stressing in the steel section is at an average of 8000 pounds per square inch, there is a compression resultant in the upper part of the steel section of $5\times8000=40{,}000$ pounds and a tension resultant at the lower part of $5\times8000=40{,}000$ pounds. This tensional force produced by the dead load uses 40,000 pounds of the available tensile strength and reduces it to 360,000 pounds. But the compression resultant of 40,000 pounds in the upper part of the steel section increases the available tensile strength by 40,000 pounds and restores it to the original 400,000 pounds, because the 40,000 pounds compression cannot be released without applying 40,000 pounds tensional stresses. It follows that the initial stresses in the steel section cannot influence the tension resultant R^t of the composite section.

The distance jd can only be changed by changing the location of the center of action of the tensional stresses of the composite section. It is obvious that at the moment of failure, when the entire steel section has reached the yield point, the center of action is identical with the center of gravity of the steel section itself, where it is assumed to be in designing the section.

The initial stresses in the steel cannot have any influence on the location of the center of action at the moment of failure simply because at that moment they are already eliminated. In the earlier stages of loading of the composite beam the initial stresses in the steel do change the location of the center of action of the tensional stresses, but obviously in a downward direction, and so increase the distance jd and, therefore, the resisting moment. This is shown in stress diagram Fig. 5*d*.

Since the magnitude of the tensional resultant R^t and the distance jd of the composite section are not influenced by initial stresses in the steel, the resisting moment of the composite section, that is the carrying capacity of the composite section, is not influenced.

Based upon this, according to the present invention, all initial stresses in the steel beam of a composite section, in fact any stresses in the steel beam due to dead load, shrinkage, change in temperature, etc. may be disregarded in the design of a composite section, as long as these stresses do not produce any horizontal resultant.

Fig. 4 shows the combination of the composite section with its permanent supporting members. Said section 9 is supported at its ends by pillars or the like 10 and 11, respectively. The live load for which the composite beam is calculated is represented by the vertical arrows 12, which cause flexing of the section 9 as shown in broken lines 13. The same principles apply to any length of span.

In Fig. 5*a* is shown a reinforced concrete section consisting of steel beam 1, a spiral or other shear reinforcement 4, welded to the steel section, a concrete haunch 5 in which steel section 1 is entirely embedded, and which is poured monolithically with the concrete slab 6. To insure a better bond between steel section and concrete, wire mesh or reinforcing bars 14 may be placed around steel section and reach up into the slab. If enough bars are used the shear reinforcement 4 may be omitted. The steel section has a shallow depth compared with the total depth of the composite section and reinforced concrete formulas may be used for the design. The neutral axis 15 of the composite section is far above the steel section.

Fig. 5*b* shows the stress diagram of the steel beam for the stresses due to the dead load. At the lower part is the tension resultant t which equals the compression resultant c at the upper part of the beam.

Fig. 5*c* shows the stress diagram of the composite section. The line 16—17 is the zero line representing a state of no stress. A small load applied on the composite section, after the concrete has set, produces stresses as shown by the line 18—19, which intersects the zero line at the neutral axis 15. The tensional stresses in the concrete are neglected as of no importance for

ultimate load. A load increase may produce tensional stresses in the steel as shown by horizontal arrows 20 and compressive stresses as shown by horizontal arrows 21. R^t represents the tension force of the composite section, in other words the average of the stresses, represented by the arrows 20, multiplied by the area of the steel. R^c represents the compression force of the composite section. These two forces with their rectangular distance jd determine the two resisting moments of the reinforced concrete section, namely the resisting moment of the steel and the resisting moment of the concrete.

Fig. 5*d* shows the two stress diagrams of Figs. 5*b* and 5*c* combined into one. The concrete stresses are the same as in Fig. 5*c*. Theoretically, the stress diagram of the steel is as indicated by the line 22—23—24. However, the dotted line 25—26—24 comes nearer the actual condition. It is obvious that the average magnitude of the tensile stresses is the same as in stress diagram Fig. 5*c*. The center of action through which R^t passes, however, is farther down than in diagram 5*c*, which means that the distance jd increases and also the resisting moment. The initial stresses in the steel beam due to the dead load, therefore, do not reduce but rather increase the resisting moment of the steel of the composite section.

Fig. 5*e* shows the stress diagram at the moment of failure. The neutral axis and consequently the compression resultant R^c has moved up a little. The tension resultant R^t passes through the center of gravity of the steel section and is, therefore, at exactly the same position as assumed in the design, and as shown in Fig. 5*a*. The entire steel section is stressed to the yield point and it is obvious that any prestresses in the steel produced by pure bending must balance themselves since pure bending produces the same amount of compressive as well as tensile stresses.

From the above it follows that in a reinforced concrete section with rigid reinforcement, the initial stresses in the steel section due to the dead load reduce the tensile stresses of the composite section in the upper part of the steel section by the same amount as they increase the tensile stresses of the composite section in the lower part of the steel section. The tension resultant R^t is therefore not influenced and its center of action but little, and if so in a favorable way so that the distance jd rather increases than decreases. Since the initial stresses in the steel do not influence either R^t or jd, and since $R \times jd$=resisting moment of the steel of the reinforced concrete section, it is safe to disregard all initial stresses in the steel in the design of a reinforced concrete section with rigid reinforcement, as long as the initial stresses are pure bending. The dead load cannot produce any other stress in the tension steel of the composite section than the initial stresses produced therein before steel and concrete act together and form a statical unit. Therefore, such a section is designed to resist only the bending moment produced by the live load, and the bending moment produced by the dead load is entirely neglected.

Fig. 6*a* shows a steel section 1, a shear reinforcement 4, attached to the steel section 1 and a concrete slab 6 poured on top of the steel section. The neutral axis of the composite section 15 passes through the steel section. It has been said that the neutral axis of the composite section must be above the steel section in order that the pre-stresses in the steel, the tension in the lower part and the compression in the upper part do not produce any horizontal resultant with respect to the tension resultant of the composite section. If part of the steel section is in the compression part of the composite section, it means that part of the initial compressive stresses in the steel section are not available to balance the initial tensile stresses in the steel with respect to the tension resultant of the composite section R^t. In order to simplify the explanation of how the stresses in such a section are distributed the steel section 1 is assumed to be a plate with uniform width of one unit from top to bottom. The stress diagram then represents also the diagram of the compressive and tensile forces of the steel, namely f_s, tension times A_s and f_s, compr. times A_s respectively.

In a composite section in which the neutral axis passes through the steel section, the compression resultant R^c is composed of a compression resultant of steel $r_s{}^c$ and a compression resultant of concrete $r_c{}^c$. The center of action through which R^c passes is somewhere between $r_s{}^c$ and $r_c{}^c$.

The line 27 is the neutral axis of the steel section itself.

Fig. 6*b* shows the stress diagram in the steel section due to the dead load. The horizontal arrows 28 in the lower part of the section represent the tensile stresses, the horizontal arrows 29 in the upper part the compressive stresses in the steel. The heavy arrow 30 is the resultant of the tensile stresses and passes through the center of attack of the tensile stresses. The heavy arrow 31 is the resultant of the compressive stresses passing through the center of attack of the compressive stresses. It can easily be seen that the two resultants are balanced with respect to the tension resultant R^t of the composite section if the neutral axis is outside the steel section and the entire steel section as part of the composite section, is stressed in tension. However, in the section under consideration the neutral axis of the composite section 15 passes through the steel section and that part of the compressive stresses 32 above axis 15 is not available to balance the tensile stresses 33. Only the compressive stresses 34, which are between the neutral axes 15 and 17, are available to balance the same amount of tensile stresses 32. The compressive stresses 32 in the steel section, due to the dead load, increase therefore the compressive stresses in the steel section as part of the composite section, and the tensile stresses 33 increase the tensile stresses of the composite section.

Fig. 6*c* shows the stress diagram of the composite section. Assuming that the stresses increase with the distance from the neutral axis, the two triangles formed by the zero line 36—37 and the line 38—39 intersecting at the neutral axis 15, represent $r_c{}^c$ and R^t, respectively. Combining this diagram with the diagram of Fig. 6*b* by tracing line 40—41, the diagram of dead and live load stresses, as shown by the horizontal arrows 42, 43 and 44, appears. The arrows 42 represent the tensile stresses in the steel, also represented by R^t, the arrows 43 represent the compressive stresses in the steel and the arrows 44 the compressive stresses in the concrete. The two latter form together R^c, the compression resultant of the composite section. The diagram of the tensile forces reveals that they are increased by the area of triangle 38—40—45 which

has the same area as the triangle of the tensile forces in Fig. 6*b*. But the tensile forces are also reduced by the area of triangle **45—15—46**, because part of the steel which was stressed in compression by the dead load is now stressed in tension by a live load applied on the composite section. Thus it is seen that gradually part of the initial stresses in the steel are eliminated. If the actual location of the neutral axis is known the amount of the tensile and compressive forces which are eliminated by the live load can accurately be computed. Using the location of the neutral axis given by the usual design formulas to compute the amount of the eliminated prestresses is always safe, because the actual neutral axis is always farther up than those formulas indicate.

Fig. 6*d* shows the diagram of ultimate stress. The neutral axis **15** of the composite section moved up and is about in the extreme fibre of the steel section and lower fibre of the concrete slab. Most or all the compressive stresses are taken by the concrete and all the steel, or almost all, is stressed in tension. In this particular case the steel area is in tension and it is obvious that in eliminating the initial compressive stresses in the steel, the same amount of tensile force was made available for R^t. Though the upper part of the steel section does not sustain tensile stresses of high magnitude, the total ultimate tensile force R^t and the distance jd are greater than assumed in the design of the section. Therefore, in this particular case one may disregard the dead load even when the neutral axis is in the steel section. The conditions are not so favorable for all conceivable sections, but it is safe to assume that at least the initial compressive stresses in the steel section which are below the actual neutral axis of the composite section gradually balance an equal amount of initial tensile stresses in the steel section as soon as live load is applied on the composite section. Consequently these two amounts of the initial stresses can be neglected in designing the composite section.

Fig. 7 shows a cross-section of a composite beam where the steel section **1** is embedded in concrete **47** which may have the form as shown or may fill the entire depth of the structure as indicated by the dotted lines **48**. The neutral axis **15** is above the steel section and in the concrete, the beam therefore forms a rectangular section. To increase the area of the tension steel a cover plate **49** is welded or riveted to the bottom flange of steel section **1**. A shear reinforcement **4** may be attached to the top flange of said steel section to insure the transmission of the horizontal shear.

Fig. 8 shows a cross-section of a composite beam wherein the tension steel **1** is an all welded section with a smaller top flange and a heavier bottom flange. The concrete slab **6** has a haunch **5** resting on the top flange of the steel section. Such a concrete haunch may be required in order to bring the neutral axis **15** of the composite section above the steel section. **50** is a shear reinforcement of 2 bars, bent in wave-like form and welded or riveted to the top flange.

Fig. 9 shows a composite section wherein a timber joist **51** is used as the tension member. The concrete slab **6** is attached to the timber joist **51** by means of shear reinforcements **4** in form of spirals, nailed to the joist, or in form of triangular spikes driven into the joists and embedded into the concrete slab. The neutral axis **15** is above the timber section.

Fig. 10 shows the combination of the composite section with its permanent supports. Said section **9** is supported at its ends by pillars or connections **10** and **11** respectively. The live load, for which the composite beam is computed, causes the composite beam to deflect. This deflection due to the live load is about the same as for most conventional designs and rarely will exceed the allowable deflection. However, due to the fact that a composite section designed according to the present invention, comparatively has a light steel section, the deflection of the steel section due to the dead load may be inconvenient. Since temporary supports cannot be used, the dead load deflection may be eliminated by cambering the beams. The broken line **52** shows the dead load deflection of the steel beam, which can be computed. If the steel beam, before being erected is bent or cambered, in the other direction, in just the same amount, as shown by the broken lines **53** then the composite section **9** will be horizontal as shown. As the cambering of the beam produces pure bending, and in the opposite direction than the dead load, the cambering may offset the dead load stresses in the steel, but does not affect the ultimate load of the composite section.

To show the saving obtained by the use of the present invention, one may compare the design with that obtained by using the prior formulas. In so doing, according to the present formula, one assumes that the dead load stresses in the steel section do not influence the carrying capacity of the composite beam and are therefore neglected. In computing the design according to the previously used formulas, two cases have to be considered:

1. A beam with temporary intermediate supports where it is assumed that the composite section carries both dead and live load, and
2. A beam without temporary supports where it is assumed that the steel alone carries the dead load and the composite section the live load only.

Example 1

A highway bridge is constructed consisting of stringers with a span of 40 feet, spaced 6 feet on center. It has a concrete slab 7.5 inches thick and is to resist the following bending moment:

$$M_{D.L.} = 1{,}960{,}000 \text{ inch pounds}$$
$$M_{L.L.} = 2{,}340{,}000 \text{ inch pounds}$$

The allowable extreme fibre stress for the steel is 18,000 pounds per square inch and for the concrete 1000 pounds per square inch; n was assumed to be 12.

A design made in accordance with the present invention shows that a 16 inch wide flange section with a weight of 50 pounds per lineal foot is required. However, the deflection due to the dead load would be too great to eliminate by cambering and the stresses in the steel due to the dead load would be higher than 18,000 pounds per square inch. Therefore, a 16 inch wide flange section with a weight of 64 lbs. per lineal foot is used. The section moduli of steel and concrete of the composite section are:

$$S_c = 4770 \text{ in.}^3 \qquad S_s = 178 \text{ in.}^3$$

the extreme fibre stresses in steel and concrete are:

Concrete, due to $L.L.\ f_c = \frac{2,340,000}{4770} = 491$ lbs./sq. in.

Steel, due to $L.L.\ f_s = \frac{2,340,000}{178} = 13,150$ lbs./sq. in.

The design according to the prior formulas, for case No. 1 where temporary intermediate supports are used, requires a 16 inch wide flange section with a weight of 88 pounds per lineal foot. The section moduli of steel and concrete of the composite section are:

$S_c = 5570$ in.^{3} $S_s = 239$ in.^{3}

The extreme fibre stresses in concrete and steel are:

Concrete, due to $D.L.+L.L.\ f_c =$

$$\frac{1,960,000+2,340,000}{5570} = 772 \text{ lbs. per sq. in.}$$

Steel, due to $D.L.+L.L.\ f_s =$

$$\frac{1,960,000+2,340,000}{239} = 18,000 \text{ lbs. per sq. in.}$$

In a design according to the prior formulas for case No. 2 where no temporary supports are used, there is required a 16 inch wide flange section, having a weight of 114 pounds per lineal foot. The section moduli for the steel section and the composite section are:

$S_s^1 = 197.4$ in.^{3} $S_c = 6250$ in.^{3} $S_s = 305$ in.^{3}

The extreme fibre stresses in steel and concrete are:

Concrete, due to $L.L.\ f_c =$

$$\frac{2,340,000}{6250} = 375 \text{ lbs. per sq. in.}$$

Steel, due to $D.L.\ f_s^1 =$

$$\frac{2,022,400}{197.4} = 10,200 \text{ lbs. per sq. in.}$$

Due to $L.L.\ f_s = \frac{2,340,000}{305} = 7,680$ lbs. per sq. in.

Total stress $f_s = 17,880$ lbs. per sq. in.

The difference between the dead load moment of case No. 1 and case No. 2 is due to the difference in weight of the steel section.

The saving in steel by the present invention as compared with the prior art is as follows:

Compared with case No. 1:

16 WF88, total weight $= 40 \times 88 = 3250$ lbs.
16 WF64, total weight $= 40 \times 64 = 2560$ lbs.

Saving per beam = 960 lbs.

In addition to 960 lbs. more steel, case No. 1 requires intermediate supports.

Compared with case No. 2:

16 WF 114, total weight $= 40 \times 114 = 4560$ lbs.
16 WF 64, total weight $= 40 \times 64 = 2560$ lbs.

Saving per beam = 2000 lbs.

Example 2

A floor for a warehouse is constructed consisting of beams between girders, with a span of 20 feet and a spacing of 5 feet center to center. The concrete slab is 4'' thick and the structure fireproofed by 2'' of concrete. The bending moments are:

$M_{D.L.} = 241,800$ inch pounds
$M_{L.L.} = 590,200$ inch pounds

The allowable extreme fibre stresses are: steel = 18,000 pounds per square inch, concrete 800 pounds per square inch; n is assumed to be 15.

A design made in accordance with the present invention shows that a 12 inch light beam section with a weight of 16.5 pounds per lineal foot is required. The section moduli of steel and concrete of the composite section are:

$S_c = 1780$ in.^{3} $S_s = 37.5$ in.^{3}

The extreme fibre stress in steel and concrete are:

Concrete, due to $L.L.\ f_c =$

$$\frac{570,000}{1780} = 320 \text{ pounds per sq. in.}$$

Even if it is computed on the total load, the stress in the concrete is only

$$f_c = \frac{811,000}{1780} = 456 \text{ pounds per sq. in.}$$

Steel, due to $L.L.\ f_s =$

$$\frac{570,000}{37.5} = 15,200 \text{ pounds per sq. in.}$$

The stress in the steel due to the dead load, tension in bottom and compression on top, is:

$$f_s = \frac{241,000}{17.5} = 13,780 \text{ pounds per sq. in.}$$

17.5 = section modulus of steel section alone. This stress is not taken into consideration according to the present invention.

The design according to the prior formulas, for case No. 1, where temporary intermediate supports are used, requires a 12 inch light beam section with a weight of 22 lbs. per lineal foot. The section moduli of steel and concrete of the composite section are:

$S_c = 1890$ in.^{3} $S_s = 46.2$ in.^{3}

The extreme fibre stresses in concrete and steel are

Concrete: due to $D.L.+L.L.\ f_c =$

$$\frac{242,000+570,000}{1890} = 430 \text{ lbs. per sq. in.}$$

Steel: due to $D.L.+L.L.\ f_s =$

$$\frac{242,000+570,000}{46.2} = 17600 \text{ lbs. per sq. in.}$$

In a design according to the prior formulas for case No. 2 where no temporary supports are used, a 12 inch wide flange section (Standard Mill Beam) with a weight of 28 lbs. per square inch is required. The section moduli of steel and concrete are:

$S_c = 1995$ in.^{3} $S_s^1 = 32.6$ in.^{3} $S_s = 57.4$ in.^{3}

The stresses in steel and concrete are:

Concrete:

due to $L.L.\ f_c = \frac{570,000}{1995} = 286$ lbs. per sq. in.

Steel:

due to $D.L.\ f_s = \frac{270,000}{32.6} = 8280$ lbs. per sq. in.

due to $L.L.\ f_s = \frac{470,000}{57.4} = 9920$ lbs. per sq. in.

Total $f_s = 18,200$ lbs. per sq. in.

The saving in steel by the present invention as compared with the prior art is as follows:

Compared with case No. 1:

12 *L.B.* 22 total weight=20×22 =440 lbs.
12 *L.B.* 16.5 total weight=20×16.5=330 lbs.

Saving per beam=110 lbs.

Compared with case No. 2:

12 *M.B.* 28 total weight=20×28 =560 lbs.
12 *M.B.* 16.5 total weight=20×16.5=330 lbs.

Saving per beam=230 lbs.

In Example 1 the saving in the weight of steel in favor of the new design amounts to 27% compared with case No. 1 design, and to 44% compared with case No. 2 design. In Example 2 it is 25% compared with case No. 1 and 41% compared with case No. 2. Assuming a cost of five cents per pound of steel, the actual saving in cost per beam is:

For Example 1, compared with design case No. 1=$ 48.00
For Example 1, compared with design case No. 2=$100.00

For Example 2, compared with design case No. 1=$ 5.50
For Example 2, compared with design case No. 2=$11.50

By using the present invention on reinforced concrete or composite structures, various advantages are realized. Due to the fact that the dead load moment is neglected and much lighter steel sections are used, there is a saving in costly steel, and in fireproofed structures, also a saving in concrete. Compared with conventional composite design, the saving in cost of the steel is substantial as shown by the examples.

The present invention makes it possible to build a structure in composite design with less steel than is required for reinforced concrete design. Such a composite section is easier to erect, does not require temporary supports, is lighter and saves in concrete. This saving in concrete is considerable where no fireproofing is required, less pronounced where the steel has to be protected. Besides, such a composite section has technical advantages against a reinforced concrete section. Shrinkage of the concrete, which produces compressive stresses in the top flange of the steel section of a higher magnitude than the tensile stresses produced in the bottom flange produces, therefore, a horizontal compression resultant in the steel section which tends to reduce the tensile stresses of the composite section produced by the live load. Shrinkage may increase the tensile stresses in a reinforced concrete structure. Cracks in the concrete on the tension side which may be harmful in reinforced concrete are of no importance in composite design because no structural concrete is required there. Plastic flow of concrete in such a composite section in less pronounced, because the concrete receives less permanent stress, and its influence is therefore much less than for a reinforced concrete beam.

The heretofore known systems of pre-stressing help the concrete by increasing its area of compression and by making impossible tensional stresses in the concrete on the tension side of the structure. Therefore, with the same concrete area greater stresses can be sustained and the disadvantage of concrete cracks on the tension side is eliminated. However, considerably more steel area is required or steel with much higher tensile strength.

The system according to the present invention helps the concrete somewhat, as the concrete does not receive dead load stresses, and it makes possible a considerable reduction in steel area. Concrete cracks on the tension side of a composite section are of no importance, as the concrete there has no structural function. Whereas the prestressing in the heretofore used pre-stressed reinforced concrete structures is costly and complicated and takes much time, the prestressing according to the present invention does not require any expense or work, neither in the designing nor in the erecting of the structure. Besides all temporary supports are eliminated which also means a saving in cost.

Heretofore, composite concrete and timber floors were not used extensively because the concrete slab is more costly than floor boards and the higher weight of the concrete increases the dead load so much that the saving by the composite action is almost balanced. With a composite floor construction of concrete and timber according to the present invention, the entire dead load is disregarded and the saving, therefore, considerable.

In the above description the invention has been applied to simple beams, wherein only positive moments occur. The invention is not limited thereto but applies as well to continuous beams wherein positive and negative moments occur. In the negative moment the stresses are reversed and the steel section, due to the dead load, is stressed in tension in the top flange, and in compression in the bottom flange. The live load applied on the composite section produces compressive stresses in the steel section, as against tensile stresses in the positive moment.

In the above description the invention has been applied to pre-stresses due to the dead load of the structure itself. It is obvious that some load could be applied to the steel section during pouring and setting of the concrete and then, when the concrete has set, the load is removed. That load produces additional initial stresses in the steel, similar to the initial stresses produced by the dead load. These initial stresses will have no influence on the ultimate load of the composite section. Then, when the load is removed, the deflection of the composite section will diminish and the composite section now sustains the release moment. This means that the steel section sustains compressive stresses and the concrete tensile stresses. This stress, with the opposite sign as the stresses produced by the live load, could be used to balance part of the live load stresses. However, it is doubtful that the small additional saving will offset the additional cost for applying and removing the load.

What I claim is:

1. A method of making a prestressed composite structure which comprises providing substantially rigid reinforcements in the form of structural shapes having shear reinforcing, mounting the same on permanent supports without intermediate temporary supports, pouring concrete about said reinforcements to impart dead load prestresses of pure bending thereto allowing the concrete to set, the stresses in said structure such that the live load applied on the completed reinforced concrete beam acts to neutralize said prestresses, the area of said reinforcements being sufficient to take the live load stresses only, the initial dead load stresses being entirely neglected, the positioning of the concrete relative to said structural shapes being such that the neutral axis of the composite structure is above said structural shapes.

2. A method of making a prestressed composite structure which comprises providing substantially

rigid reinforcements in the form of structural shapes having shear reinforcing, mounting the same on permanent supports without intermediate temporary supports, pouring concrete about said reinforcements to impart dead load prestresses of pure bending thereto allowing the concrete to set, the stresses in said structure such that the live load applied on the completed reinforced concrete beam acts to neutralize said prestresses, the area of said reinforcements being sufficient to take the live load stresses only, the initial dead load stresses being entirely neglected, the stresses in the reinforcements being computed according to the formula

$$f_s=\frac{M_{L.L.}}{S_s}$$

wherein f_s represents the unit tensile stress in the extreme fiber of the reinforcing material, $M_{L.L.}$ the bending moment due to the live load, and S_s the section modulus of the composite section, the positioning of the concrete relative to said structural shapes being such that the neutral axis of the composite structure is above said structural shapes.

3. A method of making a prestressed composite structure which comprises providing substantially rigid reinforcements in the form of structural shapes having shear reinforcing, mounting the same on permanent supports without intermediate temporary supports, pouring concrete about said reinforcements to impart dead load prestresses of pure bending thereto allowing the concrete to set, the stresses in said structure such that the live load applied on the completed reinforced concrete beam acts to neutralize at least most of said prestresses, the depth of said structural shape being a substantial portion of the depth of said composite structure, and the neutral axis of the composite section being above said structural shape.

4. A method of making a prestressed composite structure which comprises providing substantially rigid reinforcements in the form of structural shapes having shear reinforcing, mounting the same on permanent supports without intermediate temporary supports, pouring concrete about said reinforcements to impart dead load prestresses of pure bending thereto allowing the concrete to set, the stresses in said structure such that the live load applied on the completed reinforced concrete beam acts to neutralize said prestresses, the area of said reinforcements being sufficient to take the live load stresses only, the initial dead load stresses being entirely neglected, the sum of said prestresses and the stresses due to the live load being less than the fatigue strength of the reinforcing material for the calculated live load, the positioning of the concrete relative to said structural shapes being such that the neutral axis of the composite structure is above said structural shapes.

5. A method of making a prestressed composite structure which comprises providing substantially rigid reinforcements in the form of structural shapes having shear reinforcing, mounting the same on permanent supports without intermediate temporary supports, pouring concrete about said reinforcements to, impart dead load prestresses of pure bending thereto allowing the concrete to set, the stresses in said structure such that the live load applied on the completed reinforced concrete beam acts to neutralize said prestresses, the area of said reinforcements being sufficient to take the live load stresses only, the initial dead load stresses being entirely neglected, the resisting moment of the reinforcements being represented by the formula

$$M_{R_s}=R^t\times jd$$

wherein M_{R_s} represents the resisting moment of the steel, R^t the tension resultant, and jd the rectangular distance between the tension resultant and the compression resultant of the composite section, the positioning of the concrete relative to said structural shapes being such that the neutral axis of the composite structure is above said structural shapes.

6. A method of making a prestressed composite structure which comprises providing substantially rigid reinforcements in the form of structural shapes having shear reinforcing united therewith, mounting the same on permanent supports without intermediate temporary supports, cambering said beam to reduce the deflection due to the dead load, pouring concrete about said reinforcements to impart dead load prestresses of pure bending thereto, allowing the concrete to set, the stresses in said structure such that the live load applied on the completed reinforced concrete beam acts to neutralize said prestresses, the area of said reinforcements being sufficient to take the live load stresses only, the initial dead load stresses being entirely neglected, the positioning of the concrete relative to said structural shapes being such that the neutral axis of the composite structure is above said structural shapes.

7. A method of making a prestressed composite structure which comprises providing substantially rigid reinforcements in the form of structural shapes having shear reinforcing united therewith, mounting the same on permanent supports without intermediate temporary supports, pouring concrete about said reinforcements to impart dead load prestresses of pure bending thereto, allowing the concrete to set, the stresses in said structure being such that the live load applied on the completed reinforced concrete beam acts to neutralize said prestresses, the area of said reinforcements being sufficient to take the live load stresses only, the initial dead load stresses being entirely neglected, the positioning of the concrete relative to said structural shapes being such that the neutral axis of the composite structure is above said structural shapes, the prestresses in the steel plus the stresses due to the live load not exceeding the fatigue strength of said steel for a predetermined loading condition.

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