A prestressed, segmented concrete beam, has the tensile members so positioned and stressed as to effectively utilize the prestressing forces while preventing vertical shearing or splitting at the ends of the beam. A method of making such a beam is provided.

CROSS REFERENCES TO RELATED APPLICATIONS

This application is a divisional application of copending application, Ser. No. 460,904, filed June 31, 1965, now issued as U.S. Pat. No. 3,407,554 on Oct. 29, 1968.

BACKGROUND OF THE INVENTION

This invention relates to a prestressed, segmented concrete beam of improved design and structure and to a method of making same. Such beams find use as horizontal supporting members in various structures including buildings and bridges.

The forces acting on beams so employed are well known. These forces include the vertical forces such as reaction and shear produced by the dead load of the beam and its external load and the accompanying axial forces such as tension and compression of the beam fibers and horizontal shearing forces between the fibers.

For obvious reasons, concrete makes an ideal material for structures and it has often been proposed to utilize concrete in horizontal beams. However, it is an inherent characteristic of concrete that while it withstands compressive loads with relative ease, it is notoriously weak under tensile loading. As a horizontal beam in normal use encounters both tensile and compressive forces, the use of concrete for such beams has been severely restricted in the past. Special designs have been devised to limit the tensile stress in the concrete to a value below the modulus of rupture of the concrete. However, these have been extremely expensive to manufacture, heavy and awkward to install and limited in length which may be spanned.

Attempts have been made to remedy the above problems by reinforcing the concrete with steel rods. The rods, having a high resistance to tensile stresses, provide sufficient strength to the concrete to permit moderate tensile loading. However, even this structure did not provide an entirely satisfactory concrete beam.

The most successful structure employed to a satisfactory concrete beam is the prestressed beam. As the name implies, the beam is compressively stressed, prior to loading, by means of tendons inserted in the structure and the tensile forces generated in the beam by the load work against these compressive stresses. These structures have resulted in light weight concrete beams which may be subjected to considerable loading.

While such beams are at present generally manufactured by casting the concrete around the tendons in a mold, it has become more desirable to manufacture the beams from a plurality of individual abutting blocks or segments. This method of manufacture has numerous advantages, including the ability to manufacture the individual blocks on a standard concrete block machine without the use of expensive molds required by the cast beam, considerable flexibility in the length of beam manufactured due to the ability to increase or decrease the number of blocks employed, and general ease of manufacturing as the blocks may be individually handled until formed into the beam. These advantages have led to numerous attempts to provide a satisfactory prestressed, segmented concrete beam. In general, these attempts have involved arranging the individual blocks in abutting relation, threading the tendons through holes therein and applying tensile force to the tendons. This tensile force is then transferred to the blocks in the form of compressive loading by anchors at the ends of the beam or by bonding the tensile members to the blocks to hold the blocks together. In spite of these attempts, the prior art has been unable to produce a really satisfactory beam of this type.

In a typical application of a prestressed, segmented concrete beam supported at either end and subjected to uniform loading, compressive stresses will be generated in the upper fibers of the beam while tensile stresses are generated in the lower fibers of the beam. To overcome these tensile stresses, the tensile members, or tendons, are generally placed in the lower portion of the beam. However, in prior art designs, if sufficient tensile force was applied to the tendons to develop the required compressive stress throughout the beam necessary for useful loads, horizontal shear planes developed at either end of the beam extending inward. These shear planes were produced because the bottom portion of the beam was compressively loaded to a greater extent than the top portion. The development of such shear planes was aided by the dead load and design load imposed on the beam as the combination of the load and the prestressing force developed additional shearing forces in the beam.

Additionally, the compressive stresses in the lower portion of the beam tended to rotate the end blocks causing excessive camber of the beam. Besides being excessive, the amount of this camber was difficult or impossible to control and gave rise to problems when a plurality of such beams were used as a roof or floor.

The prior art has included structures in which the tendons have been moved upward toward the center of the beam. While this has tended to equalize the compressive stress over the entire cross-sectional area of the beam, it has decreased the effectiveness of such prestressing, resulting in a heavier structure and a shortened span.

It has also been proposed to decrease the amount of stress applied to the blocks by tendons in the lower portion of the beam. Such a reduction of prestress permits tensile stress to appear in the beam during loading. A beam so stressed is termed partially prestressed as compared with a fully prestressed beam in which little or no tensile stress appears. While partially prestressing the beam lessens horizontal shearing it also limits the utility of the beam.

A further method applied by the prior art to produce a satisfactory beam has included providing a controlled upward camber to the beam. This has permitted the ends of the straight tensile member to be placed in the middle of the end blocks while the center of the tendon is in the lower portion of the raised center blocks of the beam. However, the shaping of the abutting edges of the blocks or the insertion of wedges in the top of the beam required for this method has resulted in a very expensive manufacturing process.

In addition to the aforementioned horizontal shearing caused by the tensile forces of the tendons, concrete beams of the present type may also be subject to splitting along a vertical plane in the beam due to improper location and application of the tensile force. For example, if a pair of tendons located near each of the outside vertical edges of the beam place the beam under compre-
sion, the compressive stresses generated by the tendons will attempt to rotate each half of the end blocks of the beam outward in much the same manner as placing the tendons too low in the beam produced an upward camber to the beam. The stresses applied to each half of the end blocks will cause the beam to split in a vertical direction along its center line near the ends. Similar problems may occur if the forces of the tendons are not applied to the beam uniformly and simultaneously when compressively loading it.

It must be mentioned that while the above-mentioned destructive shearing forces occur in both one piece, cast beams and block, or segmented beams, their effects are more limiting in the latter. In cast beams, reinforcing rods or stirrups may be inserted in the mold and cast into the concrete to resist the above mentioned forces. This cannot be done on segmented beams as the concrete work is done in segments in block machines. Hence, the features of the present invention find particular utility in segmented beams.

SUMMARY

It is, therefore, the object of the present invention to provide a prestressed segmented concrete beam having a plurality of tendons which is not subject to failure by vertical splitting at the ends of the beam because of the location, application, or magnitude of the compressive forces exerted by the tendons.

The beam is comprised of a plurality of abutting concrete blocks having at least two prestressing tendons extending therethrough, to provide a compressive stress in the zone of tensile stress of the blocks.

The gist of the present invention is to so locate and stress the tendons or prestressing members as to produce a uniform compressive stress along a given horizontal line on any given vertical cross section of the concrete blocks. With the compressive stress so equalized, there is no force along such line or across the cross section of the beam tending to cause vertical splitting of the beams.

For this purpose, the tendons are laterally located on the vertical centers of gravity of fractional cross sectional areas of the block corresponding to the total cross sectional area divided by the number of tendons. For example, if two tendons are employed in the beam, two such cross sectional areas are formed.

The size of the fractional cross sectional areas is arranged to provide the uniform horizontal compressive stress. Thus, the greater the prestressing force on the tendon located on a given vertical center of gravity, the greater must be the size of the fractional cross sectional area in order to provide the uniform horizontal compressive stress.

In the making of the beam, the forces applied to the plurality of tendons must be simultaneously and equally applied so as to maintain the equal horizontal compressive force on the blocks.

BRIEF DESCRIPTION OF THE DRAWING

FIGS. 1A, B, C, D, E, F and G show a simple, doubly supported, uniformly loaded beam and graphs illustrating various mechanical properties thereof;

FIGS. 2, 3 and 4 show cross sectional configurations of concrete blocks which may be employed to construct a prestressed, segmented concrete beam of the present invention;

FIGS. 5A, B and C show a prestressed concrete beam of the present invention and graphic illustrations of certain mechanical properties thereof, and

FIGS. 6A, B, C and D show steps in the process of the present invention.

DESCRIPTION OF THE PREFERRED EMBODIMENT

Referring now to FIG. 1, there is shown in FIG. 1A a simple beam of the length L designated by the numeral 2. This beam is supported on either end by an abutment or the equivalent which provides upward supporting forces labelled R₁ and R₂ respectively. The beam is subjected to a uniform loading W per foot along its entire length. The total load on the beam is W×L. As is well explained by the laws of mechanics, the forces W₁ and R₁ and R₂ generate vertical shear forces in beam 2. These forces are illustrated in FIG. 1B and are maximum at the ends of the beam and zero at the center of the beam.

As may also be shown by the laws of mechanics, the forces applied to beam 2 generate an external bending moment thereon. This bending moment, illustrated in FIG. 1C, is greatest at the center of the beam and has a maximum magnitude of

\[ \frac{W L^2}{8} \]

The external bending moment applied to the beam is opposed by the internal resisting moment. The internal resisting moment of beam 2 consists of compressive and tensile forces generated therein by the load. FIG. 1D is a free body diagram of the left half of beam 2 showing the forces acting thereon. These forces include reaction R₁ acting through a length L/2 and the uniform loading which may be considered the equivalent of a concentrated load W L/2 acting through a distance L/4. The resultant of such forces is the above described maximum moment

\[ \frac{W L^2}{8} \]

which is resisted by the internal moment illustrated by the arrows labelled C, for compression, and T, for tension acting through the distance a.

In a simple beam, such as that indicated by the numeral 2, it may easily be appreciated that the compressive and tensile forces will be greater at the outer edges of the beam and will be equal to zero at some internal point in the beam. The magnitude of the compressive and tensile forces at any point in the beam depends, of course, on the configuration of the beam. However, the general formula is

\[ F = \frac{M Y}{I} \]

where F is the maximum fiber stress, or force per unit of area, M is the bending moment, Y is the distance from center of gravity of the beam cross section to the fiber under analysis, and I is the moment of inertia of the section of the beam being analyzed. Other formulae may be developed for specific beam configurations. The distribution of these stresses is the double triangle shape shown in FIG. 1E with the compressive stress 5 above the point of zero stress, called the neutral axis, and the tensile stress 4 below the neutral axis. As a general rule, the neutral axis corresponds with the center of gravity of the cross section.

As a concrete beam is unable to satisfactorily withstand the tensile stress indicated by the area 4 in FIG. 1E, an axial compressive load is placed on the beam at least equal to the maximum tensile stress as determined by the above formula. This may be accomplished by extending metal tendons 6 through beam 2 as shown in FIG. 1F and placing a tensile force thereon. The tendons are then affixed to beam 2 either through a mechanical bond obtained by cementing the metal tendon to the beam with grout or by retaining the tendon in position by metal plates at either end of beam 2. The tensile force of tendons exerts an equal and opposite force on beam 2 which provides a compressive loading equal to the force exerted by the tendons 6 divided by the cross sectional area of beam 2. When this compressive loading 7 is combined with the loading on beam 2 produced by the uniform load W×L the result is the inverted triangular stress configuration 8 shown in FIG. 1G. The base of the triangle is formed by the addition of the compressive stress 7 produced on beam 2 by tendons 6.
and the compressive stress produced by the external load. The compressive stress decreases as it approaches the neutral axis as does the sum of the forces in the inverted triangle stress pattern 8. When the internal stress in beam 2 becomes tensile as indicated by 4 in FIG. 1E, such stress acts to reduce the compressive stress exerted by tendons 6. By applying the correct amount of compressive loading 7 to equal tensile stress 4 at the lower fiber of beam 2 the summation of stresses at that point may be made to equal zero. This prevents any tensile loading of the lower concrete fibers of beam 2 under design loads.

FIG. 1G shows graphically the principles of prestressed beams described above. As previously mentioned, in order to achieve the advantages of prestressed construction effectively and efficiently without destroying beam 2, particularly when the beam is constructed of segments, the application of the compressive force of tendons 6 to resist the external loading is extremely critical in location, sequence and amount. The location of the prestressing tendons is determined at least in part by the cross-sectional configuration of the beam and hence features of the invention relating to that aspect are considered initially.

In the following, the term longitudinal refers to a direction parallel to the tendons and the axis of the beam, whereas the direction perpendicular to said dimension of the blocks forming the beam. Cross sections are taken perpendicular to the longitudinal direction and the exposed surface, such as that existing at either end of a block, termed a face. In determining the cross sectional configuration of the block, the rough geometric plan is first ascertained. Rough dimensions may be obtained from such factors as the maximum breadth of block that available machines can handle and the depth to span ratio defined by various building, engineering, and construction codes. These factors give the maximum breadth and depth of the block. The specific geometric configuration, is determined by the specific use to which the beam will be put.

The minimum cross sectional area of such specific geometric configuration is determined by the maximum unit stress that the concrete can withstand in compression. It will be appreciated that such stresses are determined by the compressive force produced by the tendons and load divided by the cross sectional area and that there is, therefore, a limit to that area below which maximum compressive stress of the concrete will be exceeded by any given force. Another limiting factor in determining the configuration of the cross section of the block is the minimum thickness of section that can be manufactured. The above factors determine, for example, the size of cavities which may be placed in the block for plumbing, electrical, or air conditioning conduits. Once the basic geometric configuration has been determined, the maximum tensile stress applied to the fibers of the block during loading may be by the aforementioned fiber stress formula. Knowing the maximum tensile stress to be encountered, the prestressing force required to be supplied by the tendons may be accurately appraised and the number of tendons required to produce such prestressing force determined. The number of prestressing tendons required depends upon the type of material to be used in the tendons and the cross sectional area of the tendons required to produce the necessary prestressing force without exceeding the proportional limit of the material. Ascertainment of the number of tendons required determines the number of vertical webs required in the cross section of the beam. The above mentioned rough geometric configuration may have to be altered to include the requisite number of webs. There must be a sufficient number of webs to provide sufficient vertical cross sectional area to the block to resist the horizontal shearing forces arising therein from the forces of the tendons and the load. In blocks of this sort, there may be one or more tendons located in each vertical web.

The foregoing applies generally to any beam of the prestressed type, the features of the present invention are obtained by the considerations relating to cross-sectional configuration discussed below.

As noted, the design of a satisfactory prestressed, concrete beam requires that the beam effectively resist and utilize both the above determined prestressing forces applied by the prestressing tendons the load forces applied thereto. Turning initially to the first criterion, the concrete beam of the present invention obtains the desired effective utilization of the prestressing forces by employing a cross-sectional configuration incorporating the principles of what may be termed "balanced design." Such a design is particularly effective in preventing vertical splitting of the beam at its ends. It is a major premise of "balanced design" that the stress encountered at any point along a horizontal line or incremental horizontal band on a face or cross section in the beam is equal at all points in such direction. This prevents shear and tensile forces from developing due to differential fiber stresses which tend to vertically split the beam at its ends.

As fiber stress in the beam is determined by the force exerted thereon and its area, either of these factors may be varied in balanced design to produce the aforementioned fiber stress. Taking the simplest case, in which the force exerted by a given tendon is equal to the forces exerted by the other tendons in the beam, the cross sectional area of the beam must be distributed in a manner to obtain equal stress. The cross sectional area of the block is therefore divided into individual areas surrounding each tendon, such that the area surrounding each of the tendons is equal and is separated from adjacent similar areas by a vertical line. These vertical lines may be termed "lines of influence" to indicate their analytical function of determining the area limits of the force applied by a given tendon. While the word "line" is used in reference to the cross section of a concrete block, it is to be understood that the line is developed into a plane extending through the block perpendicular to the cross section. This plane may be termed the "vertical plane of influence."

Another fundamental premise of balanced design is that the individual tendon must be located on the vertical center of gravity of the individual section which the force applied by any given tendon may be said to influence. The center of gravity of the individual sectional areas of the cross section of the block may be determined in accordance with the well known methods of analytic mechanics. Application of the forces of the prestressing tendons along the vertical center of gravity of the individual sections eliminates the force attempting to rotate the portions of the end blocks of the beam outward, as for example when the tendons are placed near the outside vertical edges of the blocks, thus eliminating vertical splitting at the ends of the beam.

In instances where the forces applied by each individual tendon are not equal, the cross sectional area influenced by a given tendon is varied in direct proportion to the force exerted by the tendons to maintain equal stress in the fibers along a horizontal line. The same principles of determining the vertical lines of influence and locating the tendon and applying the prestressing force along the vertical center of gravity are utilized even though the areas of the individual sections of the beam differ.

FIGS. 2, 3, and 4 illustrate cross sectional views of concrete blocks made in accordance with the principles of the invention. Referring to FIG. 2, a block suitable for use as a roof or floor beam 2 in a structure is indicated by the numeral 10. Because of its intended use, the block is generally rectangular in cross section. The rectangular dimensions are determined by the factors mentioned above. One vertical edge of block 10 includes a locking tongue 12 while the other vertical edge includes a mat-
ing groove 13. This tongue and groove configuration serves to join adjacent blocks when beams 2 constructed therefrom are used in a roof or floor. Block 10 is provided with a center cavity 15 to lighten the block structure and provide for electrical conduits, plumbing pipes, air conditioning vents, or other mechanical appliances. The size of cavity 15 is determined by the minimum cross sectional area required in the block and other previously mentioned factors.

It may be noted that two tendons 6 applying equal forces are required to provide the necessary characteristics to concrete beam 2. The cross sectional area of concrete block 10 is, therefore, divided into two equal areas 16 and 18 separated by a vertical line of influence 23. These areas are generally C shaped in configuration. It will be appreciated that vertical line 23 will be located slightly to the left of the center of the breadth of block 10 as area 16 includes looking tongue 12 while area 18 is lessened by mating groove 13. The vertical centers of gravity of areas 16 and 18 are next determined and are labelled by the numerals 25 and 27. In accordance with the principles of "balanced design" holes 17 and 19 for the insertion of tendons 6 to provide compressive loading to the beam are located on vertical centers of gravity 25 and 27.

Holes 17 and 19 may be elongated for a purpose herein after mentioned and the long axis of each hole is placed on the respective vertical center of gravity. The vertical location of holes 17 and 19 may be such that the holes will lie substantially within the tensile zone to be encountered in block 10 with the upper portion of the holes near the horizontal center of gravity or the neutral axis of the block. The zone extends from the neutral axis to the fiber of maximum tensile stress. When block 10 is used in a simply supported beam the tensile zone is in the lower portion of block 10. If the block is used in a cantilever beam, the tensile zone would be in the upper portion of the block.

FIG. 3 shows a slightly more complicated structure in which three tendons applying equal forces are employed to provide the necessary prestressing force. As three tendons are employed, the cross sectional area of block 10 of FIG. 3 must be divided into three sections of equal areas separated by two lines of vertical influence. The three sections of equal area are indicated in FIG. 3 by the numerals 20, 22, and 24 and divided by lines of influence 23. Section 20 is in the shape of a C, as is section 24, while section 22 is roughly in the shape of an I. The vertical centers of gravity are determined in accordance with the cross sectional configuration of the area and holes 30, 32 and 34 are located thereon.

FIG. 4 shows the cross section of a concrete block 10 in which the forces applied by the tendons 6 are not equal. For example, the force applied by tendon 6A is greater than the force applied by tendon 6B. For purposes of illustration, it may be assumed that the force applied by tendon 6A must, therefore, be twice as great as the cross sectional area of area 16A. This change in area may be accomplished by increasing the external dimensions of the block or decreasing or altering the shape of cavity 15. The latter approach is shown in FIG. 4 in which cavity 15 is reduced in size to increase the section of section 16A. The vertical line of influence 23 is placed such that section 18A has twice the cross-sectional area of section 16A. The vertical center of gravity for each of the sections is determined as above and holes 17 and 19 to receive tendons 6A and 6B located thereon. It will be appreciated, that although the numerals of FIG. 1 may be replaced by numerals 6A it is two times that provided by tendon 6B, the fact that section 18A has twice the area of section 16A insures that the fiber stress along any given horizontal line on a cross section of beam 10 will remain equal along that line.

The use of blocks manufactured by the above outlined method will prevent vertical splitting of the beam near its end, which is prevalent in prior art beams of this type. Prevention of the other common failure of segmented concrete beams, that is, horizontal shear of the concrete blocks near the ends of the beam, is obtained in part by the positioning of the tendons in the blocks at the ends of the beam and in part by the construction features of the beam assembled from the above described concrete blocks. These latter features may be seen by reference to FIG. 5 which shows a beam 2 instead of a plurality of blocks 10 which may, for example, be one of the configurations shown in FIGS. 2 through 4. FIG. 5 uses the configuration of FIG. 2 for illustrative purposes. The blocks are arranged in lengthwise abutting relation. It is desirable, although not essential, to prepare the abutting surfaces 11 of the blocks by grinding them to insure parallelism. If desired, or required by the specific utilization of the beam, the abutting surfaces 11 may be ground non-parallel, introducing a keystone shape to the blocks and a positive or negative camber to the beam. The spaces between the blocks may also be filled with mortar, building card board, or other materials if desired.

As previously mentioned, elongated holes 17 and 19 contain tendons 6. While in present practice tendons 6 are generally cold drawn steel members of various configurations, other materials, such as fiberglass, may be utilized if desired. The material utilized should have an ultimate tensile strength to fiber maximum tensile stress of at least 130,000 lbs. per square inch. Tendons 6 should be stressed to at least 125,000 lbs. per square inch in order to provide a satisfactory concrete beam.

Tendons 6 are located in the upper portion of elongated holes 17 and 19 as shown in FIG. 21 of beam 2 (see FIG. 5B). This places them at or near the horizontal center of gravity, or the neutral axis of the blocks.

In the center of the beam, however, tendons 6 are located in the lower portions of holes 17 and 19. Pushrods 36 are inserted in beam 2 to deflect or "harp" tendons 6 to the bottom of holes 17 and 19 (see FIG. 5C). At least one pushrod 36 is provided for each tendon 6. Pushrods 36, which may be also constructed of steel rods, are shaped at the lower end to mate with tendons 6. If desired, a hook-shaped rod may be inserted through the bottom of the beam to pull the strand downward. In either instance, the rods may be inserted through holes 30, 32 and 34 and in the appropriate concrete block. For reasons later explained, such insertion generally occurs at the point of maximum external bending moment along the beam and serves to increase the internal resisting moment of the beam at that point. In standard designs, such holes may be predrilled prior to assembly of beam 2. Rods 36 are fastened in beam 2 by grout or some other bonding agent and secured flush with the surface of the beam. Subsequent to the deflection of tendons 6, holes 17 and 19 are also filled with grout to provide a unitary structure. If desired, rods 36 may be removed after the beam is filled with grout.

Turning for a moment to the stresses existing at the ends of the beam, it will be appreciated that the ends of the beam are the points of zero or minimum bending moment (see FIG. 1C). Therefore, there is no need to arrange the tendons to provide a large internal resisting moment at the ends of the beam. The vertical line of influence 23 at or near the horizontal center of gravity of concrete blocks 10. By being at or near the horizontal center of gravity, tendons 6 apply a force which stresses the fibers of the beam approximately equally in a vertical direction across the beam. This pattern of stress is similarly shown in FIG. 4. The application of the force of tendons 6 normal to the horizontal center of gravity of the end blocks 21 of the beam eliminates horizontal shearing in the end blocks of the beam caused by placing the tendons in the lower portion of the beam to secure a maximum internal resisting
moment at other parts of the beam as done in the prior art. Excessive camber of beam 2 from the same cause is also eliminated. Since the force of tendon 6 is equally distributed across the blocks 10 at the ends of the beam, sufficient tensile force may be applied to the tendons, without splitting the blocks, to place beam 2 in a full prestressed condition. However, if desired, beam 2 may be manufactured with less than full prestress in a partially prestressed condition.

Turning now to the stresses existing in the beam other than at the ends thereof, for a simply supported beam, as shown in FIG. 1A, the maximum external bending moment will occur at the center of the beam. See FIG. 1C. Thus, pushrods 36 are inserted in beam 2 in the center thereof to deflect tendon 6 further into the tensile zone of beam 2. For beams other than simply supported beams, pushrods 36 will be inserted at a different place along the beam. If desired, a plurality of such pushrods may be inserted at the point of maximum moment for each portion of the beam. If beam 2 is used in a cantilever structure, in the lower part of the beam, where the tensile force lies in the upper fibers, tendon 6 would be deflected upward.

FIG. 5D is a graphic illustration of the stresses occurring in the center section of the beam shown in FIG. 5A. The horizontal center of gravity of the concrete is indicated by the line CGC. The center of gravity of the steel tendons 6 is indicated by the line CGS and may be considered the point through which the prestressing forces of tendon 6 are exerted. The center of gravity of tendons 6 is, of course, considerably below that of the center of gravity of the concrete due to the deflection of tendons 6 by pushrods 36. The distance between line CGC and line CGS is generally labeled i in the art.

The compressive stress applied to the center section of beam 2 by tendons 6 is indicated by the numeral 40 in FIG. 5D. This stress may be considered to be comprised of two portions. There is first, the compressive stress 38 which is uniform across the cross section and is equal to the force on beam 2 provided by tendons 6 divided by the cross-sectional area of the beam. The second component of prestress exerted by tendon 6 is an internal moment in the beam due to the fact that the force provided by tendon 6 is eccentric to the center of gravity of the concrete at the center section of the beam. This causes a compressive stress to appear in the lower fibers of the beam through the area a.

The magnitude of these stresses may be determined by the general formula \( \frac{M_y}{I} \) where \( F \) is the compressive force, \( y \) is the distance of any given fiber from the center of gravity of the concrete and \( I \) is the moment of inertia of the section. The summation of compressive stress 38 and the stress due to eccentric prestress is shown by the generally trapezoidal configuration 40 having the greater compressive stress on the bottom fibers of the beam.

The internal resisting moment of the beam at the center section is provided by the resisting force of the concrete of blocks 10 and the compressive force exerted by tendons 6. The force exerted by the concrete acts through the center of gravity of stress configuration 40. The centroid or center of gravity of this area, labelled CG(b) Stress, is one-third to one-half of a distance from the base of configuration 40 to the apex, depending upon the exact shape of configuration 40. The letter a indicates the distance between CG(c) Stress and CGS or the center of gravity of the steel tendons 6. This distance a provides the lever arm for the internal resisting moment of the beam at this point. It will be noted that distance e is rather small, being less than distance a.

The stresses applied to beam 2 by the external loading of the beam are shown in FIG. 5D by the numeral 41 and are determined by the previously described general formula

These stresses, when combined with the stresses illustrated by the configuration 40, provide the summation of all the stresses acting on beam 2 under design load. These stresses are indicated by the configuration 42. As will be noted, this configuration is in the shape of an inverted triangle with the maximum compressive stresses existing on the upper fibers of beam 2 and essentially no stress on the lower fibers of beam 2 due to the prestressing forces provided by tendons 6. While the prestressing stress in the lower fibers of beam 2, if desired, a tensile stress may exist therein, not to exceed the modulus of rupture of the concrete. As stress diagram 42 is triangular in shape, its centroid is one-third of the distance from the base of the triangle to the apex. The distance from the center of gravity of tendons 6 to the centroid of stress diagram 42 is again indicated by a.

It will be immediately noted that distance a has substantially increased, thereby increasing the internal resisting moment of the beam. It is also apparent that by placing the center of gravity of the steel, CGS, in the lower portion of the beam, through deflection of tendons 6 by pushrods 36, the internal resisting moment of the beam is maximized at the point of maximum external bending moment. If the center of gravity of the steel was allowed to remain at or near the center of gravity of the concrete at the point of maximum external moment, distance a would be much less and the internal resisting moment of the beam a small fraction of the magnitude shown in FIG. 5D.

In addition to the increased performance of the beam permitted by the increased internal resisting moment, the beam of the structure shown in FIG. 5 permits a substantial increase in design load due to the fact that a larger moment of inertia is attained by this prestressed, segmented concrete beam over those in the prior art. In determining the moment of inertia for concrete beams, only the area of concrete in compression and the area of the steel members may be considered under present design codes. In the prestressed beams of the prior art where a portion of the concrete was placed in tension due to the fact that sufficient prestressing force to overcome this could not be applied to the beam without destroying it, only a portion of the entire cross sectional area of the beam could be used in computing the moment of inertia. In the fully prestressed beam of the present invention, the entire cross sectional area of the beam is in compression under design load and the entire area may thus be used for determining the moment of inertia. It will be understood that for any given design load a reduction of the stresses occurring in the beam will result from the above feature of the present invention.

While FIG. 5 shows tendon 6 deflected by only one pushrod, 36, tendon 6 may also be deflected by two pushrods spaced, for example, equidistant from the center of the beam to extend the length of the portion of the length of the beam in which the increased internal resisting moment of the beam exists.

The manufacturer of the prestressed, segmented concrete beam in accordance with the present invention initiates with the design and manufacture of concrete blocks as shown in FIGS. 2, 3 or 4. As previously described, the concrete blocks must be designed so that fiber stress across the beam in a cross sectional horizontal direction will be equal at all points in that direction. Equal fiber stress in a horizontal direction across the beam is obtained by placing the tendons on the vertical center of gravity of each of the plurality of individually defined sections of the cross sectional area of the beam.

In a typical manufacturing process, concrete blocks of the above construction are laid end to end in abutting relation on a flat surface with the holes for the tendons, such as 17 and 19, and cavities, such as 15, in longitudinal alignment. As previously described, the faces of the blocks may be ground parallel for a better fit, or if desired, non-parallel to produce a camber in the beam. The tendons 6
are inserted in the tendon holes in blocks 10 and positioned at or near the horizontal center of gravity of the beam by metal plates 50 at either end thereof. Metal frames 56 are mounted on plate 50 at either end of the beam and tendons 6 extend through the frames and chucks, or strand wires, 54. Chucks 54 grip tendons 6 during stressing and retain them in that condition during subsequent processing of the beam. At one, or both, ends of the beam, tendons 6 extend beyond chucks 54. The jack frames 56 is mounted on plate 50 outside frame 52. Jacks 58 are positioned on the end of jack frames 56 and tendons 6 extend through and, after stressing and through and after stressing and jackchuck 60 mounted on the movable element of the jack. Chucks 60 grip tendons 6 in a manner similar to chucks 54. Jacks 58 may be of either the hydraulic or mechanical type and are mounted so that the movable element moves away from the end of the beam. As shown in FIG. 6, one jack 58 is provided for each tendon 6, although other mechanical configurations may, of course, be devised. The tendons are then stressed to the extent required by the design load conditions of the beam by applying hydraulic or mechanical force to jacks 58. Satisfactory construction of the concrete beam in accordance with the present invention requires that the stressing forces be applied to the tendons by jacks in a manner to produce equal stress along any given cross sectional horizontal line or incremental band. The reason for this is the same as the reason for applying the forces along the vertical center of gravity of the stations of the block. That is, to prevent the splitting along a vertical plane which would occur if one section of the block were stressed to a greater extent than the other sections by the application of a greater force at any instant to one section of the block than to another. In this way, the tendons take place of compressive forces on the blocks, the stress is applied to tendons 6 by jacks 58 simultaneously and at a uniform rate. When tendons 6 have been stressed, they are retained in that state by chucks 54. The hydraulic or mechanical force on jack 58 may then be released and jacks 58, jacking frames 56, and jackchucks 60 removed as shown in FIG. 6B. After the tendons 6 have been stressed, the pushrods 36 may be inserted in holes in the beam to deflect the tendons downward from their position at or near the horizontal center of gravity of concrete blocks 10. The simple C-clamp 62, shown in FIG. 7A, is one method of performing this step. The amount of deflection required for any given application is determined by the moment arm needed between the tensile forces provided by tendons 6 and the opposing forces generated in the concrete blocks 10. As previously mentioned, the tensile forces provided by the tendons act along line CGS while the opposing forces of the concrete act along the line CG(c) stress, in FIG. 5D, and the distance between the two is indicated by a. It will be appreciated that by the amount of deflection provided to the tendon, the distance a may be increased or decreased any desired amount. Further, the amount of deflection may be affected by the amount of initial stress of the tendons 6 lost due to deformation of the blocks and creep and plastic flow of the steel. It is desired to regain by deflection. It will be easily understood that deflection of the tendon produces an additional elongation thereto which tends to overcome some or all of the shortening due to the above factors. Again, in accordance with the principles of balanced design, the deflection of the tendons 6 by pushrods 36 must be simultaneous so as not to exert unbalanced stresses on the beam. After the deflection of the tendons by the pushrods, the entire structure is bonded together. This is generally done by inserting grout around pushrods 36 and in holes 17 and 19. The forces exerted by the pushrods 36 on the concrete block through which they are inserted may be analyzed by first looking at the rods before grouting and then after. In the first instance, there is no vertical component of force on the blocks forming the beam. There is, of course, compressive forces exerted on the block by frames 52 at each end of the beam due to the tensile stresses in the tendons. With the other clamping means, is placed around the plank to hold the pushrods in the deflected position, a force is exerted on the blocks of the beam at that time. This force is an upward force caused by pushrod 36. After bonding, and removal of the clamping means, an upward force is exerted by the rod on the surrounding bonding agent, such as grout. This transmits an opposing force to the concrete block which is resisted by the compressive force and the coefficient of friction existing at the faces of the block in which the pushrod is inserted. It may be noted, that the upward force on the blocks in which the pushrods 36 are inserted serves to counterbalance the load placed on the beam, thereby relieving some of the stresses which would otherwise be applied to the beam. After grouting, the prestressing forces are transferred from chucks 54, which retain tendons 6 in the stressed condition, to anchors at each end of the beam. These anchors may be plates, such as 50, to which the tendons are fastened, or may be the tendons themselves. In the latter instances, will be appreciated that if the tendons are severed beyond the end of the beam, there will be no stress on them at that point; the stress being confined to the portions of the tendon within the beam. A resulting increase in diameter of the tendons beyond the end of the beam occurs in accordance with Poisson's ratio. The increased dimensions of the tendon when wedged in the bonding agent surrounding it in the beam will form an anchor for the tendon, eliminating the need for separate anchor plates. The anchoring by the tendons themselves takes place over a discrete longitudinal distance called the transfer length. In the above described anchoring processes the tendons 6 at one end of the beam must be released uniformly, assuming the tendons are equally stressed and at the same instant so as to avoid destructive forces in the beam. If desired, the tendons 6 may be released at both ends of the beam simultaneously. This may be done by releasing the chucks 54. Another method of transferring the forces to the anchors is subjecting the tendons to uniformly increasing temperatures in the area between the end of the beam and chucks 54 until the tendons have lost their strength. FIG. 6C illustrates the tendon force has been uniformly and gradually transferred to the concrete beam through such loss of strength. For example, the tendons 6 may be subjected to heat from heating elements of the electric resistance type, or from acetylene or other torches. FIG. 6D shows a heating device having a manifold 64 and one heat distribution pipe 66 for each tendon. The device may be inserted in frames 52 during application of the heat. It is important that the heat be applied simultaneously to all the tendons in the beam and to a degree that the elastic properties of the steel are altered sufficiently at the point of heat application to release the prestressed forces in the tendons. In beams in which the tendons are stressed other than equally, the stress is transferred to the ends of the beam in a manner to produce equal stress along any given cross sectional horizontal line or band. After the prestressing force has been transferred to anchors at the ends of the beam, frames 52 and chucks 54 may be removed and tendons 6 ground flush with the end of the beam or anchor plates 50. This completes the manufacture of the beam. It may be noted that the above described process is essentially one of providing a post-tensioned concrete beam and then converting that beam to a pretensioned concrete beam. Post-tensioning refers to the process in which the prestressing force of the tendons is applied only after the concrete has hardened. Pretensioning, on the other hand, refers to a manufacturing process in which the tendons are prestressed before the concrete. 

has hardened. Therefore, in the above described manufacturing process, the blocks of hardened concrete are initially post-tensioned by stressing the tendons placed in the holes in the blocks after the blocks have been assembled. Subsequent to that, the entire structure is grouted which, when the grout has hardened, creates a mechanical bond to the tensioned members. By transferring the tension from the above described frames and chucks to anchors at the ends of the beam, by means of heating the tendons or some other process, the tension of the tendons is transferred to the concrete so that the end product is the equivalent of a pretensioned structure.

While the foregoing invention has been described in terms of concrete beams, it will be appreciated that its features are equally applicable to beams manufactured from terra cotta, fired clay, cinders or blast furnace slag, and pumice.

I claim:

1. A prestressed, segmented concrete beam of the transversely rigid type capable of withstanding loading producing virtually adjacent zones of internal tensile and compressive stresses comprising:
   a plurality of concrete blocks of uniform lateral cross section formed with spaced upper and lower parallel panel portions joined by at least a pair of laterally spaced web portions, each of said web portions having a tendon receiving, longitudinal hole extending through the blocks, said uniform lateral cross section being divisible into at least two laterally adjacent fractional cross sectional areas each having a defined vertical center of gravity, at least a portion of one of said tendon receiving holes lying on each of said vertical centers of gravity, said blocks being arranged in abutting relation with said longitudinal holes in alignment;
   a plurality of tendons formed of a high tensile strength material having an ultimate strength of 250,000 p.s.i. and a proportional limit of 190,000 p.s.i., at least one such tendon being longitudinally positioned in each of said holes, said tendons being laterally positioned on the vertical centers of gravity of said fractional cross sectional areas, said tendons being stressed in tension to at least 130,000 p.s.i. for providing a compressive stress in the zone of tensile stress sufficient to resist substantially all of the tensile forces generated in said beam, the tendon positioned on the vertical center of gravity of any given one of said fractional cross sectional areas being stressed in tension sufficiently, with respect to the other tendons, to provide a compressive stress on said given fractional cross sectional area equal to the compressive stress exerted by the other tendons on the other fractional cross sectional areas along any given horizontal line extending laterally across any given lateral cross section of the blocks thereby preventing the development of longitudinal shear forces in said beam; and
   means for affixing said tendons to said blocks.

2. The prestressed, segmented concrete beam of claim 1 wherein said laterally adjacent fractional cross sectional areas are defined by the vertical dividing lines extending across the cross section of said blocks parallel to the vertical centers of gravity.

3. The prestressed, segmented concrete beam of claim 2 wherein all of said tendons are equally stressed and all of said fractional cross sectional areas are equal in size.

4. The prestressed, segmented concrete beam of claim 2 wherein said tendons are unequally stressed and said fractional cross sectional areas are unequal in size, the size of any given fractional cross sectional area with respect to any other fractional cross sectional area being proportional to the ratio of the amount of stress provided by the tendon located at its vertical center of gravity to the amount of stress provided by the tendon located at its respective center of gravity of the other fractional cross sectional area.

5. The prestessed, segmented concrete beam of claim 1 further defined in that said tendons are located in the zone of tensile stress at the point of maximum external bending moment of the beam.

6. The prestressed, segmented concrete beam of claim 5 wherein said blocks have a neutral axis between the vertically adjacent zones of internal tensile and compressive stresses and said holes are vertically elongated, said holes extending from the neutral axis into the zone of tensile stress, the ends of said tendons being located in said holes adjacent the neutral axis.

7. The prestressed, segmented concrete beam of claim 6 including means engaging said tendons inserted in said plurality of blocks and affixed to the latter for inclining deflecting said tendons from their longitudinal position intermediate the ends of said plurality of blocks into the zone of tensile stress.

8. The prestressed, segmented concrete beam of claim 7 wherein said means inclining deflecting said tendons comprise pushrods engaging said tendons inserted in said blocks and affixed thereto.

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