Oct. 29, 1968 J. M. YOUNG 3,407,554

PRESTRESSED, SEGMENTED CONCRETE BEAM

Filed June 3, 1965 2 Sheets-Sheet 1

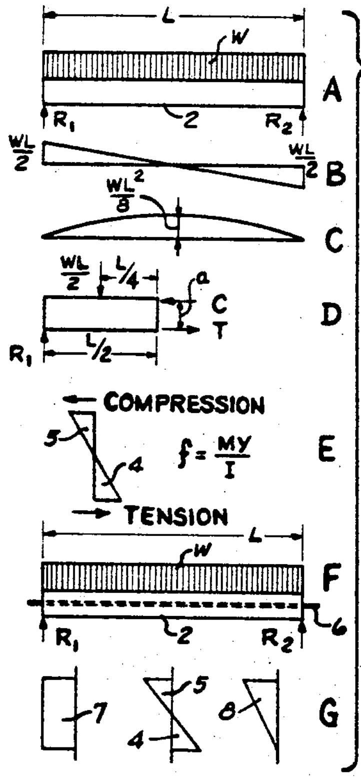

Fig. 1.

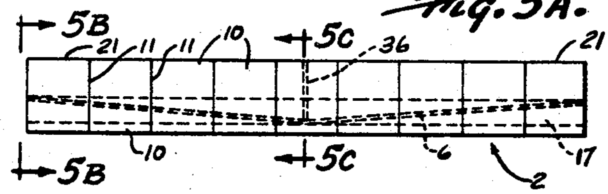

Fig. 5A.

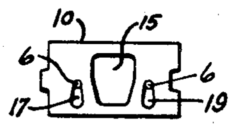

Fig. 5B.

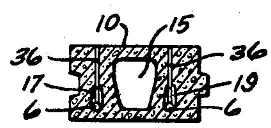

Fig. 5C.

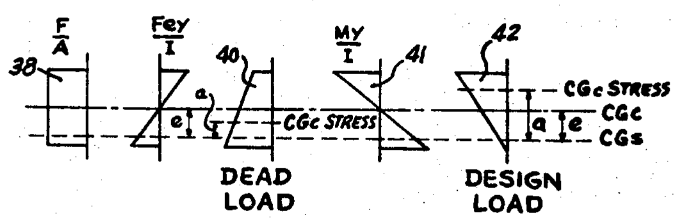

Fig. 5D.

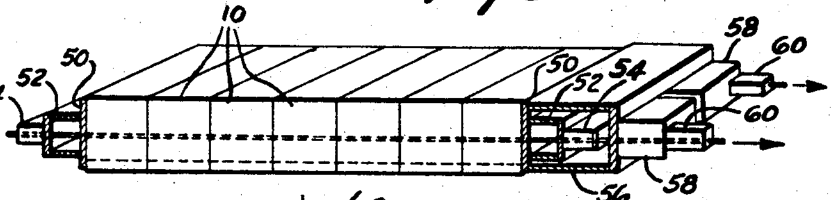

Fig. 6A.

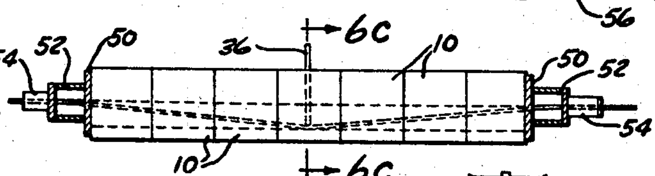

Fig. 6B.

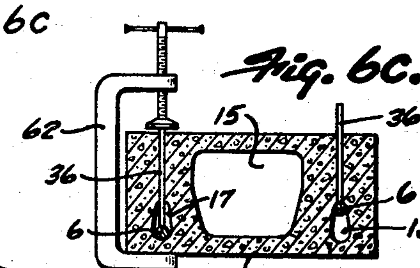

Fig. 6C.

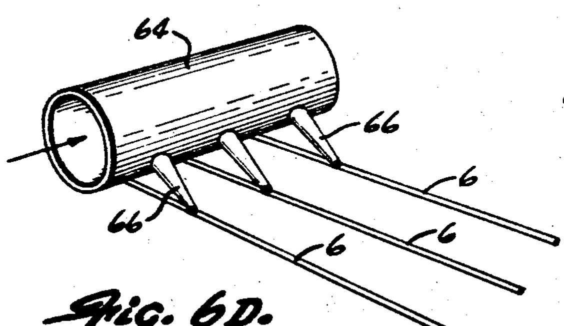

Fig. 6D.

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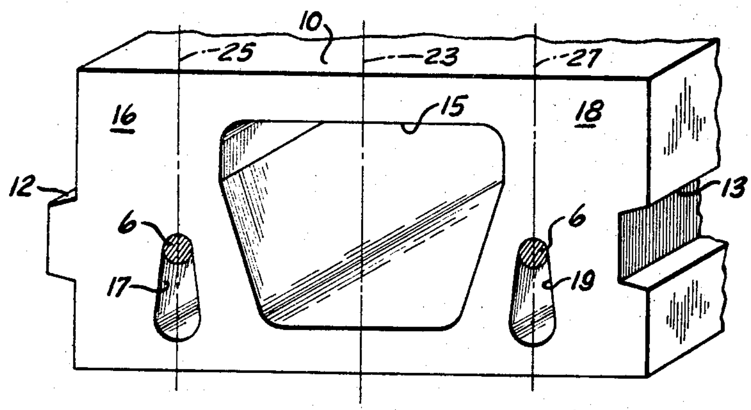

Fig. 2.

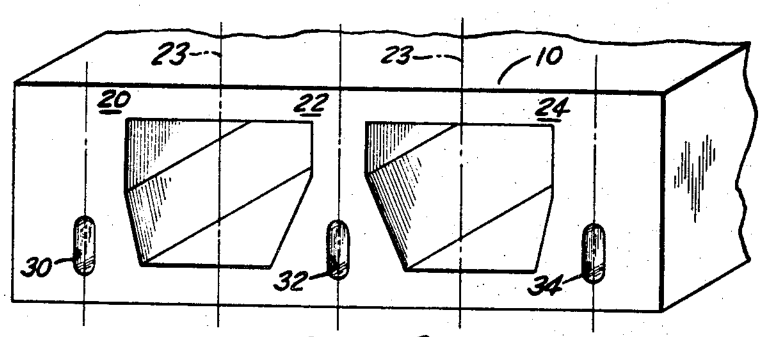

Fig. 3.

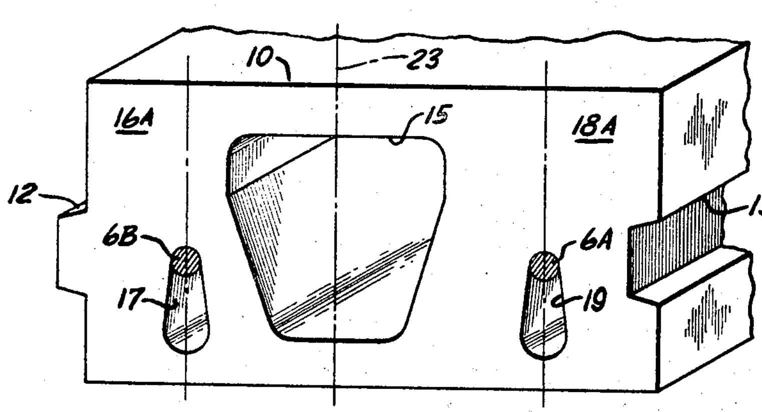

Fig. 4.

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PRESTRESSED, SEGMENTED CONCRETE BEAM

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ABSTRACT OF THE DISCLOSURE

A prestressed concrete beam, constructed of a plurality of blocks or segments, has the tensile members so positioned as to utilize the prestressing forces effectively while preventing horizontal or vertical shearing or splitting at the ends of the beam.

This invention relates to a prestressed, segmented 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 loads, 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 the 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 provide 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

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stressing the tendons. This tensile stress 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 the prestressed, segmented concrete beam supported at either end and subjected to uniform loading, a compressive force will be generated in the lower fibers of the beam while a tensile force is generated in the lower fibers of the beam. To overcome this tensile stress, 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 force throughout the beam under 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 forces 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 force 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 was 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 compression, such compressive force 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 force 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.

The present invention provides a prestressed, concrete beam which is not subject to failure by horizontal shearing of the concrete from the compressive forces of the tendon. As such, the present invention may provide a segmented concrete beam which may be fully prestressed. If desired, the concrete beam of this invention may also be of partial prestressed design.

The present invention provides a prestressed, concrete beam, including one of the segmented type, which is not subject to failure by vertical splitting at the ends of the beam because of the location or application of the tensile forces.

The concrete beam of the present invention utilizes the prestressing force applied by the tendons in a most effective manner to provide greater load-carrying capacity to the beam and a greater span.

The concrete beam of the present invention utilizes blocks which may be produced on standard machines, thereby lending economy to its manufacture. Special blocks at the ends of the beam or at various points along its length are not required nor is special treatment, such as non parallel grinding required.

The structure of the improved beam is such that the forces absorbed by the beam, due to either or both of prestressing and the load may be closely controlled, thereby permitting accurate calculation and application of loads to the beam. The similarity of reaction to loading of the beam permits a plurality of such beams to be used to provide a floor which is level and even.

The invention, including both the structure of the improved concrete beam and its method of manufacture, may be better understood by reference to the following specification and drawings, forming a part thereof, in which:

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 designs for concrete blocks which may be employed to construct a prestressed, segmented concrete beam of the present invention:

FIGS. 5A, B, C and D 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 apparatus which may be employed during the manufacture of a concrete beam of the invention.

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 provide upward supporting forces labelled R_1 and R_2 respectively. The beam is subjected to a uniform loading W per foot along its entire length. The total load on the beam is $W \times L$.

As is well explained by the laws of mechanics, the forces WL and R_1 and R_2 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 $WL^2/8$.

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 R_1 acting through a length $L/2$ and the uniform loading which may be considered the equivalent of a concentrated load $WL/2$ acting through a distance $L/4$. The resultant of such forces is the above described maximum moment $WL^2/8$ 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 **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 $f=My/I$ where f is the maximum fiber stress, M is the bending moment, y is the distance from center of gravity of the beam cross section to the fiber and I is the moment of inertia of the section of the beam being analyzed. Other formulas may be developed for specific beam configurations. The distribution of this force is the double triangle shape shown in FIG. 1E with the compressive force **5** above the point of zero force, called the neutral axis, and the tensile force **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 FIGURE 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 exert 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 is combined with the loading on beam **2** produced by the uniform load $W \times L$ 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 rods **6** and the compressive stress **5** produced by the external load. The compressive force **5** 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 **7** 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 forces 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.

FIGURE 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, even though such direction may be the shorter dimension of the block. Cross sections are taken perpendicular to the longitudinal direction and the exposed surface termed a face. In determining 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, such as an enclosed block with cavities therein or a single or multiple T 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 forces applied 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 or the distance between the webs in a T or I configuration.

Once the basic geometric configuration has been determined, the maximum tensile stress applied to the fibers of the block during loading may be determined 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 a material. Ascertainment of the number of tendons required determines the number of vertical webs required in the cross sectional configuration. 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 feature 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 the above determined prestressing forces applied by the prestressing tendons as well as 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 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 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 equal horizontal 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 limits of the force applied by a given tendon to the area surrounding it. 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 tendons must be located on the vertical center of gravity of the individual section which the force applied by that 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 forces 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 block, 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 that tendon is varied in direct proportion to the force exerted by the tendons to maintain equal stress in the fibers along a horizontal plane. 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.

FIGURES 2, 3, and 4 illustrate cross sectional views of concrete blocks made in accordance with the principles of the present 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 mating 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 assumed that two tendons **6** 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 locking 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** are elongated for a purpose hereinafter 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** will also be hereinafter explained but it may be stated as a general principle that such 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, as shown in FIG. 1, the tensile zone is in the lower portion of block **10**. If the block was used in a cantilever beam, the tensile zone would be in the upper portion of the block.

FIGURE 3 shows a slightly more complicated structure in which three tendons 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 equtl 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** 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 force 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** is twice as great as that applied by tendon **6B**. The cross sectional area **18A** influenced 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 area of section **18A**. 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 compressive loading provided by tendon **6A** 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 in 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 shearing of the concrete blocks near the end of the beam, is prevented 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 of the invention may be seen by reference to FIG. 5 which shows a beam **2** comprised 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 cardboard, 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 of approximately 250,000 lbs. per square inch and a proportional limit of about 190,000 lbs. per square inch. Tendons **6** should be stressed by a force equal to at least 130,000 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** in end blocks **21** of beam **2**, see FIGURE 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 FIGURE 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 drilled 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 these points and the tendons may be placed 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 by the numeral **7** in FIG. 1G or the numeral **38** in FIG. 5D. The application of the force of tendons **6** near the horizontal center 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 fully 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 which the tensile zone 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, considerable 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 labelled *e* 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 force to appear in the lower fibers of the beam and a tensile force to appear in the upper fibers. The magnitude of this force may be determined by the general formula Fey/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 force **38** and the force due to eccentric prestress is shown by the generally trapezoidal configuration **40** having the greater compressive force 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(c) 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 a is rather small, being less than distance e.

The forces 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 My/I. These forces, when combined with the forces illustrated by the configuration **40**, provides the summation of all the forces acting on beam **2** under design load. These forces are indicated by the configuration **42**. As will be noted, this configuration is in the shape of an inverted triangle with the maximum compressive forces existing on the upper fibers of beam **2** and essentially no forces existing on the lower fibers of beam **2** due to the prestressing forces provided by tendon **6**. While FIG. 5D shows no tensile 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 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 of the beam, the beam of the structure shown in FIGURE 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 FIGURE 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 manufacture of a 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 the fiber stress across the beam in a horizontal direction is equal at all points in that direction, and that the tendons in the beam be placed near the center of the blocks at the end of the beam and in the zone of tension at the point of maximum external bending moment of the beam. 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 **52** are mounted on plates **50** at either end of the beam and tendons **6** extend through the frames and chucks, or strand vises, **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 frame **56** is mounted on plate **50** outside frame **52**. Jacks **58** are positioned on the end of jack frames **56** and tendons **6** extend therethrough and through jacking chuck **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 for 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 horizontal line or incremental band of the concrete. The reason for this is the same as the reason for applying the forces along the vertical center of gravity of the sections of the block. That is, to prevent splitting along a vertical plane in the beam which would occur if one section of the block were stressed to a greater extent than the other sections of the block by applying a greater stress at any instant to one section of the block than to another. When tendons **6** have been stressed, they are retained in that state by chucks **54**. The hydraulic or mechanical force on jacks **58** may then be released and jacks **58**, jacking frames **56**, and jacking chucks **60** removed as shown in FIG. 6B.

After the tendons **6** have been stressed, the pushrods **36** are 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 arrangement **62**, shown in FIG. 6C, illustrates 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 CF(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 grouting. In the first instance, there is no vertical component of force on the blocks forming the beam. There is, of course, compressive forces exterted on the block by frames **52** at each end of the beam due to the tensile stresses in the tendons. When a C-clamp, such as **62**, or other clamping means, is placed around the plank to hold the pushrods in the deflecting 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 instance, it will be appreciated that if the tendons are severed beyond the end of the beam, there will be no stress thereon 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 of 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 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 uniformly and simultaneously. This may be done by releasing the chucks **54** at a uniform rate and simultaneously. 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 at the point of heat application and the tensile 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 acetylene or other torches. FIGURE 5D 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 uniformly and 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 tendon.

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 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 a manufacturing 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 block 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, forms 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.

Various modes of carrying out the invention are contemplated as being within the scope of the following claims particularly pointing out and distinctly claiming the subject matter which is regarded as the invention.

I claim:

1. A concrete beam capable of withstanding loading producing zones of internal tensile and compressive stresses comprising:

a plurality of abutting concrete blocks of uniform construction having at least one longitudinally aligned hole extending therethrough;

at least one tendon longitudinally positioned in said hole, said tendon being stressed in tension sufficiently to provide a compressive stress in the zone of tensile stress of said concrete blocks;

means engaging said tendon inserted in said plurality of blocks and affixed to the latter to incliningly deflect said tendon from its longitudinal position intermediate the ends of said plurality of blocks toward the zone of tensile stress; and

means affixing said tendon to said concrete blocks to transfer the compressive stresses thereto.

2. The concrete beam of claim **1** wherein the abutting faces of said concrete blocks are parallel.

3. The concrete beam of claim **1** wherein said hole is vertically elongated in form and positioned entirely within the zone of tensile stress of said beam, one end of said hole being adjacent the horizontal center of gravity of the concrete blocks forming said beam, said tendon being positioned adjacent said horizontal center of gravity at its ends.

4. The concrete beam of claim **1** wherein said tendon is incliningly deflected by said means in a direction to increase the internal resisting moment of the beam.

5. The concrete beam of claim **1** wherein said tendon is incliningly deflected by said means in a manner to provide the maximum internal resisting moment of the beam at the point of maximum external bending moment.

6. The concrete beam of claim **1** wherein the tendon is incliningly deflected by said means at a plurality of points intermediate the ends of the beam.

7. The concrete beam of claim **1** wherein said plurality of concrete blocks have a top portion and a bottom portion separated by a plurality of vertical webs, said webs containing longitudinally aligned holes for said tendons.

8. The concrete beam according to claim **1** further defined in that said tendon is stressed in tension sufficiently to provide a compressive stress in the zone of tensile stress of said concrete blocks sufficient to resist a portion of the tensile forces produced in the beam.

9. The concrete beam according to claim **1** further defined in that said tendon is stressed in tension at least sufficiently to provide a compressive stress in the zone of tensile stress of said concrete blocks sufficient to resist the tensile forces produced in said beam in excess of the modulus of rupture of the concrete.

10. The concrete beam according to claim **1** wherein said means incliningly deflecting said tendon comprises a push rod engaging said tendon inserted in said blocks and affixed thereto.

References Cited

UNITED STATES PATENTS

2,340,263	1/1944	Dodson	52—227
2,769,332	11/1956	Brown	52—225
3,283,457	11/1966	Hart	52—226
9,172	10/1835	Witty	52—226
2,413,990	1/1947	Muntz	52—223
3,167,882	2/1965	Abbott	52—309
3,172,932	3/1965	Vander Heyden	52—227

FOREIGN PATENTS

1,000,107	10/1951	France.
485,552	10/1953	Italy.

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