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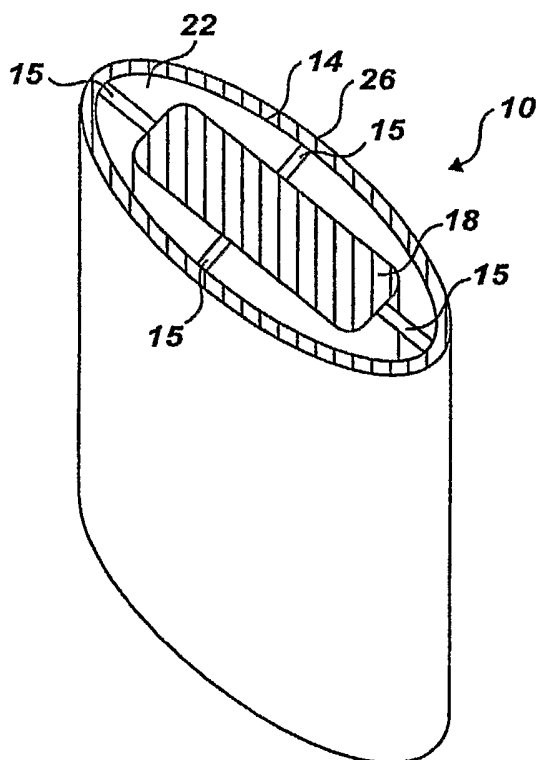
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(54) Title: SHAPE MODIFICATION AND REINFORCEMENT OF COLUMNS CONFINED WITH FRP COMPOSITES



(57) Abstract: Strengthening reinforced concrete columns (18)
by using Fiber Reinforced e Polymer (FRP) composites can b
an effective method of retrofitting existing columns. FRP com-
posites have a number of advantages over steel, including their
high strength-to-weight ratio and excellent durability. The con-
finement effectiveness of FRP materials for rectangular sections
can be improved by performing shape modification such that a
rectangular column section is modified into a shape that does not
have 90 degree corners such as an elliptical, oval or circular col-
umn. An expansive concrete (22) can be advantageously used
between the FRP material (26) and the existing concrete (18) in
order to post-tension the FRP material circumferentially and im-
prove confinement of the concrete. A finite element analytical
model is also disclosed which model describes the stress-strain
relationship for the FRP-confined columns after shape modifica-
tion.



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SHAPE MODIFICATION AND REINFORCEMENT OF COLUMNS CONFINED WITH FRP COMPOSITES

BACKGROUND OF THE INVENTION

In recent years, fiber reinforced polymer (FRP) composites have emerged as an alternative to traditional materials for strengthening and rehabilitation of structures. The light weight of FRP, high-strength to weight ratio, corrosion resistance, and high efficiency of construction are among many of the advantages which encourage civil engineers to use this material. FRP composites have been used in the retrofit of bridge columns due to insufficient capacity or displacement ductility. FRP jackets can provide lateral confinement to the concrete columns that can substantially enhance their compressive strength and ultimate axial strain. One of the most significant problems which concerns civil engineers is the constitutive law of FRP-confined concrete. Due to the increasing need for repair of structures, research has been carried out to investigate the behavior of FRP-confined concrete columns.

Many researchers have introduced stress-strain models to replicate compressive behavior of FRP-confined concrete. Some studies describe the behavior of the FRP concrete in terms of the properties of the concrete core and the confining FRP jacket. Other studies are governed by prior constitutive models and models for steel confined concrete.

Recently, some researchers proposed a confinement model, which is based on the concept of a variable strain ductility ratio. The researchers suggested that the compressive behavior of FRP-confined concrete can be separated into a strain-softening and a bilinear strain hardening component. Such a model shows agreement with experimental results for circular columns.

Researchers have also presented a simple design-oriented stress-strain model for FRP-confined rectangular columns based largely on a database of existing test results. In this model the concept of the equivalent circular column is introduced.

Most of the models mentioned above only refer to circular sections; moreover, test results are largely based on the standard 6 in. $\times$ 12 in. concrete cylinder tests. However, for FRP-confined rectangular columns, FRP jackets provide a non-uniform confinement over the cross-section and only a portion of the concrete section is effectively confined. For this reason, much less is known about the behavior of FRP-confined rectangular sections.

Unfortunately, current efforts tend to have limited value when reinforcing rectangular columns. Further, although many reinforcing methods result in moderate improvements in mechanical properties, the costs of such methods tends to outweigh the benefits and increase in strength. Therefore, materials and methods for further enhancing mechanical properties of structural columns and members continue to be sought.

SUMMARY OF THE INVENTION

It has been recognized that development of improved materials and methods for strengthening structural columns which avoid many of the above deficiencies would be a significant advancement in the industry. Accordingly, the present invention provides fiber reinforced polymer (FRP) composite structures which include a core and a fiber reinforced polymer material at least partially surrounding the core. The core includes an inner cement structure at least partially surrounded by an outer cement structure. The outer cement structure comprises or consists essentially of expansive cement or non-shrink cement. Typically, this is the result of applying the principles of the present invention to reinforce existing structures. Frequently, the inner cement structure of non-expansive cement can include steel reinforcements. However, the materials and methods of the present invention can significantly reduce or even eliminate the need for steel reinforcement in cement structures.

In another aspect of the present invention, the inner cement structure can have a cross-sectional shape which is different than a cross-sectional shape of the core. This results in a composite structure having a non-uniform gap thickness or non-uniform thickness of the non-shrink or expansive portion of the core. Thus, a pre-existing structure having, for example, a rectangular cross-section can be modified into a structure having a circular, oval or elliptical cross-section. Modification of the cross-sectional shape can have multiple advantages. The elimination of corners can reduce stress concentration and early failure of the FRP jacket. Typically, the FRP shell is cured before the grout is poured in the space between the existing column and the FRP shell. Therefore, the effect on the FRP shell is a post-tensioning, and the effect on the existing column is radial compression. For example, the FRP materials and post-tensioning of the FRP jacket can provide improved mechanical properties as described in more detail below. Additionally, elliptical, oval and circular shapes can provide a greater degree of strength under asymmetric loads than comparable rectangular configurations.

In accordance with an embodiment of the present invention, the FRP jacket can be post-tensioned and have a hoop stress along the FRP material. In one aspect, post-tensioning of the FRP jacket can be readily accomplished by using expansive concrete. The post-tensioning induced in the present invention can be in the form of tensile stress along the FRP fibers, i.e. circumferential rather than axial.

In yet another aspect of the present invention, the FRP material can include a fiber and a polymeric matrix. Typical fibers can include, but are not limited to, glass fiber, carbon fiber, aramid fiber, and combinations thereof. Glass and carbon fibers tend to be cost effective and provide good mechanical properties. Aramid fibers are light, durable and are known to have high tenacity. The selection of the fiber can be based on factors such as cost, strength, rigidity, and long-term stability. Additionally, each type of fiber offers different performance characteristics and suitability for various applications. For example, aramids may come in low, high, and very high modulus configurations. Carbon fibers are also available with a large range of moduli; with upper limits nearly four times that of steel. Of the several glass fiber types, glass-based FRP reinforcement is least expensive and generally uses either E-glass or S-glass fibers. The fiber material for use in FRP can be provided as sheets which can be cut to a desired size or as lengths of fiber which can be wrapped and/or laid as desired to form a particular shape.

The polymeric resins used as the matrix for the fiber are usually thermosetting resins. Most available FRP materials are provided with polymeric resins such as polyesters, vinylesters, or epoxies, although other polymeric materials can also be used. Additionally, the fibers and the FRP composites are heterogeneous and anisotropic which can make characterization and prediction of properties somewhat difficult.

The above described FRP composite structures can be produced in accordance with a number of optional embodiments of the present invention. In one embodiment, existing structural columns can be reinforced. This is accomplished by placing a FRP outer shell around the existing column such that there is an open space between the existing column and the outer shell. Typically, this can be accomplished by placing two pieces of a shell around the column. Once the outer shell is in place, at least one additional layer of FRP material is wrapped around the outer shell to secure the two pieces together. Optionally, the outer shell can be formed and cured around the column while leaving an open space. The open space between the existing column and the outer shell can then be filled with expansive or non-shrink cement.

In one embodiment of the present invention, the existing column has a cross sectional shape which is different than a cross-sectional shape of the outer shell. For example, the existing column may be rectangular in shape while the outer shell is circular or elliptical in shape.

Thus, there has thus been outlined, rather broadly, the more important features of the invention so that the detailed description thereof that follows may be better understood, and so that the present contribution to the art may be better appreciated. Other features of the present invention will become clearer from the following detailed description of the invention, taken with the accompanying drawings and claims, or may be learned by the practice of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

Additional features and advantages of the invention will be apparent from the detailed description which follows, taken in conjunction with the accompanying drawings, which together illustrate, by way of example, features of the invention; and, wherein:

FIG. 1 is a perspective view of an exemplary FRP composite structure according to one embodiment of the present invention.

FIG. 2 is a cross sectional view of a FRP composite structure according to one embodiment of the present invention.

FIG. 3A is a cross sectional view of a FRP composite structure in accordance with one embodiment of the present invention wherein the inner cement structure has a circular cross-sectional shape and the core has a circular cross-sectional shape.

FIG. 3B is a cross sectional view of a FRP composite structure in accordance with one embodiment of the present invention wherein the inner cement structure has a square cross-sectional shape and the core has a circular cross sectional shape.

FIG. 3C is a cross sectional view of a FRP composite structure in accordance with one embodiment of the present invention wherein the inner cement structure has a rectangular cross sectional shape and the core has an elliptical cross sectional shape.

FIG. 4 is a perspective view of a FRP outer shell around an existing column, with outer shell being configured to leave an open space between the existing column and outer shell so that the open space may be filled with expansive or non-shrink cement in accordance with one embodiment of the present invention.

FIG. 5 is a perspective view of a FRP composite outer shell which has been divided into two pieces and placed around an existing column in accordance with one

embodiment of the present invention.

FIG. 6 is a perspective view of two pieces of a FRP composite outer shell that have been spliced with a vertical FRP composite strip along the seams between the two pieces in accordance with one embodiment of the present invention.

FIG. 7A is a perspective view of a mold used for forming a FRP composite outer shell in accordance with one embodiment of the present invention.

FIG. 7B is a perspective view of a mold that has been partially wrapped with at least one layer of fiber reinforced composite material to form an outer shell in accordance with one embodiment of the present invention.

FIG. 7C is a perspective view of an outer shell which has been divided into two pieces so that it can be used in applications requiring retrofitting existing columns in accordance with one embodiment of the present invention.

FIG. 8 is a graph of concrete strength vs. aging time in accordance with one embodiment of the present invention.

FIG. 9 is a graph of expansion hoop strain for expansive cement in accordance with one embodiment of the present invention.

FIG. 10A is a graph of the expansion history of 12" circular columns in accordance with one embodiment of the present invention.

FIG. 10B is a graph of expansion history of 16" circular columns in accordance with one embodiment of the present invention.

FIG. 10C is a graph of expansion history of elliptical (1:2) columns in accordance with one embodiment of the present invention.

FIG. 10D is a graph of expansion history of elliptical (1:3) columns in accordance with one embodiment of the present invention.

FIG. 11A is a perspective view for a wrapping method of a circular column in accordance with one embodiment of the present invention.

FIG. 11B is a cross sectional view of a circular column without a fiber reinforced polymer wrap.

FIG. 11C is a cross sectional view of a circular column with a fiber reinforced polymer wrap.

FIG. 11D is a cross sectional view of a circular column with a fiber reinforced polymer wrap.

FIG. 11E is a perspective view for a wrapping method of a circular column in accordance with one embodiment of the present invention.

FIG. 11F is a cross sectional view of a circular column of expansive concrete with a fiber reinforced polymer wrap.

FIG. 11G is a cross sectional view of a circular column of expansive concrete with a fiber reinforced polymer wrap.

FIG. 11H is a perspective view for a wrapping method of a circular column in accordance with one embodiment of the present invention.

FIG. 11I is a cross sectional view of a circular column with a fiber reinforced polymer wrap.

FIG. 11J is a cross sectional view of a circular column with a fiber reinforced polymer wrap.

FIG. 12A is a perspective view for a wrapping method of a square column in accordance with one embodiment of the present invention.

FIG. 12B is a cross sectional view of a square column without a fiber reinforced polymer wrap.

FIG. 12C is a cross sectional view of a square column with a fiber reinforced polymer wrap.

FIG. 12D is a cross sectional view of a square column encircled by regular concrete and a fiber reinforced polymer wrap.

FIG. 12E is a cross sectional view of a square column with a fiber reinforced polymer wrap.

FIG. 12F is a cross sectional view of square column encircled by regular concrete and a fiber reinforced polymer wrap.

FIG. 12G is a perspective view for a wrapping method in accordance with one embodiment of the present invention.

FIG. 12H is a cross sectional view of a square column encircled by expansive concrete and a fiber reinforced polymer wrap in accordance with one embodiment of the present invention.

FIG. 12I is a cross sectional view of a square column encircled by expansive concrete and a fiber reinforced polymer wrap in accordance with one embodiment of the present invention.

FIG. 12J is a perspective view for a wrapping method of a square column in accordance with one embodiment of the present invention.

FIG. 12K is a cross sectional view of a square column with a fiber reinforced polymer wrap.

FIG. 12L is a cross sectional view of a square column with a fiber reinforced polymer wrap.

FIG. 13A is a perspective view for a wrapping method of a rectangular column in accordance with one embodiment of the present invention.

FIG. 13B is a cross sectional view of a rectangular column without a fiber reinforced polymer wrap.

FIG. 13C is a cross sectional view of a rectangular column with a fiber reinforced polymer wrap.

FIG. 13D is a cross sectional view of a rectangular column encircled by regular concrete and a fiber reinforced polymer wrap.

FIG. 13E is a cross sectional view of a rectangular column with a fiber reinforced polymer wrap.

FIG. 13F is a cross sectional view of a rectangular column encircled by regular concrete and a fiber reinforced polymer wrap.

FIG. 13G is a perspective view for a wrapping method of a rectangular column in accordance with one embodiment of the present invention.

FIG. 13H is a cross sectional view of a rectangular column encircled by regular concrete and a fiber reinforced polymer wrap.

FIG. 13I is a cross sectional view of a rectangular column encircled by regular concrete and a fiber reinforced polymer wrap.

FIG. 14A is a perspective view for a wrapping method of a rectangular column in accordance with one embodiment of the present invention.

FIG. 14B is a cross sectional view of a rectangular column without a fiber reinforced polymer wrap.

FIG. 14C is a cross sectional view of a rectangular column with a fiber reinforced polymer wrap.

FIG. 14D is a cross sectional view of a rectangular column encircled with regular concrete and a fiber reinforced polymer wrap.

FIG. 14E is a cross sectional view of a rectangular column with a fiber reinforced polymer wrap.

FIG. 14F is a cross sectional view of a rectangular column encircled by regular concrete and a fiber reinforced polymer wrap.

FIG. 14G is a perspective view for a wrapping method of a rectangular column in accordance with one embodiment of the present invention.

FIG. 14H is a cross sectional view of a rectangular column encircled by expansive concrete and a fiber reinforced polymer wrap in accordance with one embodiment of the present invention.

FIG. 14I is a cross sectional view of a rectangular column encircled by expansive concrete and a fiber reinforced polymer wrap in accordance with one embodiment of the present invention.

FIG. 15 is a side perspective view illustrating the placement of specimens in a compression machine in accordance with one embodiment of the present invention.

FIG. 16A is a cross sectional view illustrating placement of LVDT devices in accordance with one embodiment of the present invention.

FIG. 16B is a cross sectional view illustrating placement of LVDT devices in accordance with one embodiment of the present invention.

FIG. 16C is a cross sectional view illustrating placement of LVDT devices in accordance with one embodiment of the present invention.

FIG. 17 is a perspective view of a column compression machine used in testing the specimens in accordance with one embodiment of the present invention.

FIG. 18 is a graph of load versus displacement behavior of circular specimens.

FIG. 19 is a graph of stress versus strain relation for specimens with regular concrete.

FIG. 20 is a graph of stress versus strain relation for specimens with expansive cement concrete.

FIG. 21 is a graph of stress versus strain for several specimens in accordance with embodiments of the present invention.

FIG. 22 is a graph of stress versus strain for several specimens in accordance with embodiments of the present invention.

FIG. 23 is a graph of finite element results for CFRP-confined square and rectangular columns.

FIG. 24 is a graph of finite element results for CFRP-confined elliptical columns.

The above figures are provided for illustration purposes and variations in dimensions, shapes, materials and the like can be made without departing from the claimed scope of the invention.

Reference will now be made to the exemplary embodiments illustrated, and specific language will be used herein to describe the same. It will nevertheless be understood that no limitation of the scope of the invention is thereby intended.

DETAILED DESCRIPTION

Before the present invention is disclosed and described, it is to be understood that this invention is not limited to the particular structures, process steps, or materials disclosed herein, but is extended to equivalents thereof as would be recognized by those ordinarily skilled in the relevant arts. It should also be understood that terminology employed herein is used for the purpose of describing particular embodiments only and is not intended to be limiting.

It must be noted that, as used in this specification and the appended claims, the singular forms “a,” and “the” include plural referents unless the context clearly dictates otherwise. Thus, for example, reference to “a layer” includes one or more of such layers, reference to “a column” includes reference to one or more of such structures, and reference to “a lay-up process” includes reference to one or more of such processes.

Definitions

In describing and claiming the present invention, the following terminology will be used in accordance with the definitions set forth below.

As used herein, “cement” as any material which can be used to bind. For example, concrete can include crushed stone, sand, and a cement. Portland cement is a fired mixture of limestone and clay which, when hydrated, forms interlocking crystals which bind to the sand, stone, and one another. Cements can generally be classified as shrink, non-shrink, or expansive cements. The most commonly used cement for general construction is shrink cement.

As used herein, “post-tension” refers to tension created or induced in a material subsequent to formation. For example, post-tensioning of FRP shells occurs after curing of the FRP shell to create a post-tensioned shell having circumferential, or hoop stress.

As used herein with respect to an identified property or circumstance, “substantially” refers to a degree of deviation that is sufficiently small so as to not measurably detract from the identified property or circumstance. The exact degree of deviation allowable may in some cases depend on the specific context.

As used herein, a plurality of items, structural elements, compositional elements, and/or materials may be presented in a common list for convenience. However, these lists should be construed as though each member of the list is individually identified as a separate and unique member. Thus, no individual member of such list should be construed as a de facto equivalent of any other member of the same list solely based on

their presentation in a common group without indications to the contrary. For example, glass fiber and carbon fiber are listed in a common group. However, those skilled in the art will recognize that glass fiber may be more or less suitable than carbon fiber for a specific application depending on cost restrictions, strength requirements, and other factors.

Concentrations, amounts, and other numerical data may be expressed or presented herein in a range format. It is to be understood that such a range format is used merely for convenience and brevity and thus should be interpreted flexibly to include not only the numerical values explicitly recited as the limits of the range, but also to include all the individual numerical values or sub-ranges encompassed within that range as if each numerical value and sub-range is explicitly recited.

As an illustration, a numerical range of “about 1 inch to about 5 inches” should be interpreted to include not only the explicitly recited values of about 1 inch to about 5 inches, but also include individual values and sub-ranges within the indicated range. Thus, included in this numerical range are individual values such as 2, 3, and 4 and sub-ranges such as from 1-3, from 2-4, and from 3-5, etc. This same principle applies to ranges reciting only one numerical value. Furthermore, such an interpretation should apply regardless of the breadth of the range or the characteristics being described.

Invention

Due to the increasing need for repair of existing support structures, research has been carried out to investigate the behavior of FRP-confined concrete columns. The compressive stress-strain behavior of FRP confined concrete cylinders is generally nonlinear and the initial portion of the stress-strain response typically follows that of the unconfined concrete. Moreover, after reaching the peak unconfined concrete stress level, the response of the FRP-confined concrete softens. This softening can occur with either a localized descending branch that may stabilize as the dilation of the concrete core progresses, or the concrete may exhibit a somewhat linear behavior until the FRP composite jacket fails.

In accordance with the present invention, FRP materials can be used to either reinforce existing structures regardless of shape, or form new structures with improved mechanical, structural and aesthetic properties.

Referring now to FIG. 1, a fiber reinforced composite structure **10** is shown comprising a core **14** including an inner cement structure **18** at least partially surrounded by an outer cement structure **22**. The inner cement structure can have steel reinforcements

therein; however, the present invention reduces the need for steel reinforcements. The outer cement structure **22** may include a non-shrink cement or an expansive cement. Alternatively, the outer cement structure **22** may consist exclusively of expansive cement. Encircling the core **14** is an FRP material **26**, which makes up an FRP outer shell **30**. The FRP material **26** preferably comprises a fiber and polymeric matrix. Traditionally, the fiber is selected from the group consisting of glass fiber, carbon fiber, aramid fiber, and combinations thereof, although other FRP materials can also be used.

The composite structure **10** is shown in FIG. 2 with a core **14** having a cross sectional shape that is different from the cross sectional shape of inner cement structure **18**. Alternatively, the core **14** may have a cross sectional shape similar to the cross sectional shape of the inner cement structure **18**, as shown in FIG. 3A. The composite structure **10** is shown in FIGS. 3B and 3C having a core **14** with a cross sectional shape that is different from the cross sectional shape of the inner cement structure **18**. Specifically, FIG. 3B shows the composite structure **10** having a core **14** with a circular cross sectional shape and an inner cement structure **18** with a square cross-sectional shape, and FIG. 3C shows the composite structure **10** wherein the inner cement structure **18** has a rectangular cross sectional shape and the core **14** has an elliptical cross sectional shape.

Now referring to FIG. 4, a FRP outer shell **30** is shown around an existing column **34**. The existing column can have steel reinforcements therein; however, the present invention reduces the need for steel reinforcements. The outer shell **30** is configured such that there is an open space **38** between the existing column **34** and the outer shell **30**. The open space **38** can then be filled with cement **42**. The cement **42** may be either expansive cement or non-shrink cement or a combination thereof. In a preferred embodiment of the present invention, as shown in FIG. 1, pegs **15** can be placed between the inner cement structure and the FRP outer shell to secure the positioning of the outer column and existing column prior to filling the open space with cement.

FIG. 5 illustrates one embodiment of the present invention wherein the outer shell **30** comprises at least two pieces which can be placed around the existing column **34** to form the outer shell **30**. This can be achieved by separating the FRP outer shell **30** into two pieces and placing the two pieces around the existing column to form the outer shell. To reinforce an existing column **34** it is typically necessary to separate the outer shell **30** longitudinally into a first piece **46** and a second piece **48**. The first piece **46** and second piece **48** can then be placed around the existing column **34** to reform the outer shell **30**. In most cases, the outer shell **30** is designed and shaped to leave an open space **38** between

the existing column **34** and the outer shell **30**. Thus, the outer shell **30** provides a convenient avenue for shape modification of existing structures. Shape modification is particularly relevant with respect to retrofitting existing structures. An existing column **34** with a square or rectangular cross-section may be modified such that the resulting composite structure **10** has a circular or elliptical cross-section. Typically, FRP composite jackets subjected to membrane loading in accordance with the present invention are stronger than rectangular column sections having long flat sides. This is largely because of the dominant bending action of the flat sides. Therefore, shape modification of an existing column **34** using the present invention can be readily accomplished to provide improved structural and mechanical properties to the composite structure **10**.

Once the first piece **46** and second piece **48** have been placed around the existing structure **34** they can be spliced, as shown in FIG. 6, with a vertical FRP composite strip **56** along each seam **58** between the first piece **46** and second piece **48** so as to form a unitary outer shell **52**. In a preferred embodiment of the present invention, after the first and second piece of the outer shell have been spliced with a vertical FRP composite strip, additional FRP material may be wrapped around the outer shell. Typically the wrapping can be done with a single continuous sheet; however, multiple sheets can be wrapped in a wet lay-up process followed by curing of the polymer resin. Most often, the number of layers can range from 1 to about 14 additional layers.

In yet another preferred embodiment of the present invention, prior to placing the first piece **46** and second piece **48** around the existing column **34**, the existing column may be reshaped such that the edges of the existing column having an angle of about 90 degrees are rounded. One important consideration in forming FRP-confined rectangular columns in accordance with the present invention is the issue of effectiveness of FRP confinement, which may significantly decrease due to the presence of 90° corners or abrupt change of direction around the perimeter. Small-scale tests illustrate the effect of rounding the column corners on confinement efficiency. The rounding of corners on concrete columns has been shown to have an effect in ultimate strength as high as an 80% increase with respect to square columns without rounding the corners. In addition to higher strengths, higher ultimate compressive strains can be achieved for columns with rounded corners, which is more important for seismic applications than strength. Typical ultimate strain increases range from 200% to 300%. While the effectiveness of confinement increases with the corner radius, the rounding of corners cannot always be

made in practice as large as ideally desired because of the presence of the hoop steel reinforcement, typically about 1.5 - 2.5 in. from the exterior concrete surface.

In one embodiment of the invention, FRP materials can be placed along the longitudinal axis of the existing column in direct contact with the existing column, either during or after formation of the FRP shell, for increased flexural resistance of the column, if required.

Many applications will call for a FRP outer shell that is pre-manufactured. However, many applications will require manufacture of the outer shell. In these applications, a mold can be prepared in order to form the FRP outer shell. A mold can be prepared to correspond with a desired final shape of the column. A mold is not necessarily the same shape as the existing column. Frequently, an existing rectangular or square column can be modified to produce a circular or elliptical column of slightly larger width.

In one embodiment of the present invention as illustrated in FIGS. 7A, 7B and 7C, a mold **60** is prepared. The mold **60** is then wrapped with at least one layer of FRP material **64** to form an outer shell **72**. The mold can then be removed leaving the outer shell as an independent structure. Typically, the wrapping can be done with a single continuous sheet; however, multiple sheets can be wrapped in a wet lay-up process followed by curing of the polymer resin. The sheets may be cut to a desired size or as lengths of fiber strands, as shown in FIG. 7B, which can be wrapped and/or laid as desired to form a particular shape. Most often, the number of layers can range from 1 to about 14 additional layers.

In a preferred embodiment of the present invention, the FRP material **64** comprises a fiber and a polymeric matrix. Typical fibers can include, but are not limited to, glass fiber, carbon fiber, aramid fiber, and combinations thereof. Any suitable FRP material can be used which includes a fiber material and a polymeric matrix. Non-limiting examples of commercial products can include SikaWrap, Aquawrap, and the like.

Wrapping of the mold **60** may include a wet layup of resin coated fibers followed by a curing of the resin. Once the resin has cured, the outer shell **72** can be divided longitudinally into at least a first piece **76** and a second piece **78** so that it can be used in applications that require retrofitting existing columns.

For purposes of designing FRP structures for existing columns, those persons skilled in the art will recognize that it is possible to use finite element analysis to prepare the design of the FRP structure prior to retrofitting the existing column.

Examples

The following examples illustrate exemplary embodiments of the invention. However, it is to be understood that the following is only exemplary or illustrative of the application of the principles of the present invention. Numerous modifications and alternative compositions, methods, and systems may be devised by those skilled in the art without departing from the spirit and scope of the present invention. The appended claims are intended to cover such modifications and arrangements. Thus, while the present invention has been described above with particularity, the following examples provide further detail in connection with what is presently deemed to be practical embodiments of the invention.

In the following examples, the radii of curvature for the 90 degree corners of the square and rectangular columns were designed to be 3/4 in. This would allow modification of existing columns, taking into account typical existing steel reinforcement at 90 degree corners. Expansive cement was used for some examples, whereas non-shrink cement was used for other examples to fill the space between the outer shell and existing column.

Further, regular shrink concrete was used to prepare a number of test samples which were then compared to samples using expansive and non-shrink concrete. All columns were cast in one batch to eliminate variations between them; 6" x 12" and 4" x 8" standard cylinders were made along with these specimens. The compressive strength was obtained from the tests of cylinders at 28 days after casting the concrete. The concrete strength versus time relationship is shown in Figure 8. Figure 8 illustrates that the concrete strength increased during the first 6 months and after six months approaches a constant value of 2600 psi.

Expansive Cement

Unstressed FRP composite jackets do not participate in the confinement of concrete until the concrete starts expanding. Typically, this involves at least partial failure of the concrete and/or softening of the concrete. In accordance with the present invention, expansive concrete can post-tension the FRP composites jacket in the hoop direction prior to application of vertical or axial loading to the column.

The expansive cement used in the following examples includes Type-K and KOMPONENT cements, manufactured by CTS Company, Cypress, CA. The two principal constituents of KOMPONENT are calcium sulfoaluminate and gypsum (calcium sulfate). The formation of ettringite crystals, which results from the hydration of the two

ingredients, causes an expansion of the cement. When expansion is restrained by FRP composite jackets in accordance with the present invention, the expansive cement induces tensile stress in the FRP composite jackets along the circumference of the FRP jackets.

To determine the optimal mixing ratio of Type-K cement and KOMPONENT, a preliminary test was conducted. In this test, four types of expansive cements were investigated:

- (1) MIX 1: 100% Expansive KOMPONENT
- (2) MIX 2: 75% Expansive KOMPONENT + 25% Portland Cement
- (3) MIX 3: 50% Expansive KOMPONENT + 50% Portland Cement
- (4) MIX 4: 15% Expansive KOMPONENT + 85% Portland Cement

Each of the four mixtures was prepared and cast in prefabricated CFRP cylinder shells (6" x 12"). Strain gauges were placed at the middle height of the CFRP cylinders to monitor the expansion history over time. The resulting strain curves are shown in Figure 9, which shows that both mix (2) and mix (3) gave the largest hoop strain for the FRP jacket compared to the other two mixes. Data from accompanying cylinder tests show that the compressive strength of mix (3) was 920 psi compared to 850 psi for mix (2). Mix (3) was selected since it contained less expansive cement. Thus, it appears that for this particular expansive cement, volume percents of expansive cement from about 30 to about 85 can be suitable. The final mix design (based on mix (3)) for the expansive concrete is shown in Table 1.

Table 1: Mix Design for the Expansive Concrete

COMPONENT	DETAILS	Gals/%	lbs	C.F.
Cement	Type K Expansive Cement	10%	351	1.79
	Komponent	5%	166	0.84
Water	U.S. Gallons	45 gall	375	6.00
Air %	Entrained Air Target	7% +/- 1%		1.89
Rock	ASTM C-33 (SSD) 3/8s Pea Gravel		520	3.22
Sand	ASTM C-33 (SSD)		2143	13.26
Total			3555	25.3.00

Several specimens with 12 in. diameter circular, 16 in. diameter circular and elliptical (aspect ratio 1:2 and 1:3) with CFRP and GFRP jackets, were cast and then cured at an indoor temperature around 70 °F. The details of construction are described below in more detail. A data acquisition system was used to monitor the hoop expansion of the

FRP composite jacket for each specimen. Figures 10A-10D show the hoop expansion strain of the circular and elliptical columns for about 70 days.

Non-Shrinkage Concrete

As an alternative to expansive cement, a shrinkage compensated cement was also used to compare the differences between the expansive cement FRP jackets and the non-shrinkage FRP jackets. In this case, the non-shrinkage concrete was used to modify the rectangular or square sections to elliptical or circular sections as detailed below. Once the aging of the concrete was stable, the FRP jackets were wrapped using a wet lay-up process. A structural grout, Sika Grout 212 was selected as the grout to make non-shrink concrete.

Fiber Reinforced Polymer

Two FRP composite materials were used to confine the concrete columns. One was SikaWrap Hex 103C (available from Sika Canada Inc.), which is a high strength, unidirectional carbon fiber fabric. The second FRP material was Aquawrap G-06 by Air Logistics, which is a unidirectional pre-impregnated glass fiber fabric. The primary material properties determined in this study are shown in Table 2.

Table 2: Material Properties of CFRP and GFRP Composites*

FRP Composite	Tensile Strength (ksi)	Tensile Modulus (Msi)	Tensile Strain (%)	Ply Thickness (in.)
CFRP	177	12.6	1.4	0.038
GFRP	33	2.45	1.4	0.064

*Determined at University of Utah, following ASTM D3039 after curing at room temperature.

Construction of Specimens and Sample Preparation

A total of 30 test structures were prepared such that each had nearly the same cross-sectional area prior to shape modification and the same height of 3 feet. Thus, comparisons were made for different cross sections and aspect ratios. Molds for specimens were made out of plywood and sonatubes.

In addition, both CFRP and GFRP composites-confined specimens were tested and compared with baseline specimens without FRP composites. A breakdown of the test matrix is presented in Tables 3-6. Figures 11A through 11J, 12A through 12L, 13A-13I, and 14A-14I show details of the wrapping methods for each specimen. Regardless of the number of FRP layers, the entire bonded jackets were made of one continuous sheet of FRP fabric that was cut to the proper length and width. An additional 3" of overlap splice

was provided. To make expansive cement concrete specimens, the following steps were followed:

- (a) Preparation of circular and elliptical forms.
- (b) Build 1st layer of FRP shell and cut the shell into two halves.
- (c) Make stay-in-place FRP forms by lap splicing with one FRP layer and applying the other remaining layers.
- (d) Pour expansive cement concrete to fill the open space between the FRP shell and the standard concrete column.

Table 3: Matrix of Test Specimens: Circular Columns

NO.	COLUMN DESIGNATION	INITIAL TYPE	LENGTH	INITIAL SIZE	FRP TYPE	Note
1	C-0-0	Circular	36"	12"	None	
2	C-C1-0	Circular	36"	12"	Carbon 1 Layer	
3	C-G3-0	Circular	36"	12"	Glass 3 Layers	
4	C-CT-E	Circular	36"	12"	Carbon Fiber Tube(1 layer)	expansive concrete
5	C-GT-E	Circular	36"	12"	Glass Fiber Tube (3 layers)	expansive concrete
6	C-CS-0	Circular	36"	12"	Carbon Fiber Strip	2 Layers of CFRP
7	C-GS-0	Circular	36"	12"	Glass Fiber Strip	6 Layers of GFRP

Table 4: Matrix of Test Specimens: Square Columns

NO.	COLUMN DESIGNATION	INITIAL TYPE	LENGTH	INITIAL SIZE	FRP TYPE	Note
8	S-0-0	Square	36"	11" x 11"	None	
9	S-C2-0	Square	36"	11" x 11"	carbon 2 layers	3/4" radii at 90° corners
10	S-C2-F	Square	36"	11" x 11"	carbon 2 layers	

11	S-G6-0	Square	36"	11" x 11"	Glass 6 layers	3/4" radii at 90° corners
12	S-G6-F	Square	36"	11" x 11"	Glass 6 layers	
13	S-CT-E	Square	36"	11" x 11"	Carbon fiber tube (2 layers)	
14	S-GT-E	Square	36"	11" x 11"	Glass fiber tube (6 layers)	
15	S-CS-0	Square	36"	11" x 11"	Carbon fiber strip	3/4" radii at 90° corners
16	S-GS-0	Square	36"	11" x 11"	Glass fiber strip	3/4" radii at 90° corners

Table 5: Matrix of Test Specimens: Rectangular Columns (1)

NO.	COLUMN DESIGNATION	INITIAL TYPE	Length	INITIAL SIZE	FRP TYPE	Note
17	R2-0-0	Rectangular	36"	8" x 15"	None	
18	R2-C2-0	Rectangular	36"	8" x 15"	carbon 2 layers	3/4" radii at 90° corners
19	R2-C2-F	Rectangular	36"	8" x 15"	carbon 2 layers	
20	R2-G6-0	Rectangular	36"	8" x 15"	Glass 6 layers	3/4" radii at 90° corners
21	R2-G6-F	Rectangular	36"	8" x 15"	Glass 6 layers	
22	R2-CT-E	Rectangular	36"	8" x 15"	Carbon fiber tube (2 layers)	
23	R2-GT-E	Rectangular	36"	8" x 15"	Glass fiber tube (6 layers)	

Note: For the elliptical columns, the longer axis is 21.2 in. and the shorter axis is 11.4 in.

Table 6: Matrix of Test Specimens: Rectangular Columns (2)

NO.	COLUMN DESIGNATION	INITIAL TYPE	Length	INITIAL SIZE	FRP TYPE	Note
24	R3-0-0	Rectangular	36"	6" x 18"	None	
25	R3-C2-0	Rectangular	36"	6" x 18"	carbon 2 layers	3/4" radii at 90° corners
26	R3-C2-F	Rectangular	36"	6" x 18"	carbon 2 layers	
27	R3-G6-0	Rectangular	36"	6" x 18"	Glass 6 layers	3/4" radii at 90° corners
28	R3-G6-F	Rectangular	36"	6" x 18"	Glass 6 layers	
29	R3-CT-E	Rectangular	36"	6" x 18"	Carbon fiber tube (2 layers)	
30	R3-GT-E	Rectangular	36"	6" x 18"	Glass fiber tube (6 layers)	

Note: For the elliptical columns, the longer axis is 25.4 in. and the shorter axis is 8.4 in.

Testing of Specimens

The strain gauges employed in this testing program were manufactured by Measurements Group, Inc. with model designation as EA-06-125BZ-350. The resistance of these gauges at normal temperature (75 °F) is $350 \pm 0.15\%$ ohms. In order to measure the transverse strain on the FRP jacket during loading, strain gauges were placed on fibers in the hoop direction, at about the mid-height of the specimens. Special care was taken during the installation to avoid damage of the strain gauges. Considering the geometry of the cross sections, the layout of strain gauges was varied for each shape.

Linear variable differential transducers (LVDTs) are used to measure average strains when the use of strain gauges is impossible. In these tests, LVDTs are employed to measure the vertical and lateral strains. The data from LVDTs can be used to calculate the average axial and transverse strains over the column height and width. LVDTs are installed using aluminum angles with threaded rods at their ends. The angles must be solidly clamped to the specimen for accurate readings. Figure 15 shows the LVDT configuration. Two types of LVDTs used for experiments are MVL7C and MVL7, manufactured by Sensotec Company. They can measure a displacement in the range of ± 0.500 in. and ± 2.000 in., respectively, with high accuracy. For the square and

rectangular columns, additional LVDTs are installed on the two sides of the cross section to measure the transverse strain in both directions as shown in Figures 16A-16C.

The specimens were tested using a structural load frame having an actuator manufactured by Geneva Hydraulics, Inc. This actuator can impose a compression load up to 2000 kips and is capable of a 24 in. stroke. Figure 17 illustrates the setup of the column compression tests. All of the specimens were loaded monotonically under a displacement control mode with a constant loading rate of 0.05 in. per minute.

A data acquisition system was used to record the values of the strain gauges and LVDTs. The data acquisition system used in this testing program consisted of scanners, WIN5100 (manufactured by Measurements Group) with interface cards and the STRAINSMART software. The scanners can read electrical signals from the sensors and send this information to a computer via the interface cards. The software then converts these signals into the desired digital output. Prior to the start of testing, a configuration file had to be written in the software to assign the measured quantities to input and output channels. In addition, the calibration values of strain gauges and LVDTs were input into this configuration file. After the setup of the configuration file and immediately before testing, all of the initial values were set to zero to prepare for recording.

Experimental Results

In early tests, a group of 7 circular columns were tested. All of the FRP strengthened specimens showed significant increases in axial stress and axial strain capacity. As seen in Table 7, the increase in ultimate strength (f_{cc}/f_{co}) ranges from 138 to 238 percent for regular concrete specimens and 545 to 676 percent for expansive cement concrete specimens. In addition, compared with the baseline column without any reinforcement, FRP composite jackets improve the confinement of the columns which results in a significant increase in axial strain as presented in Table 7. The increases in ultimate strain ($\epsilon'_{cc}/\epsilon'_{co}$) ranges from 848 to 1421 percent for the FRP reinforced specimens.

Table 7: Results of Circular Column Tests

Specimen No.	FRP Type	Layers	Wrapping Method	f_{cc}/f_{co}	$\epsilon'_{cc}/\epsilon'_{co}$
C-0-0*	NO FRP			1.00	1.00
C-C1-0*	CFRP (wet-layup)	1	Continuous	2.20	8.48
C-G3-0*	GFRP (wet-layup)	3	Continuous	2.38	12.06

C-CS-0*	CFRP (wet-layup)	2	5 in. Strips (5 in. spacing)	1.38	9.36
C-GS-0*	GFRP (wet-layup)	6	5 in. Strips (5 in. spacing)	1.82	14.21
C-CT-E**	CFRP (prestressed)	1	Continuous	5.45	11.74
C-GT-E**	GFRP (prestressed)	3	Continuous	6.76	13.71

* Regular concrete, ** Expansive cement concrete

The specimens in this testing group exhibited several failure modes. The governing failure mode was determined by the mechanical properties of the FRP composite material and the reinforcement scheme. It was observed from the tests that the most typical failure mechanism was crushing of concrete followed by the tensile failure of the FRP at or near the mid-height of the specimens. Because the fabric was unidirectional and oriented at 0 degrees, a band or ring was typically formed as a result of the shearing off, and separation of, the fabric in the hoop direction.

The load-versus-displacement graphs for each specimen are presented in Figure 18. As well as the increased axial strain, this increased deflection is also believed to be a result of the greater energy absorption capacity of the specimens provided by the FRP composites. These results indicate that application of high performance FRP composites to a concrete member does not promote brittle failure. Therefore, the ductility of FRP-confined specimens can be described by using the principle of energy absorption by comparing the area under the load-displacement curves.

The stress-strain curves for regular concrete specimens and specimens with expansive cement concrete are shown in Figure 19 and 20, respectively. As seen from Figure 19, the loading behavior of the FRP-confined specimens with regular concrete can be divided into three phases. The first phase is from the origin to point A. Point A corresponds to an axial stress $f = 0.8f_{co}'$ (where f_{co}' is the strength of the baseline specimen C-0-0). In this phase where the behavior for all specimens (in Figure 19) is almost the same, lateral expansion was very small and the FRP stresses were very low (about 16%-33% of their ultimate strength as observed from the tests). When the load exceeded point A, the FRP stress and strain started to increase quickly. Cracking noises were heard once the loading approached f_{co}' which marked the FRP being put into tension. In the second phase, from A to B, the FRP composite participated in confinement which resulted in the

small axial strain (displacement) as seen from stress-versus-strain and load-versus-displacement curves. After point B, which marked the turning point on the stress-strain curves, the loading went into the third phase. In this phase, the FRP strain increased very quickly and the specimen stiffness decreased as observed from the tests. The specimens deformed largely in the axial direction and the fabric was deformed on the surface of the FRP composite. Finally, the concrete in the specimens crushed followed by the fracture of FRP.

These three phases represent the typical behavior of the axially loaded FRP-confined concrete specimens. In the beginning phase, the concrete has a small expansion and the FRP jacket does not participate. However, in phase AB, the concrete expands and FRP composite jacket is put into tension. Therefore, the FRP material provides partial confinement against expansion. In the last phase after B, the concrete goes into a flowing state until FRP fracture and the failure is very brittle. The behavior of the specimens with expansive cement concrete was somewhat different. Specifically, the initial slope of the stress-strain curve is lower than that of the regular concrete specimens, but the later slope after the turning point is similar to that of the regular concrete specimens. The comparisons show that the axial stress capacity was equivalent to the FRP-confined regular concrete specimens and the axial strain capacity was much larger.

Testing results for several square columns are shown in Figures 21 and 22. In each figure S-0-0 shows results for an 11 in. square column without FRP composites, S-G6-0 shows results for an 11 in. square column with 6 layers of glass FRP composite directly wrapped thereon, and S-GT-E shows results for an 11 in. square column with expansive concrete modified into a 16 in. diameter circle with 6 layers of glass FRP composite in accordance with the present invention. Figure 21 illustrates that the GFRP expansive composite column has a strength of about 3.3 times that of the unwrapped column and about 2.3 times that of the directly wrapped column. Likewise, Figure 22 illustrates that strain, i.e. ductility, for the GFRP expansive composite column is about 8 times that of the unwrapped column.

Thus, the above discussion illustrates that FRP composites are very effective in increasing the load-carrying capacity and deformation ability of existing columns. Significant increases in both ultimate stress and strain are observed from the tests. When compared to the regular concrete specimens, the specimens with expansive cement concrete show more deformation ability and ductility at failure. In addition, they have a higher increase in the ultimate strength. With the same volumetric FRP ratio, the

confinement effectiveness for specimens confined by FRP strips decreases if compared to those confined with continuous FRP. Therefore, the strengthening method with FRP strips should be used with caution for the normal retrofit of bridge columns. Otherwise, the maximum spacing of FRP strips should be limited. However, strengthening with FRP strips offers the advantage of easy inspection. The FRP composites can significantly improve the axial behavior of the columns. It is recommended that at least two layers of FRP composites be used for the retrofit of existing columns.

Finite Element Analysis

To validate the results obtained from the experimental research, a nonlinear finite analysis was conducted by using the finite element software package: ANSYS6.0 (ANSYS 2000). Four types of models were developed according to the geometric characteristics of the specimens. SOLID65, which is an eight-node brick element with 3 DOFs at each node, was used to model concrete. SHELL181 is a four-noded element that is well-suited to model FRP composite materials. The material properties for the unconfined concrete and FRP composites were obtained from compression cylinder and tensile coupon tests, respectively. Considering the symmetry of each column, only one-quarter of the column section along its longitudinal direction was modeled; symmetrical boundary conditions were applied at the symmetrical borders along the X and Y axes. To model the pre-tensioning effect of the expansive cement concrete on the FRP jackets, an equivalent thermal gradient was applied on the FRP composite jacket to obtain the pre-stressed hoop strain prior to applying the axial loading. For each model, a nonlinear analysis was conducted considering both material and geometric nonlinear behavior. The loading process was divided into many incremental steps, in which an incremental axial displacement was applied. Every increment was iterated until convergence was met with respect to the criteria of force and displacement. To optimize the calculation, each load step was divided into 20 sub-steps to expedite the process of convergence.

Analysis Results

The output of ANSYS results consists of the nodal displacement, element stress, element strain and other information. For the axial stress in each loading step, a mean value was calculated by taking the average of the longitudinal 6 elements along the central line of the model. By entering this value into the element result tables, circumferential or hoop strain was obtained. Then, the curves of axial stress versus axial strain and hoop strain were developed by joining a series of data for each loading step.

The results of finite element analysis for some rectangular/square specimens are summarized in the stress-strain curves in Figures 23 and 24. It is noted from Figure 23 that the confinement provided was not sufficient to significantly increase the axial stress for the square and rectangular sections. Both the square and rectangular models demonstrated a typical softening behavior which is characterized by a sudden drop from the peak stress (as seen from Figure 23). Observations from the results of the normal elliptical models (as shown in Figure 24) also demonstrated the softening behavior. However, this softening is not as much as that of the rectangular columns. This result illustrates that the confinement effect is directly related to the shape of the section and that the confinement efficiency of circular columns is much better than the sections with 90 degree corner radius. Another important result can be observed from the comparison of bonded and pre-stressed FRP jackets of the present invention, as shown in Figure 24, that the effectiveness of prestressing on the FRP also has a significant contribution to the confinement efficiency. This type of finite element analysis can also be used to design a retrofit to suit a specific project by choosing the desired increase in strength and efficiency and varying parameters such as shape and number of layers to balance results with cost effectiveness.

Of course, it is to be understood that the above-described arrangements are only illustrative of the application of the principles of the present invention. Numerous modifications and alternative arrangements may be devised by those skilled in the art without departing from the spirit and scope of the present invention and the appended claims are intended to cover such modifications and arrangements. Thus, while the present invention has been described above with particularity and detail in connection with what is presently deemed to be the most practical and preferred embodiments of the invention, it will be apparent to those of ordinary skill in the art that numerous modifications, including, but not limited to, variations in size, materials, shape, form, function and manner of operation, assembly and use may be made without departing from the principles and concepts set forth herein.

CLAIMS

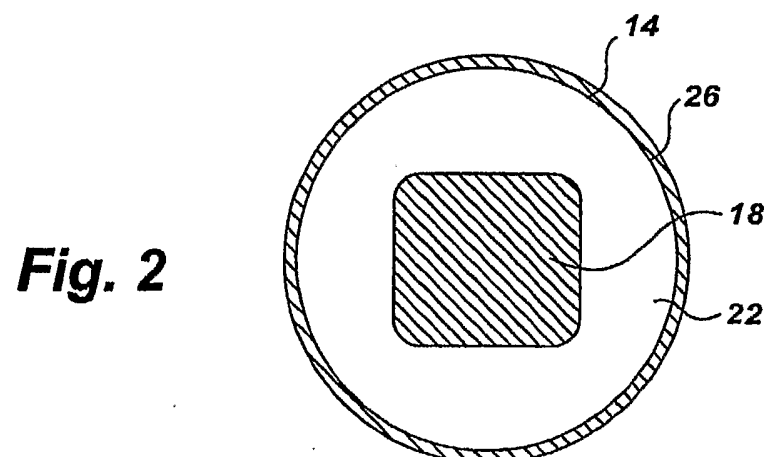
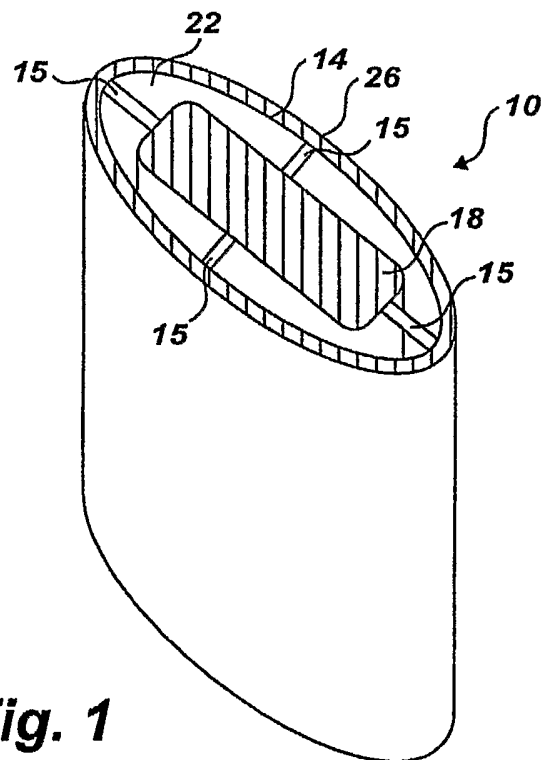
What is claimed is:

1. A fiber reinforced polymer composite structure, comprising:
 - a) a core including an inner cement structure at least partially surrounded by an outer cement structure, said outer cement structure including a non-shrink cement or an expansive cement; and
 - b) a fiber reinforced polymer material at least partially surrounding said core.
2. The composite structure of claim 1, wherein the inner cement structure has a cross-sectional shape which is different than a cross sectional shape of the core.
3. The composite structure of claim 2, wherein the inner cement structure has a rectangular shape and the core has a circular shape.
4. The composite structure of claim 1, wherein the outer cement structure consists essentially of an expansive cement.
5. The composite structure of claim 1, wherein the core is post-tensioned and has a hoop stress along the fiber reinforced polymer material.
6. The composite structure of claim 1, wherein the fiber reinforced polymer material comprises a fiber and a polymeric matrix.
7. The composite structure of claim 6, wherein the fiber is selected from the group consisting of glass fiber, carbon fiber, aramid fiber, and combinations thereof.
8. The composite structure of claim 7, wherein the fiber is carbon fiber.
9. A method of reinforcing structural columns, comprising the steps of:
 - a) placing a fiber reinforced polymer outer shell around an existing column, said outer shell being configured to leave an open space between the existing column and the outer shell;
 - b) filling the open space with expansive cement or non-shrink cement.

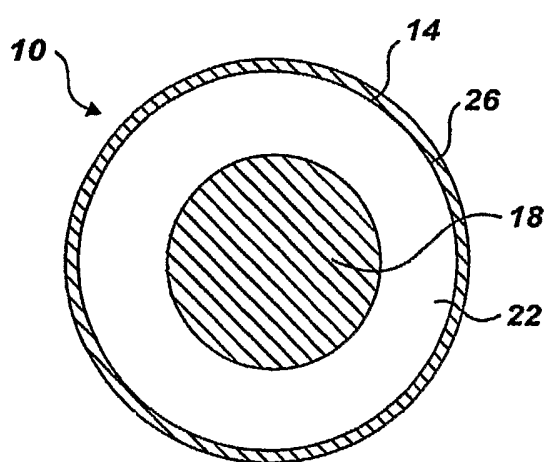
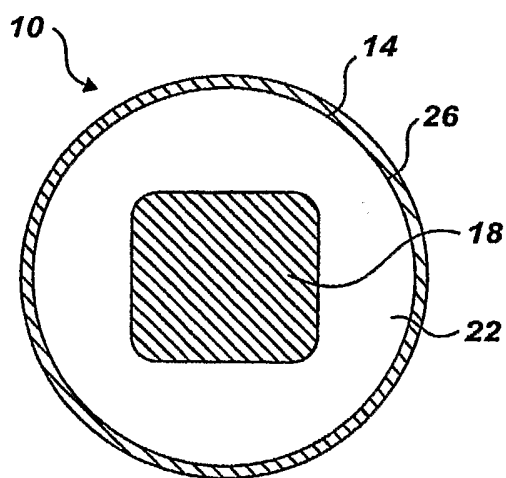
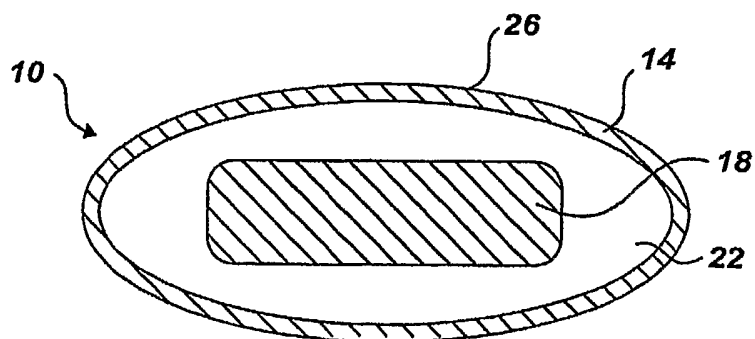
10. The method of claim 9, wherein the existing column has a cross-sectional shape which is different than a cross-sectional shape of the outer shell.
11. The method of claim 9, wherein the fiber reinforced polymer outer shell comprises a fiber and a polymeric matrix.
12. The method of claim 11, wherein the fiber is selected from the group consisting of glass fiber, carbon fiber, aramid fiber, and combinations thereof.
13. The method of claim 9, wherein the outer shell comprises at least two pieces which are placed around the existing column to form the outer shell.
14. The method of claim 13, wherein at least one additional layer of fiber reinforced polymer material is wrapped around the outer shell after placing the fiber reinforced polymer outer shell around the existing column.
15. The method of claim 13, further comprising the step of splicing the at least two pieces with a vertical fiber reinforced polymer composite strip along each seam between the at least two pieces.
16. The method of claim 9, further comprising the step of reshaping the existing column prior to placing the fiber reinforced polymer outer shell such that edges of the existing column having an angle of about 90 degrees are rounded.
17. The method of claim 9, further comprising the steps of:
 - a) preparing a mold
 - b) wrapping the mold with at least one layer of fiber reinforced polymer material to form the outer shell;
 - c) dividing the outer shell longitudinally into at least two pieces;
18. The method of claim 9, further comprising the step of designing the fiber reinforced outer shell prior to the step of placing the fiber reinforced outer shell around the existing column, said step of designing including:

- a) defining a core finite element model in three dimensions corresponding to the core of the composite structure;
 - b) defining a jacket finite element model along an outer surface of the core finite element model;
 - c) defining boundary conditions for each of the core and jacket finite element models;
 - d) post-tensioning the jacket finite element model by applying an equivalent thermal gradient; and
 - e) performing finite element analysis by incremental application of a simulated load and subsequent iteration calculate force and displacement of each node within each finite element model to form a stress-strain curve; and
 - f) comparing the stress-strain curve to a desired performance and redefining the jacket finite element model and the boundary conditions when the stress-strain curve does not meet the desired performance.
19. A method of preparing fiber reinforced polymer shells for reinforcing structural columns, comprising the steps of:
- a) preparing a mold;
 - b) wrapping the mold with at least one layer of fiber reinforced polymer material to form an outer shell; and
 - c) dividing the outer shell longitudinally into at least two pieces.
20. The method of claim 19, wherein the step of wrapping the mold includes a wet layup of resin coated fibers followed by curing of the resin.
21. The method of claim 19, wherein the fiber reinforced polymer material comprises a fiber and a polymeric matrix.
22. The method of claim 21, wherein the fiber is selected from the group consisting of glass fiber, carbon fiber, aramid fiber, and combinations thereof.
23. The method of claim 21, wherein the fiber is in the form of a sheet or a strand.

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**Fig. 3a****Fig. 3b****Fig. 3c**

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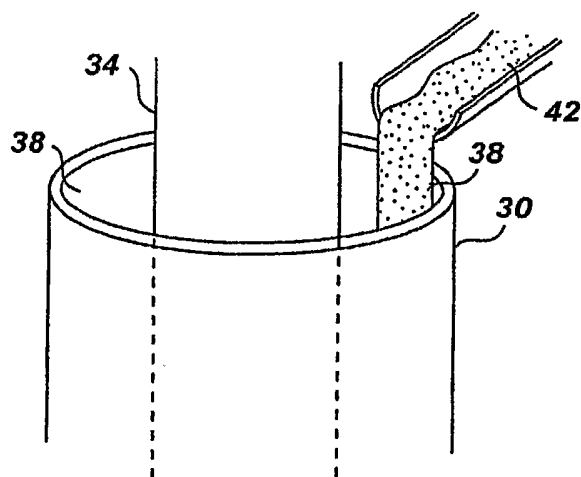


Fig. 4

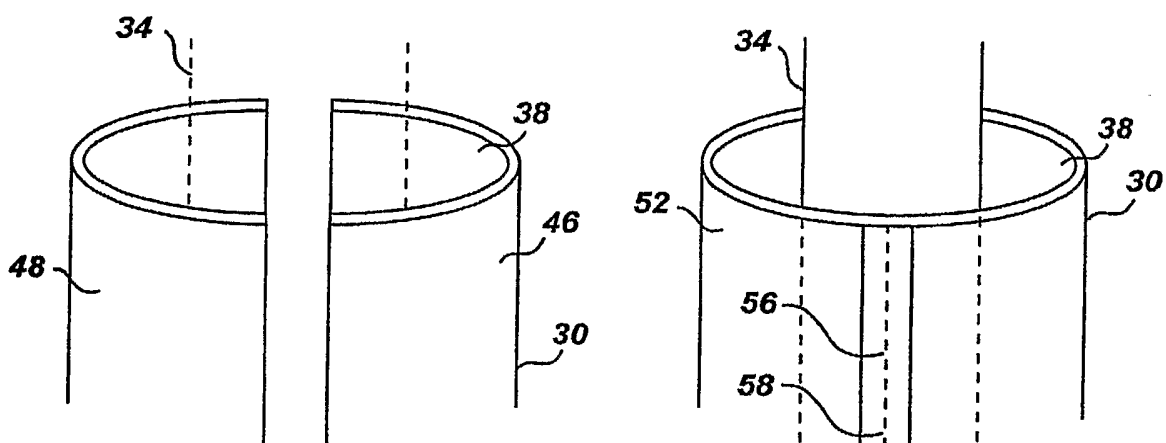


Fig. 5

Fig. 6

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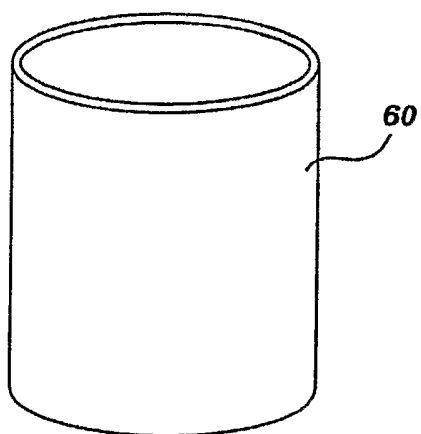


Fig. 7a

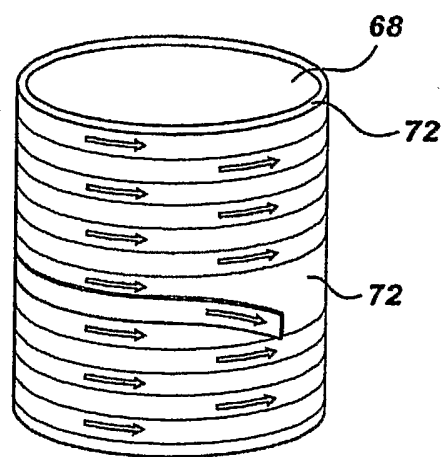


Fig. 7b

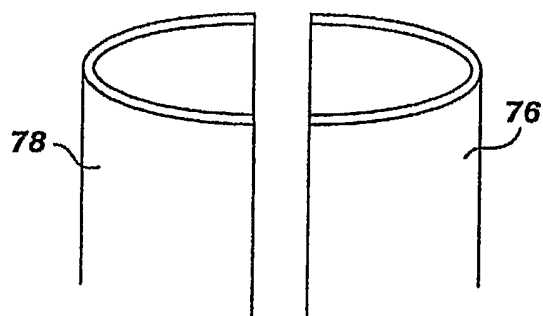


Fig. 7c

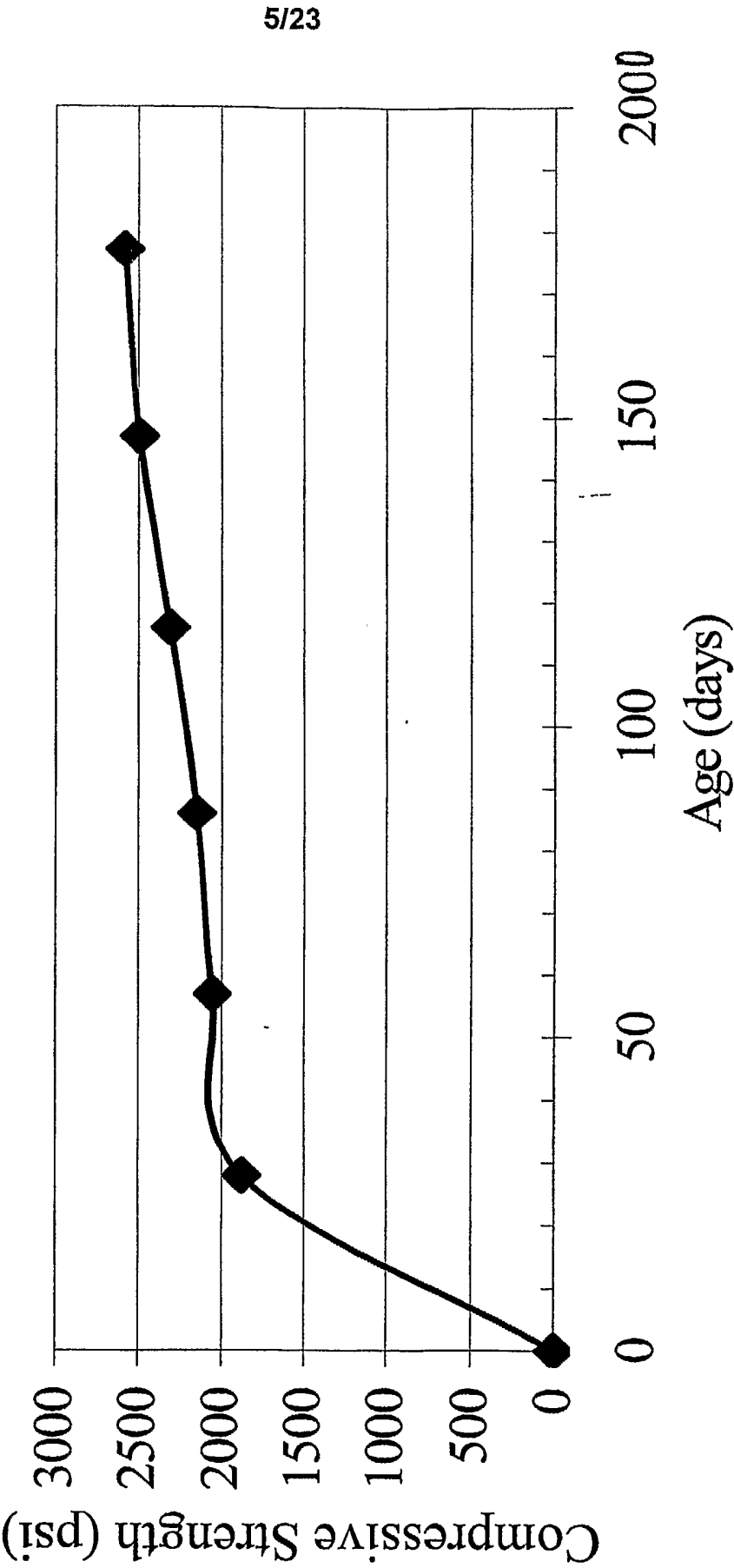


FIG. 8

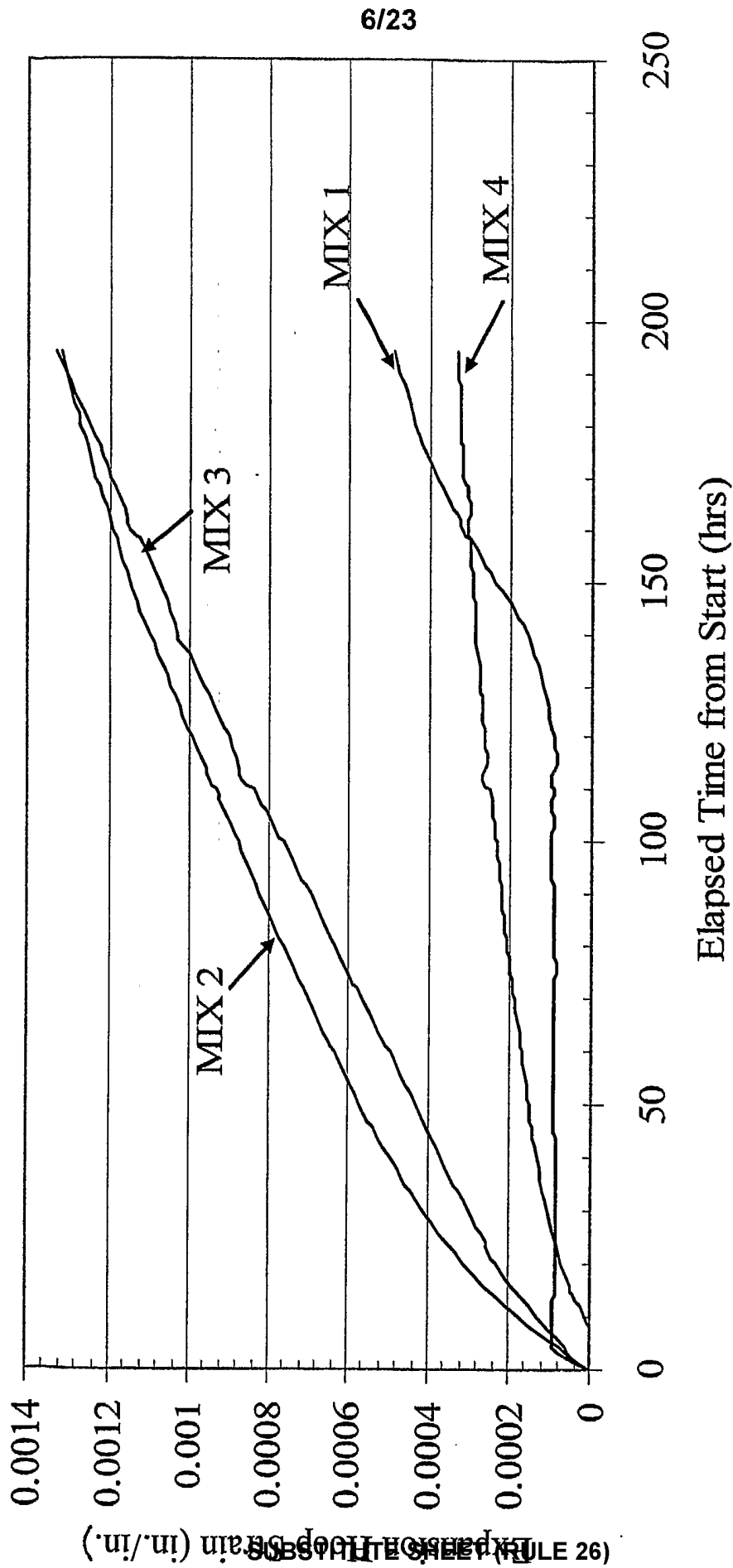


FIG. 9

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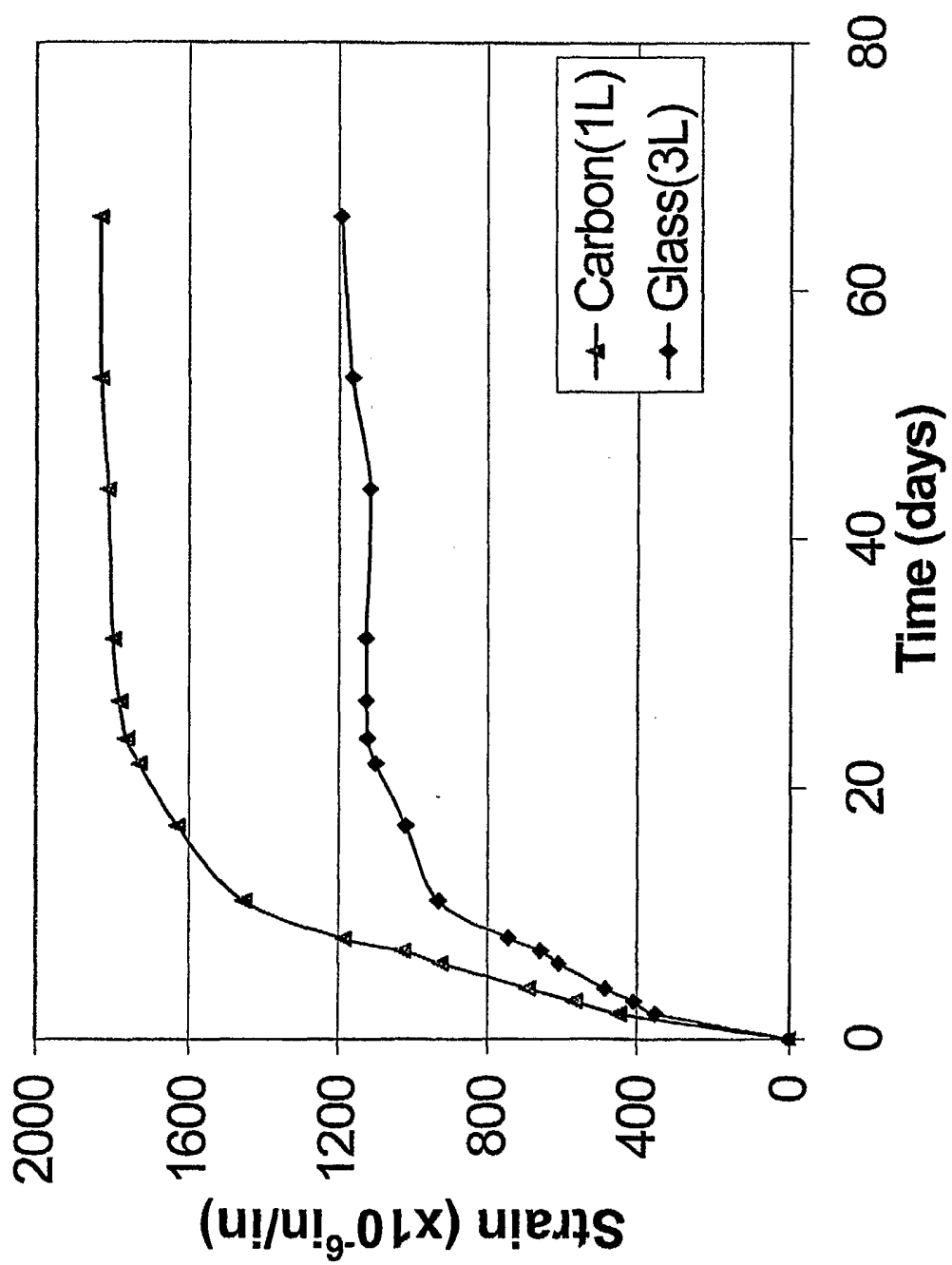


FIG. 10A

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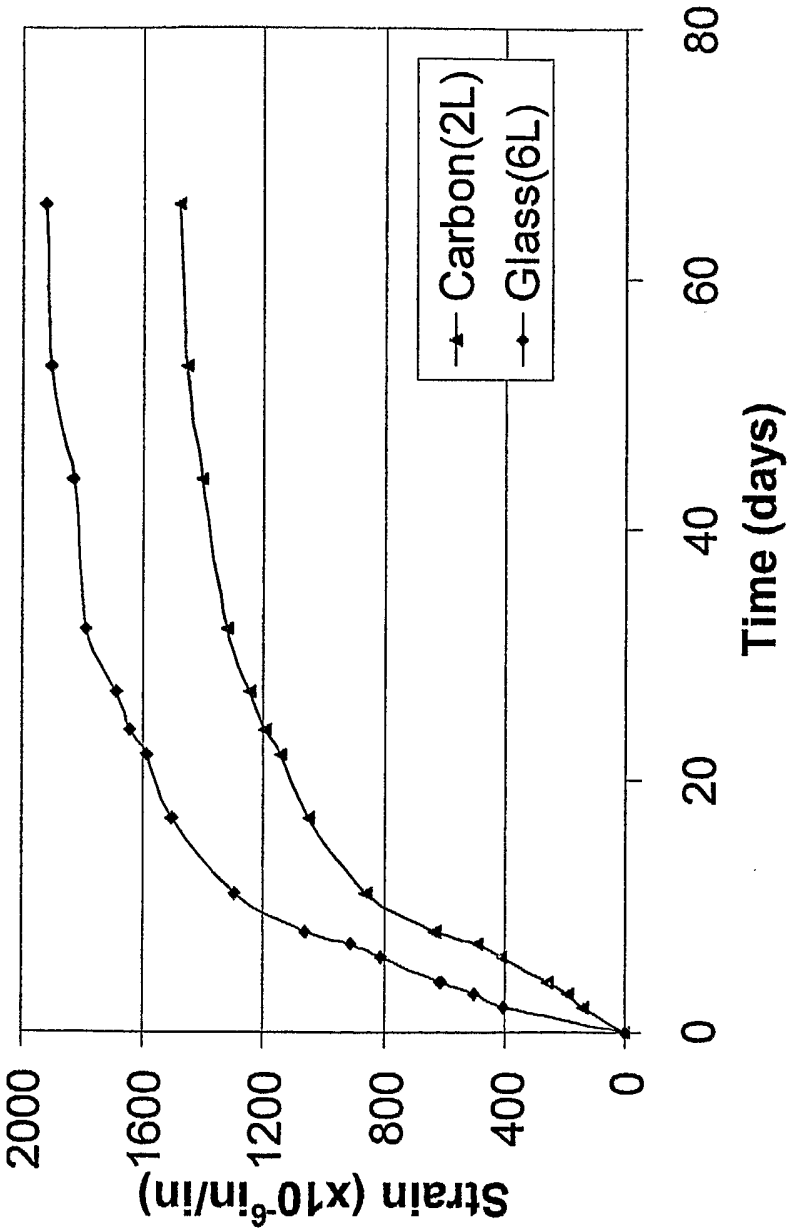


FIG. 10B

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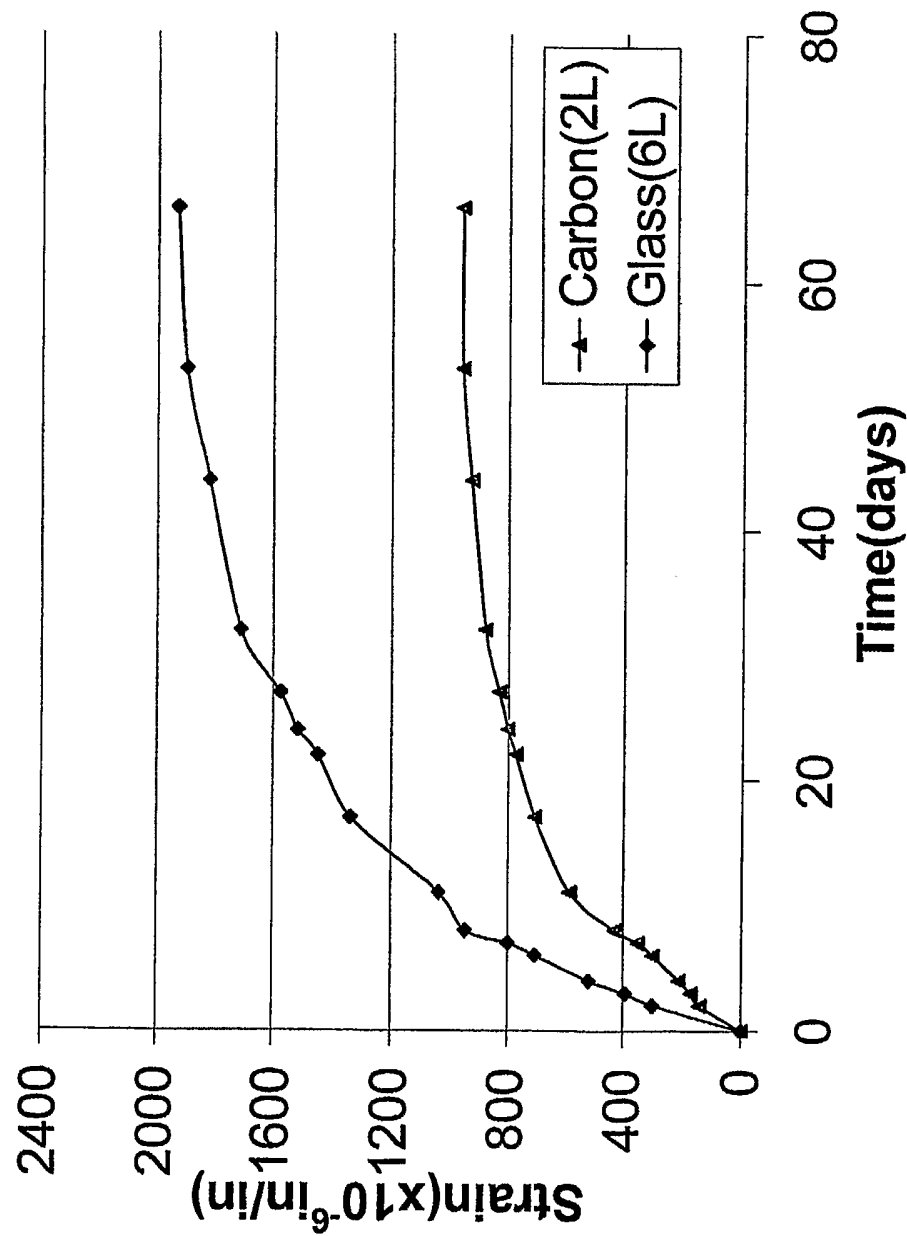


FIG. 10C

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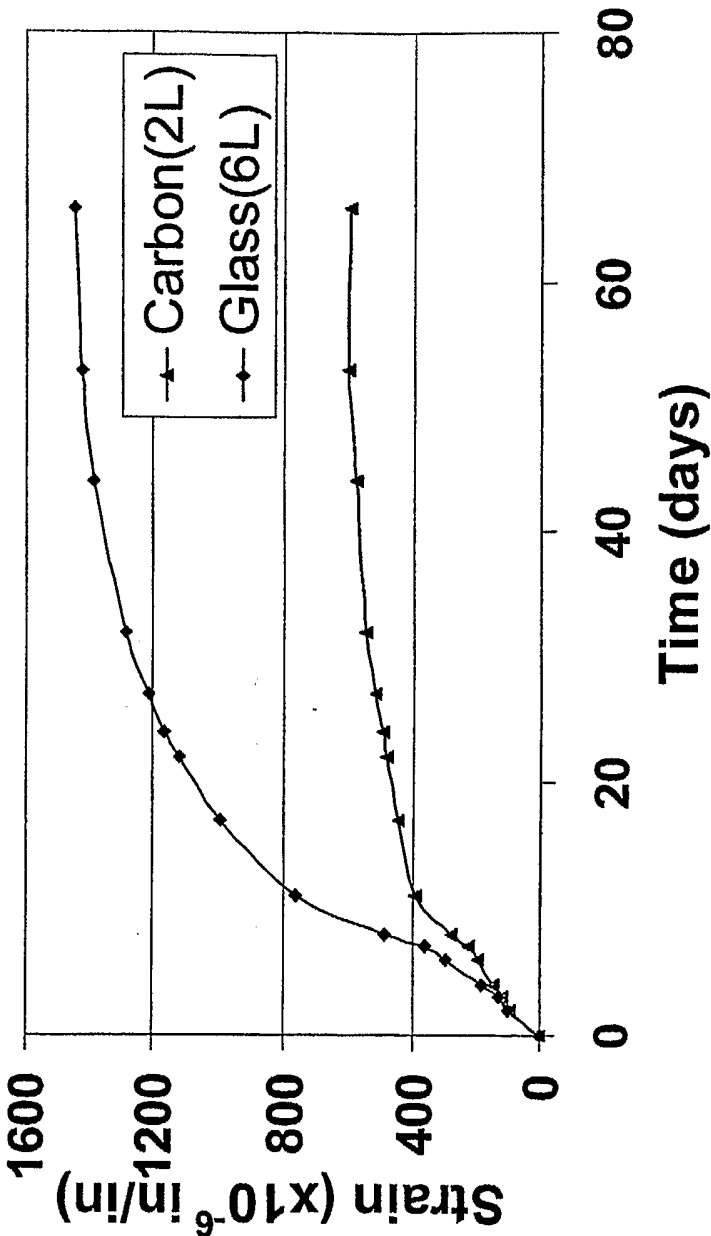
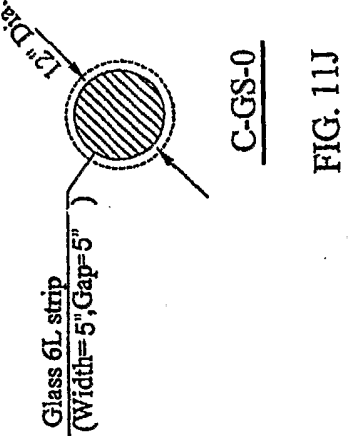
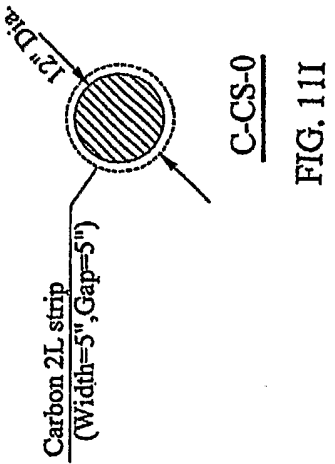
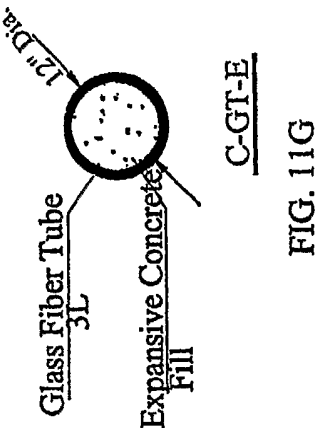
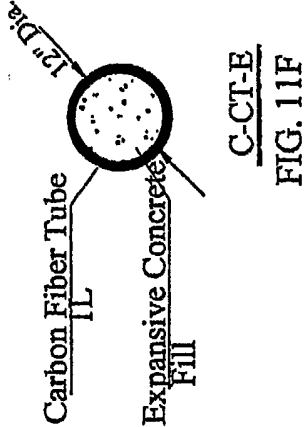
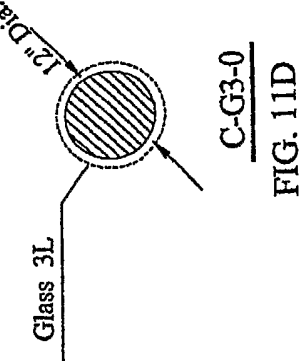
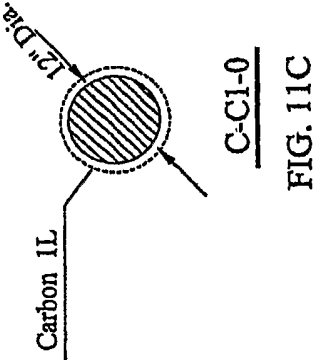
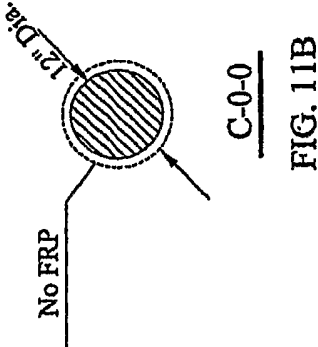
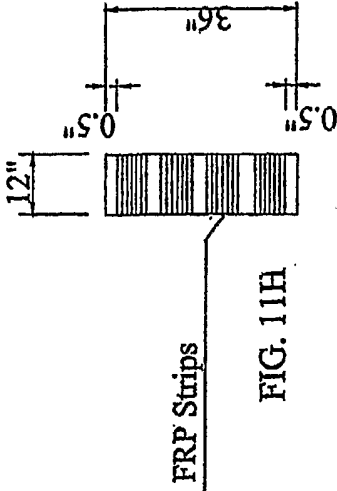
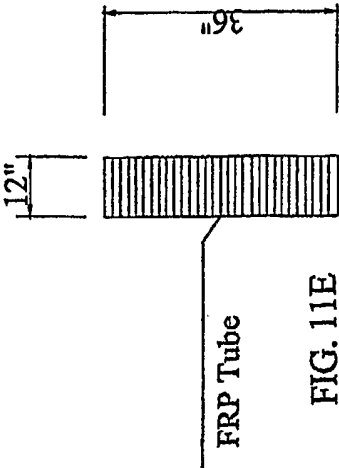
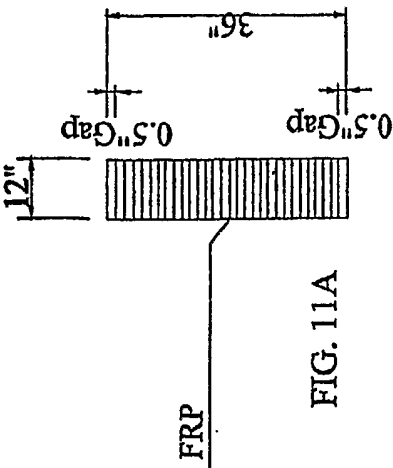


FIG. 10D



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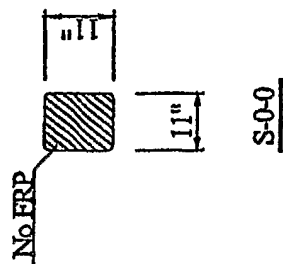
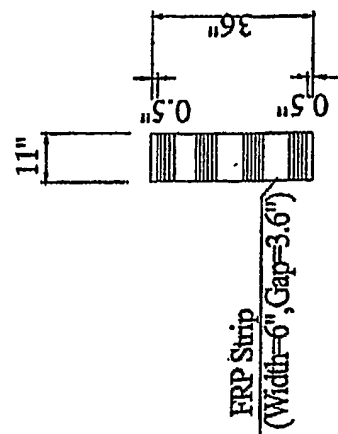
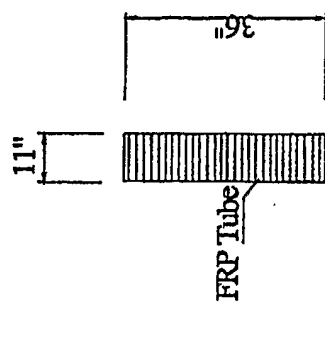
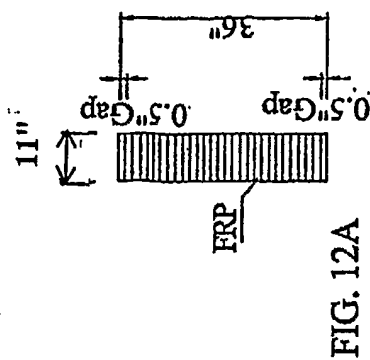


FIG. 12C

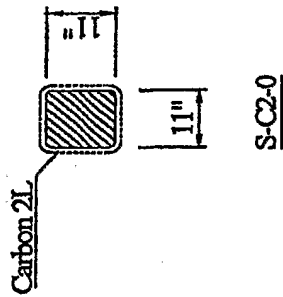


FIG. 12D

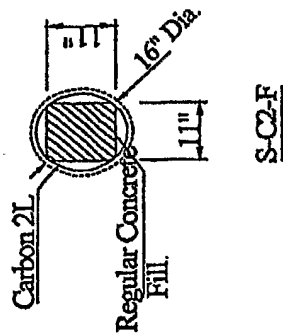


FIG. 12E

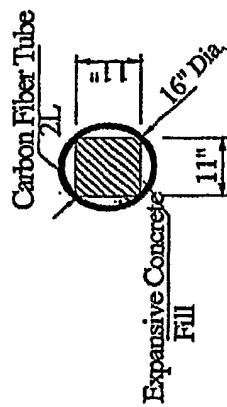
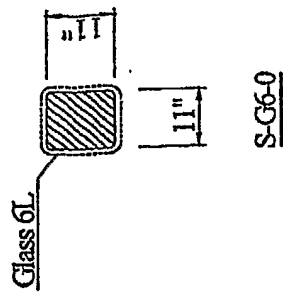


FIG. 12I

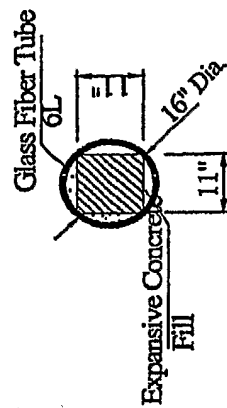


FIG. 12L

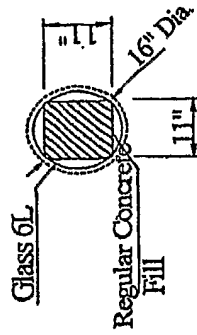


FIG. 12K

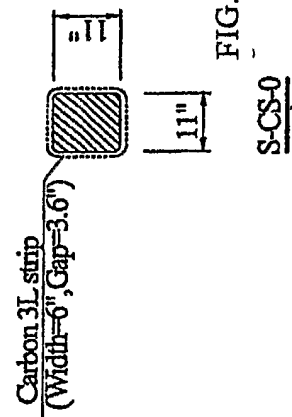
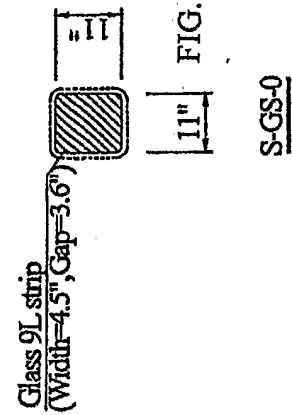
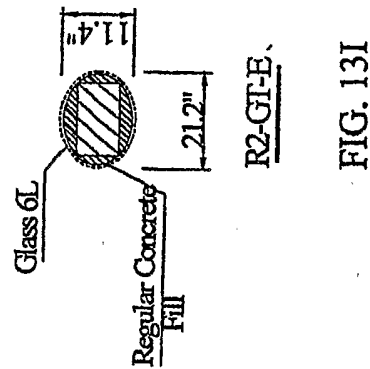
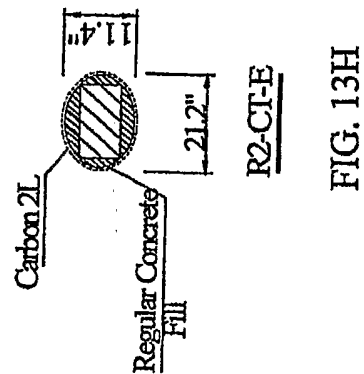
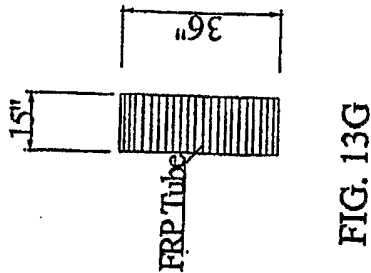
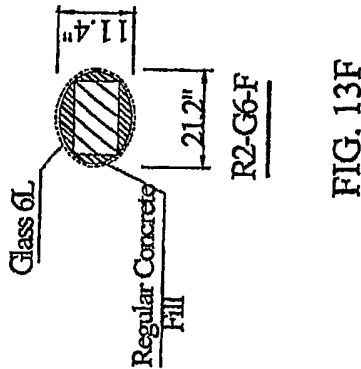
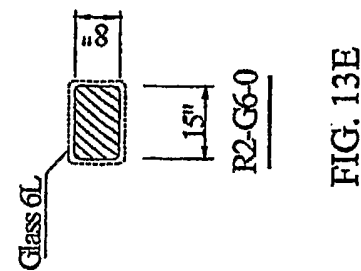
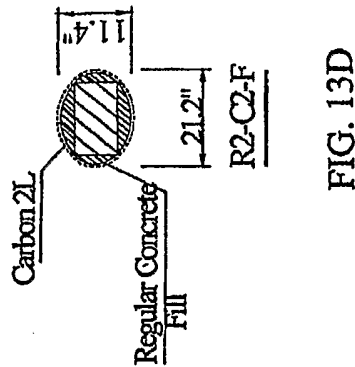
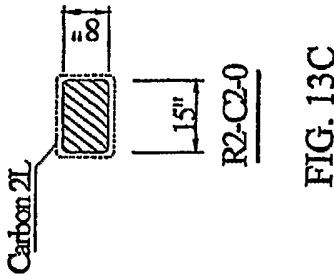
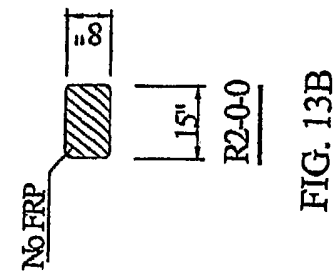
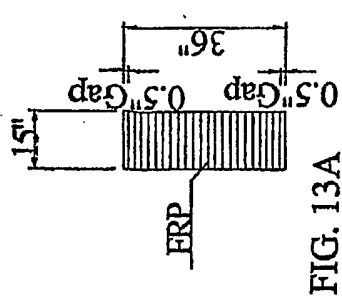


FIG. 12M





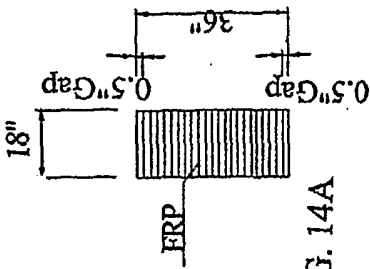


FIG. 14A

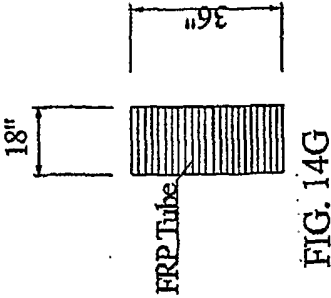


FIG. 14G

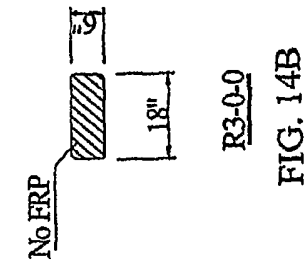


FIG. 14B

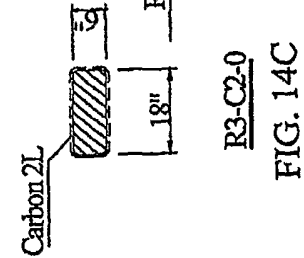


FIG. 14C

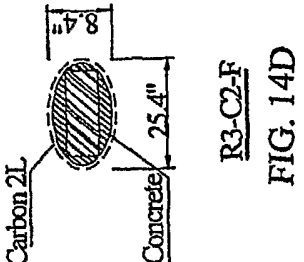


FIG. 14D

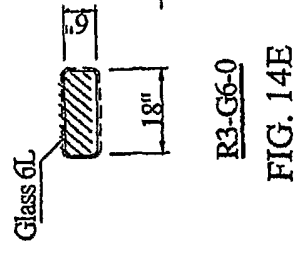


FIG. 14E

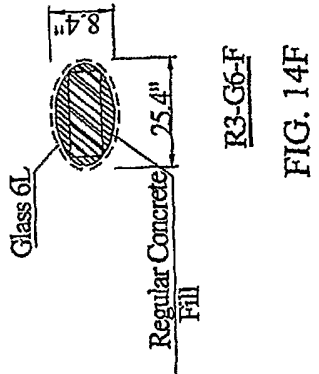


FIG. 14F

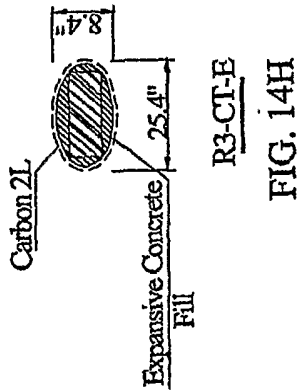


FIG. 14H

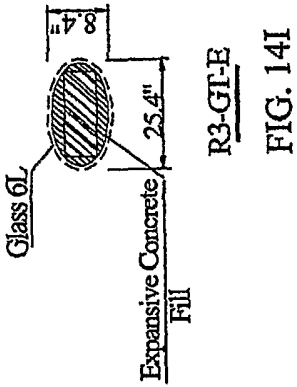
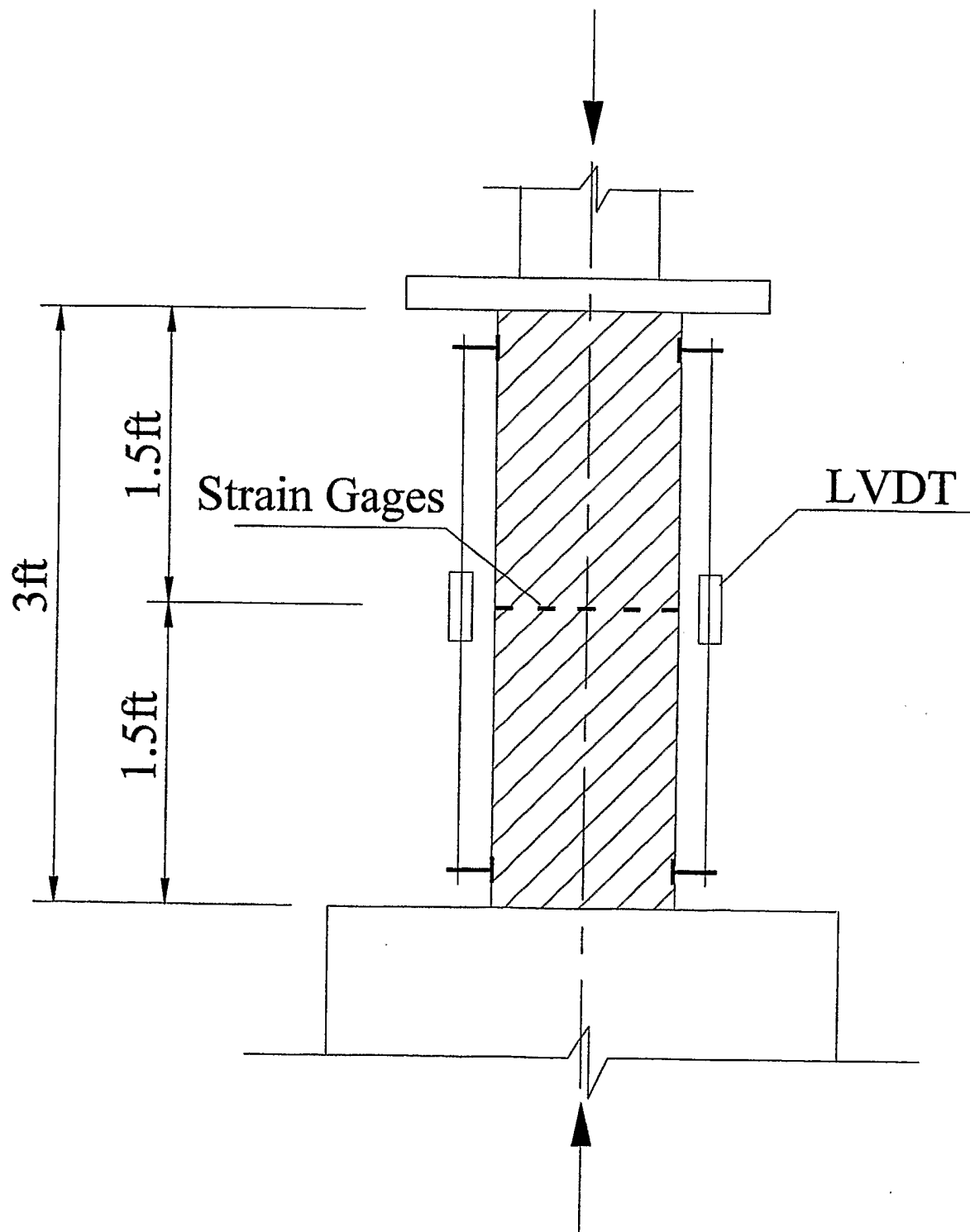


FIG. 14I

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Load From High-stiffness
Compression Machine



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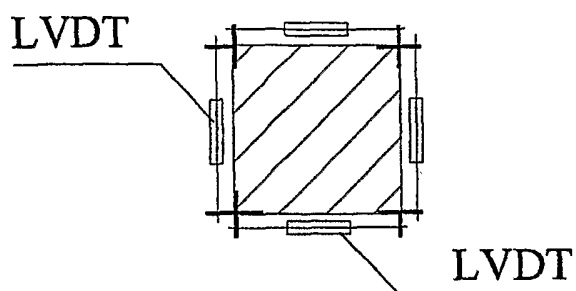


FIG. 16A

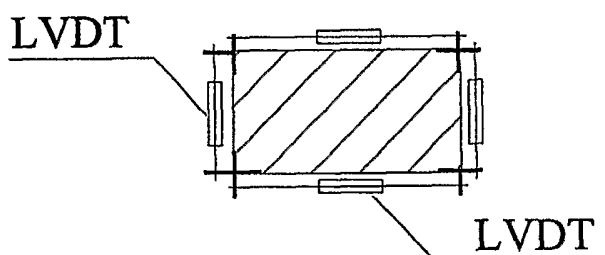


FIG. 16B

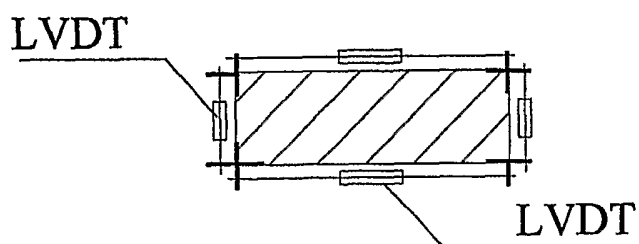


FIG. 16C

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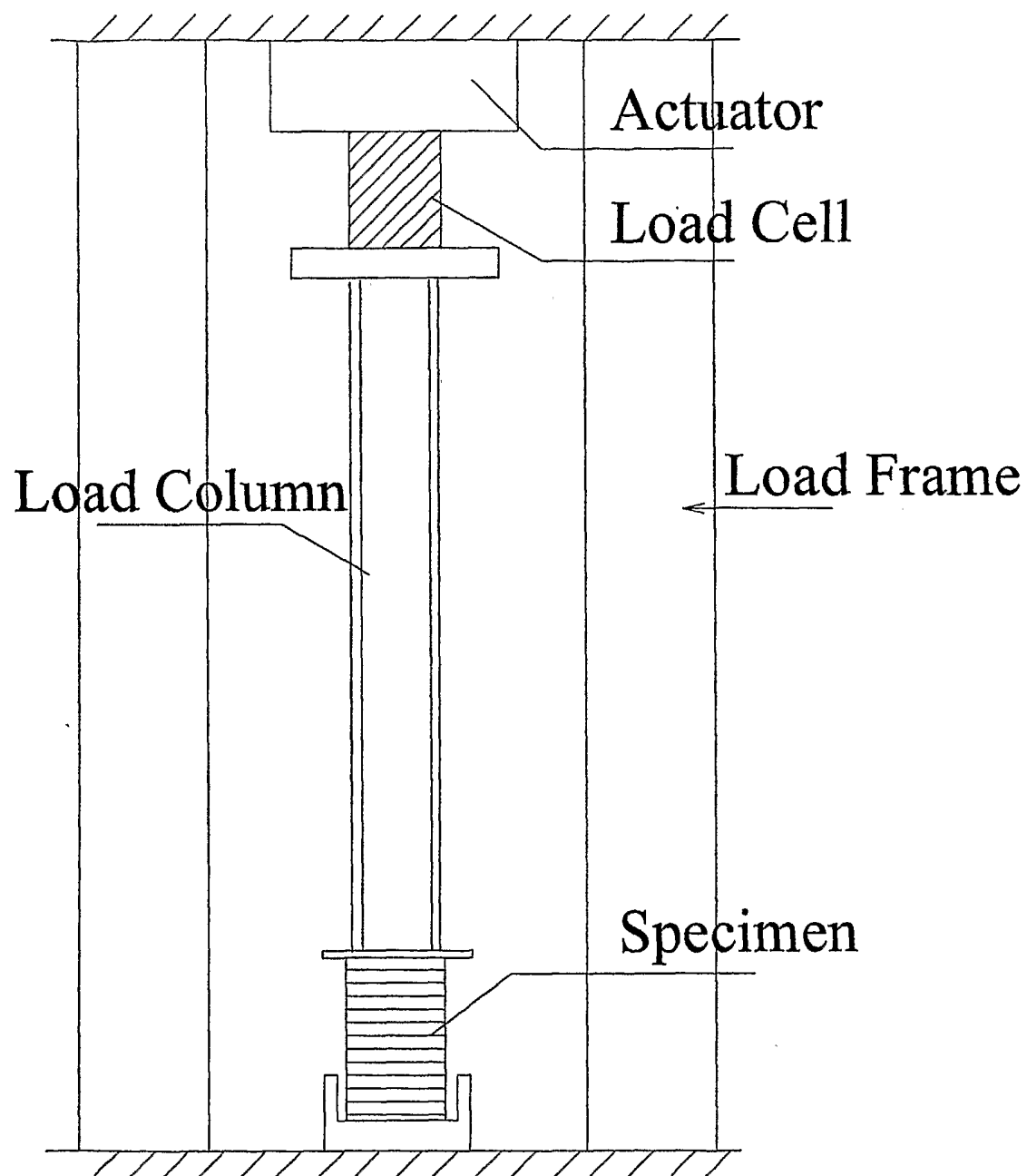


FIG. 17

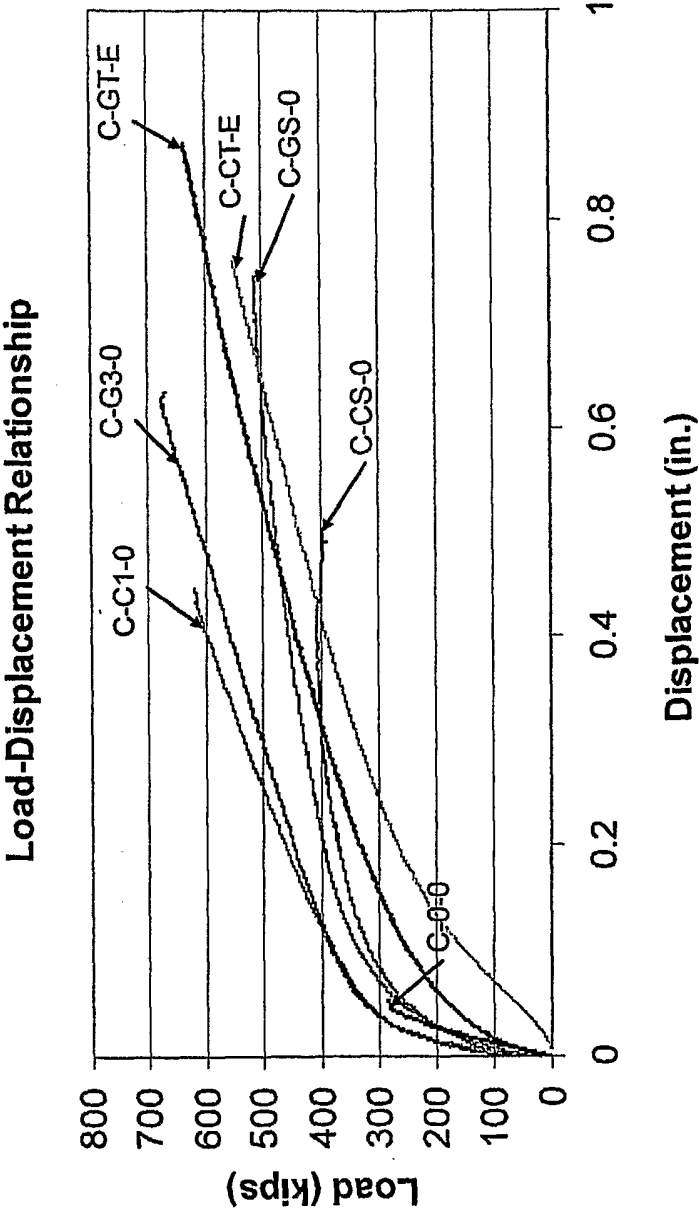


FIG. 18

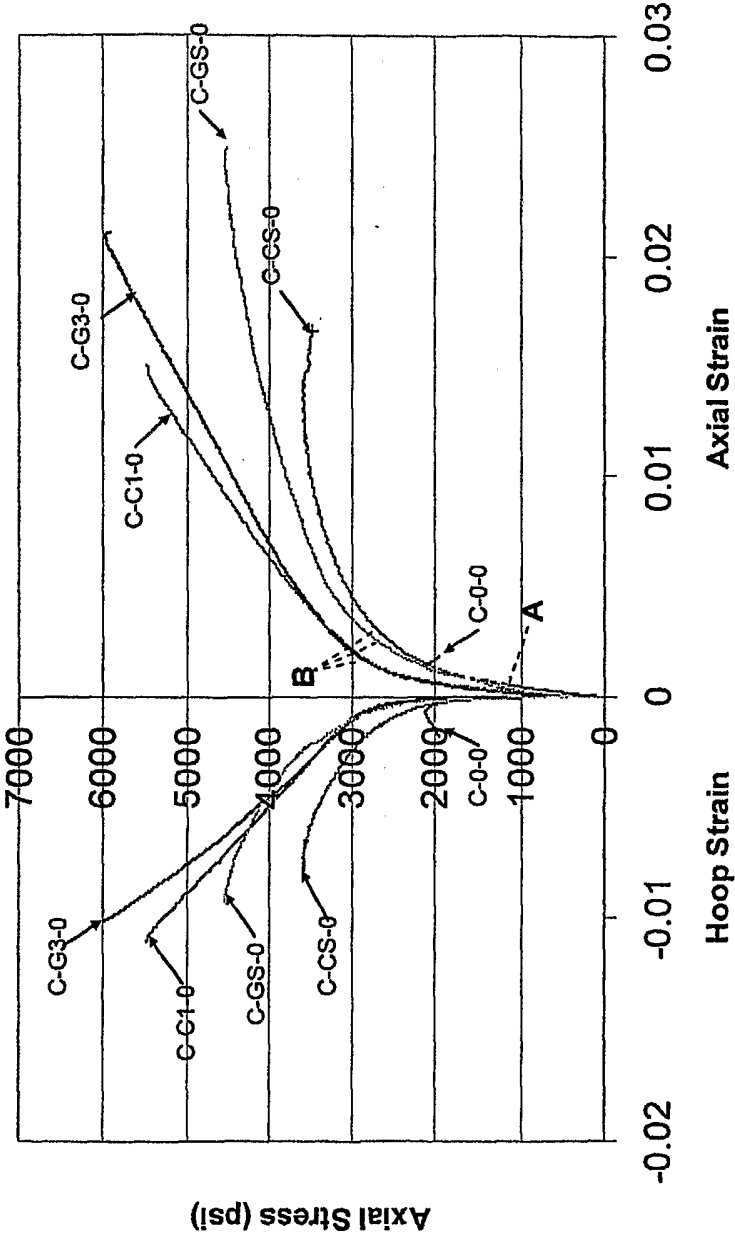


FIG. 19

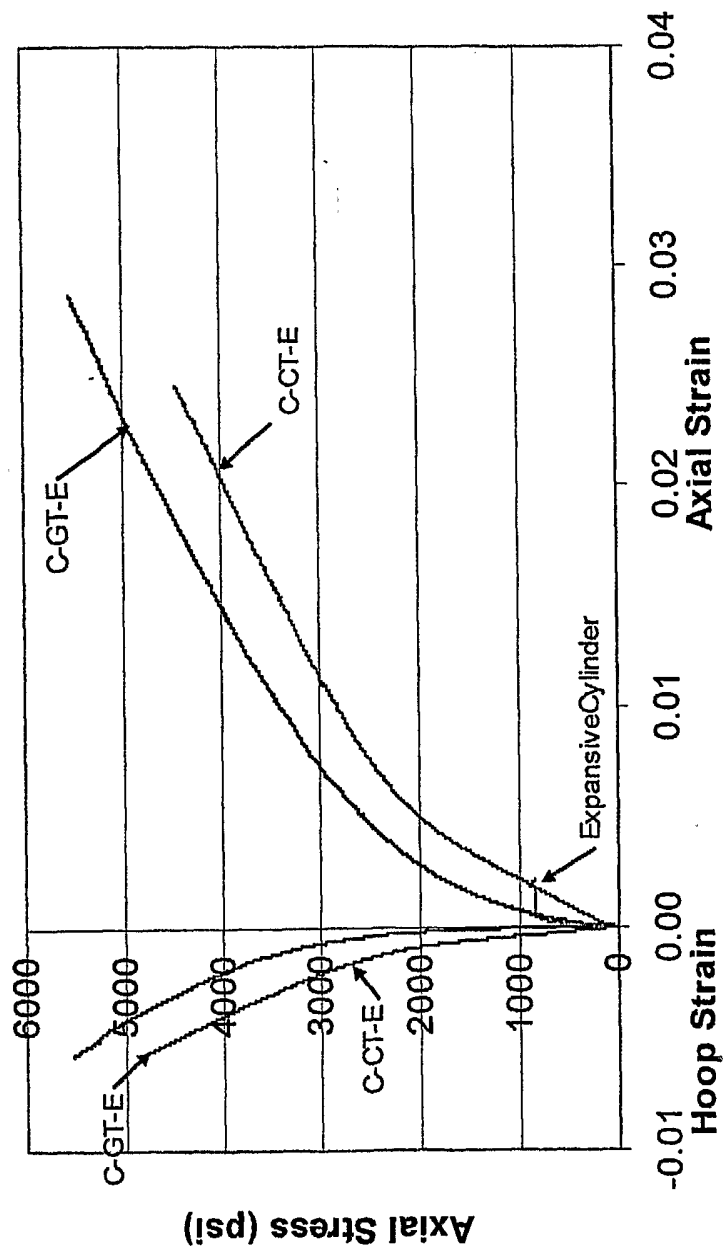


FIG. 20

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**Comparison of Stress-Strain Relationship for
S-0-0/S-G6-0/S-GT-E**

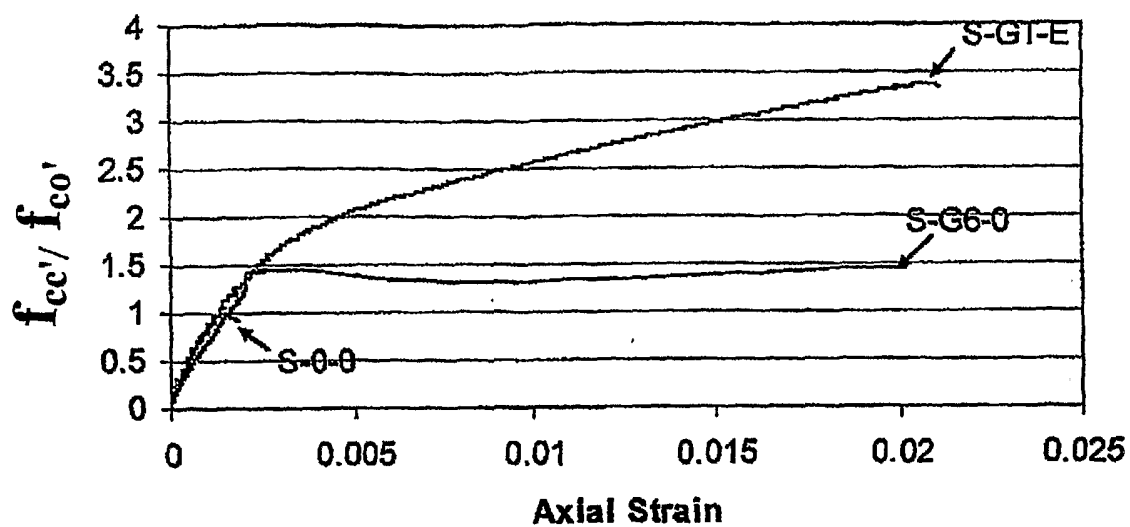
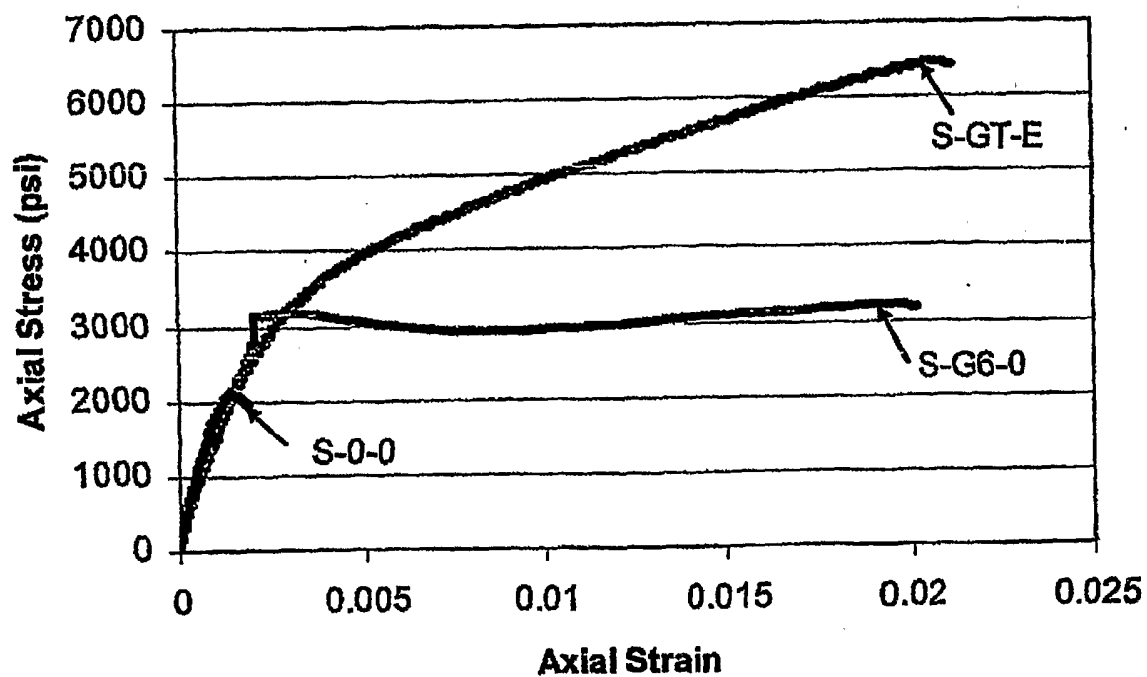


FIG. 21

**Comparison of Stress-Strain Relationship for
S-0-0/S-G6-0/S-GT-E**



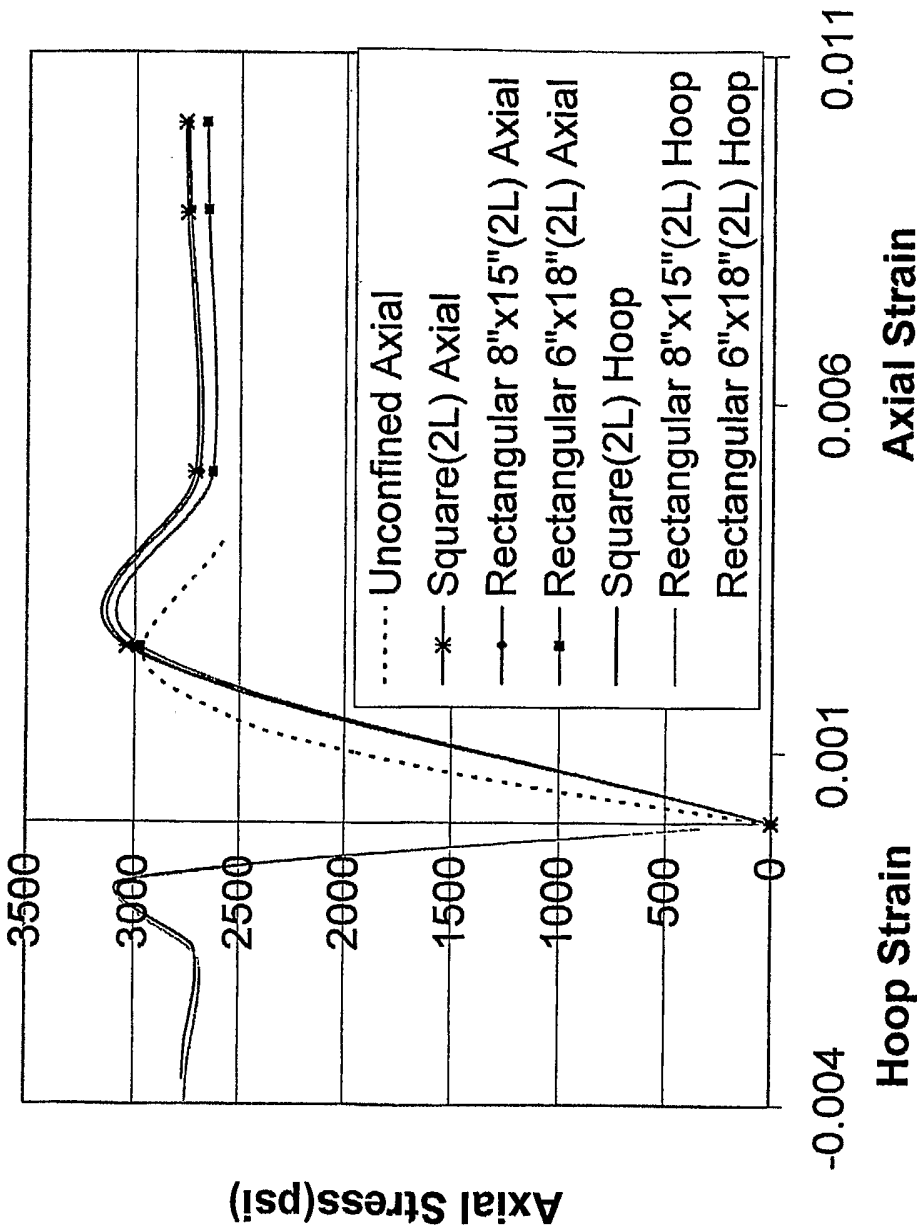


FIG. 23

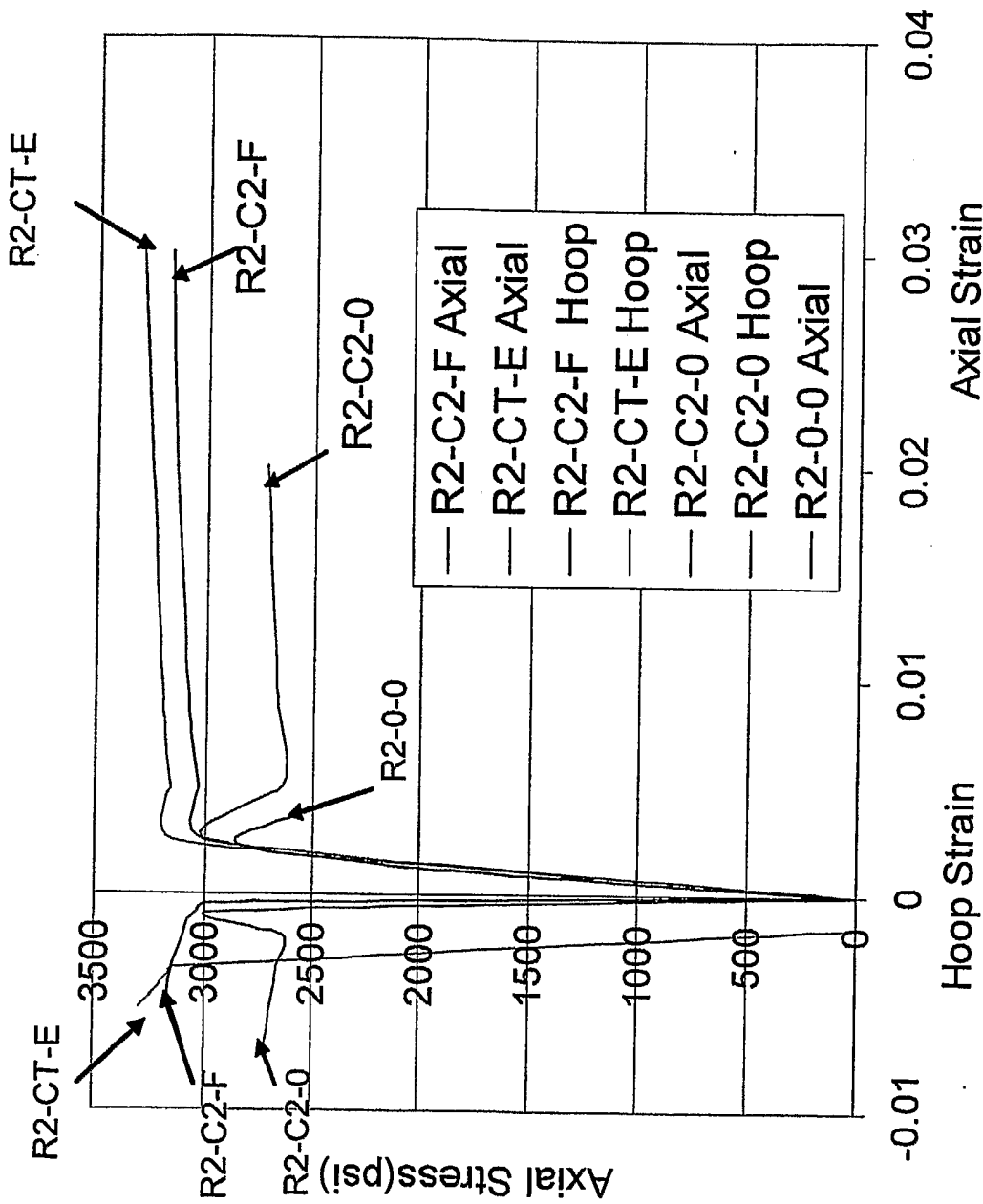


FIG. 24