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Spexarth

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(54) **SYSTEM AND METHOD OF DESIGNING A LOAD BEARING LAYER THAT INTERFACES TO A STRUCTURAL PASS-THROUGH OF AN INFLATABLE VESSEL**

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G06F 17/00	(2006.01)
B64G 1/00	(2006.01)
B64G 1/22	(2006.01)

(52) **U.S. Cl.** **703/1**; 244/158.3; 244/159.4

(58) **Field of Classification Search** 703/1
See application file for complete search history.

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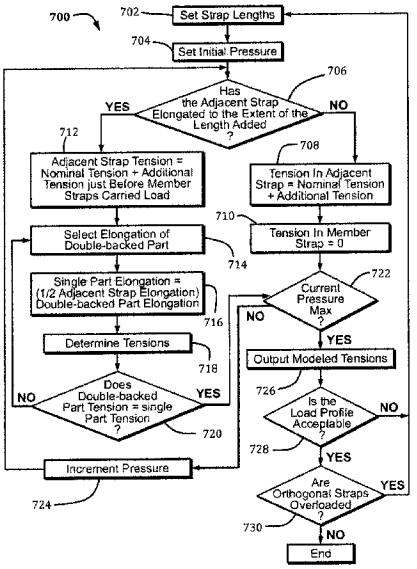
(57) **ABSTRACT**

A method for determining a design of an inflatable module including a rigid member disposed in a restraint layer, wherein the restraint layer includes orthogonal straps, includes modeling a strap adjacent to the rigid member and a strap connected to the rigid member. The adjacent strap and the member strap extend in a first direction. The method further includes selecting a first length of the member strap such that the adjacent strap carries load before the member strap during pressurization of the inflatable module, modeling tensions in the member strap with the first length and the adjacent strap during pressurization of the inflatable model, and outputting the modeled tensions in the member strap with the first length and the adjacent strap. An inflatable module includes a member strap having a length such that an adjacent strap carries load before the member strap during pressurization of the inflatable module.

29 Claims, 11 Drawing Sheets



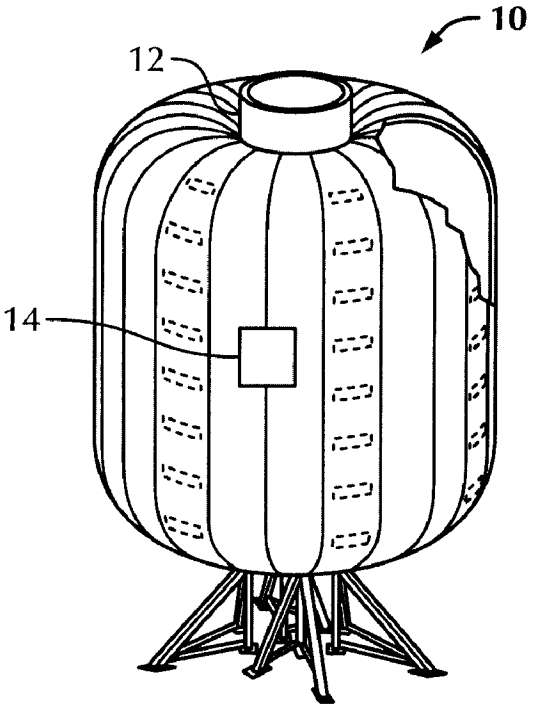


FIG. 1
(Prior Art)

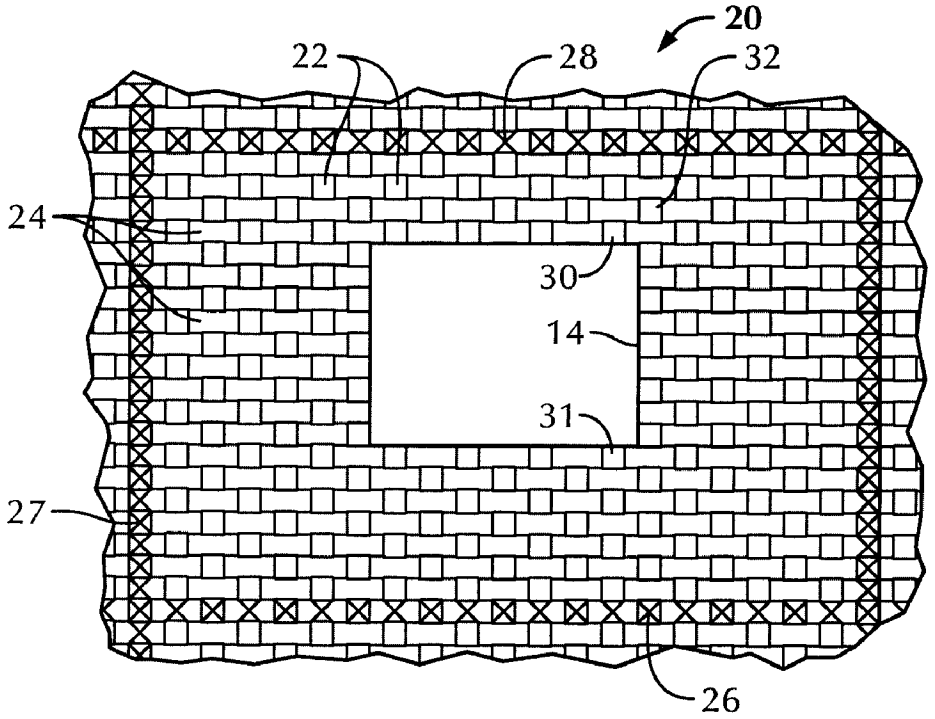


FIG. 2
(Prior Art)

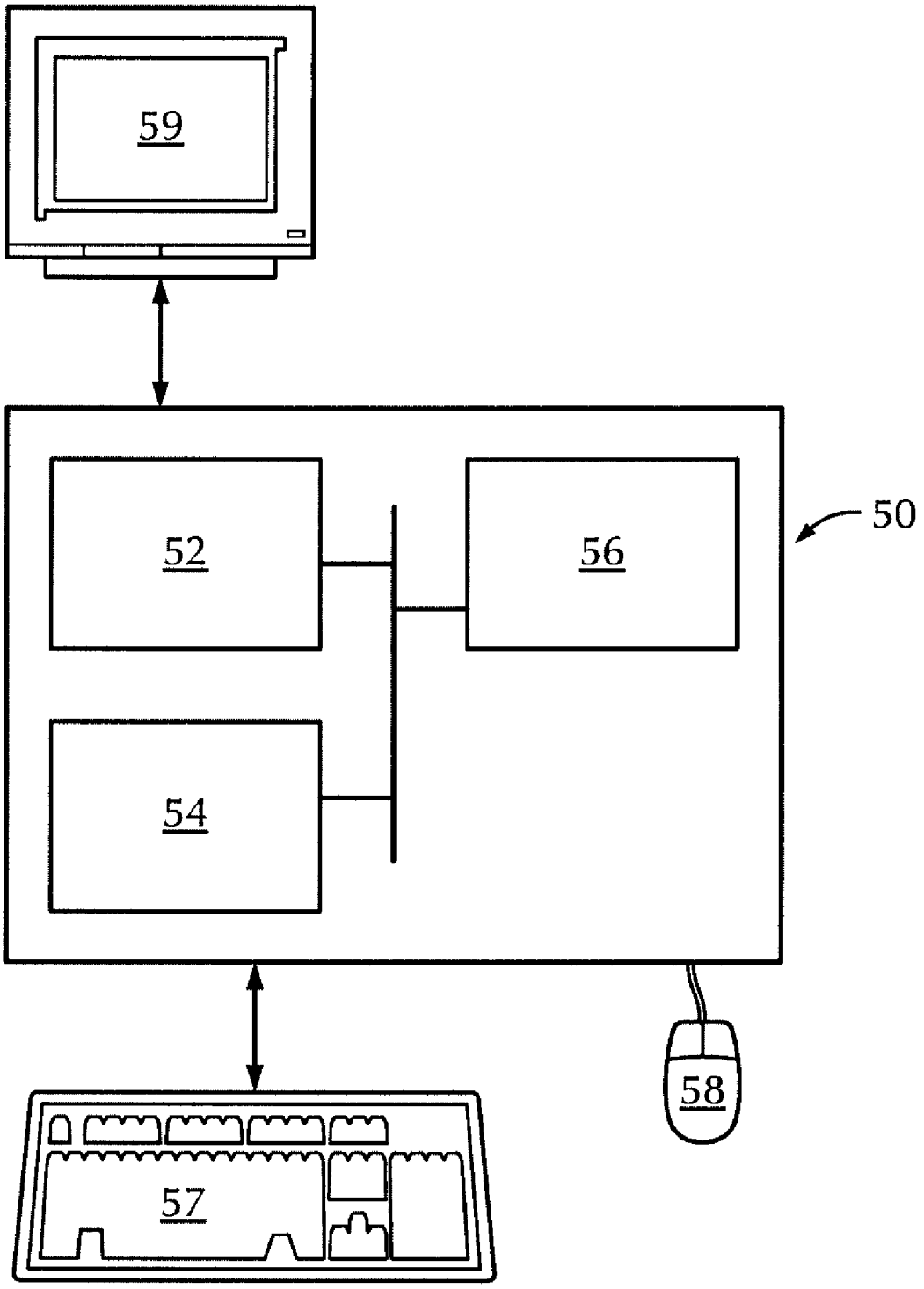


FIG. 3
(Prior Art)

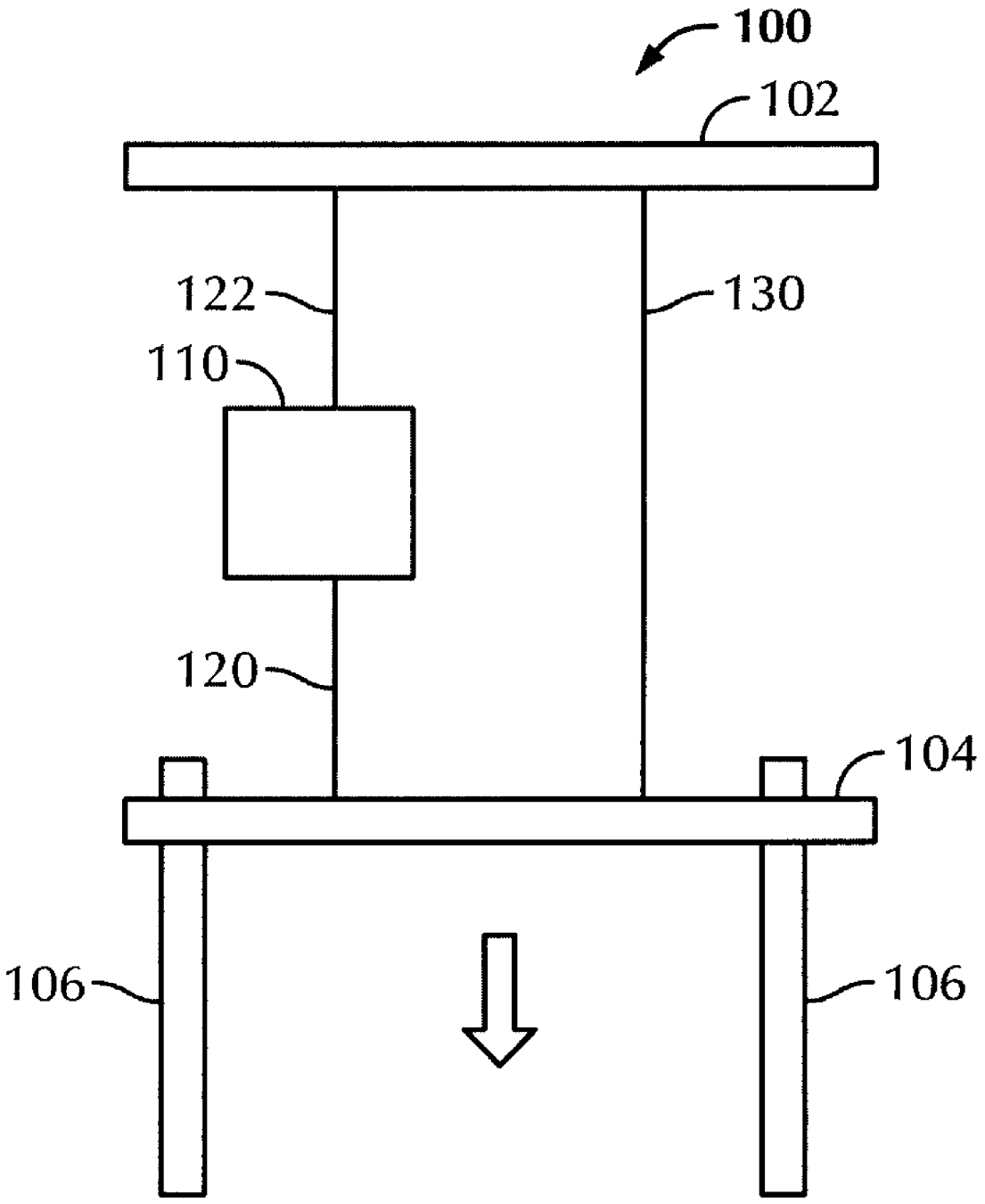


FIG. 4

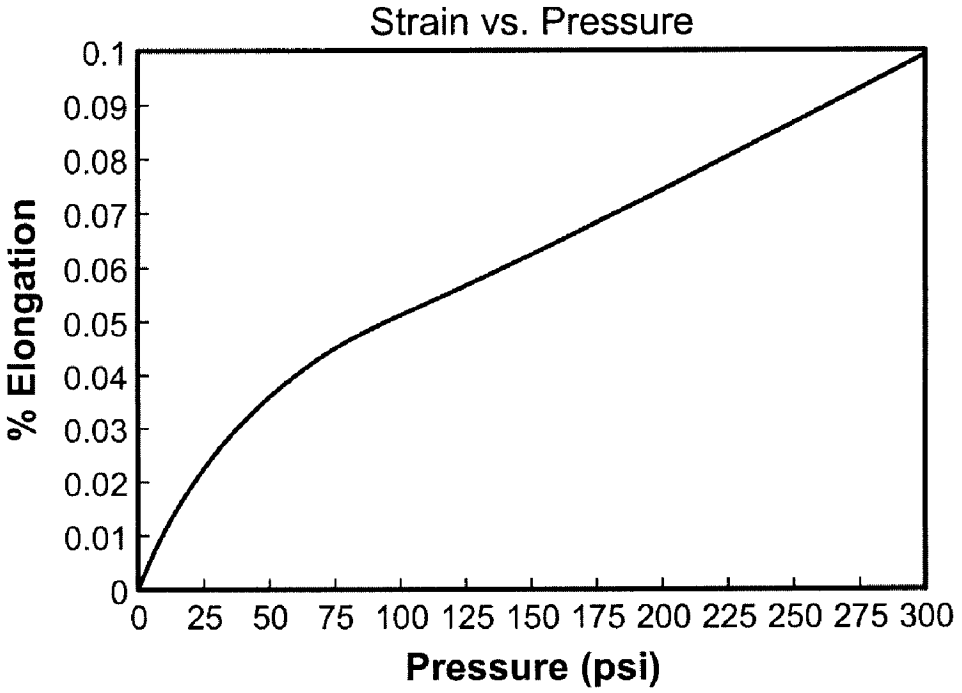

Strain vs. Pressure
% Elongation
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0 25 50 75 100 125 150 175 200 225 250 275 300
Pressure (psi)

FIG. 5A

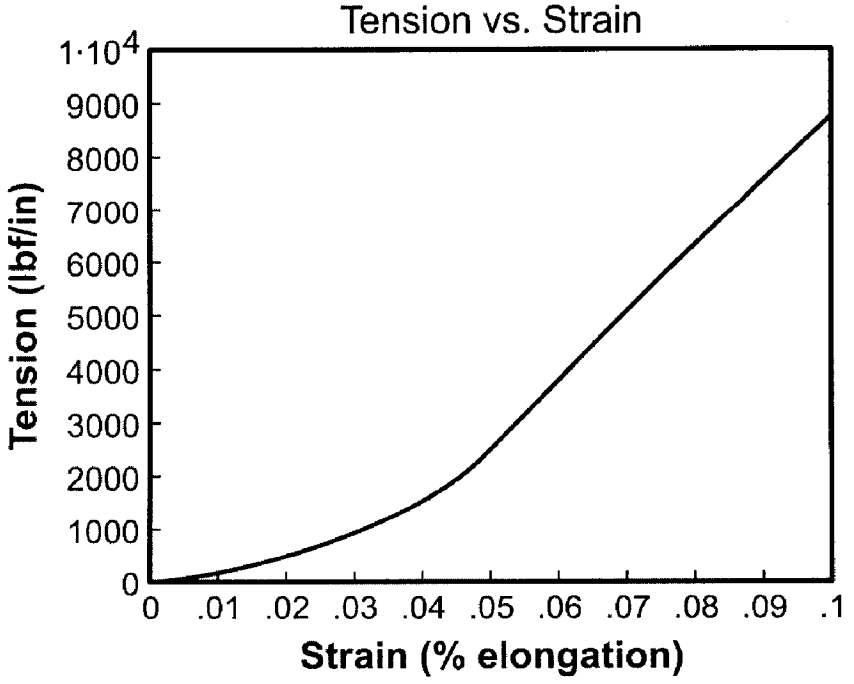

Tension vs. Strain
Tension (lbf/in)
1·10^4
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
0 .01 .02 .03 .04 .05 .06 .07 .08 .09 .1
Strain (% elongation)

FIG. 5B

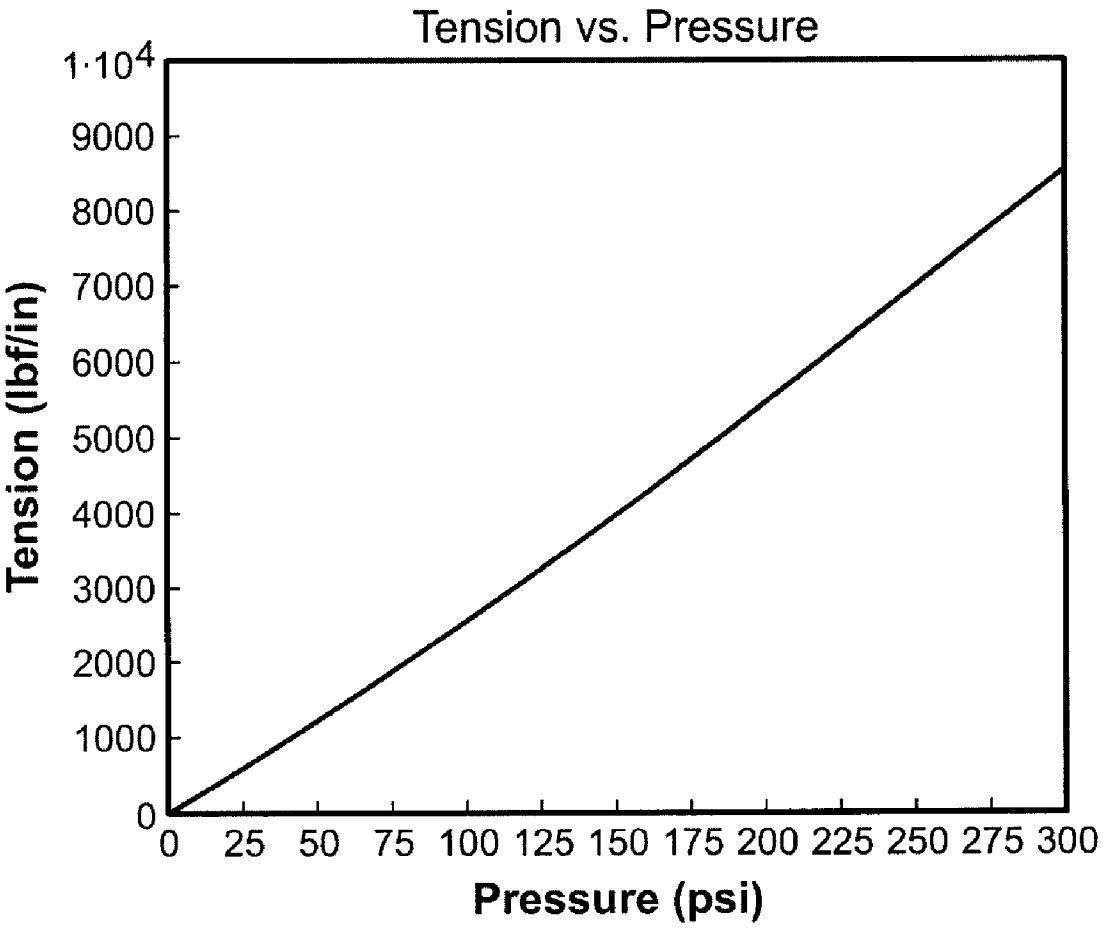

Tension vs. Pressure
1·10^4
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
Tension (lbf/in)
0 25 50 75 100 125 150 175 200 225 250 275 300
Pressure (psi)

FIG. 6

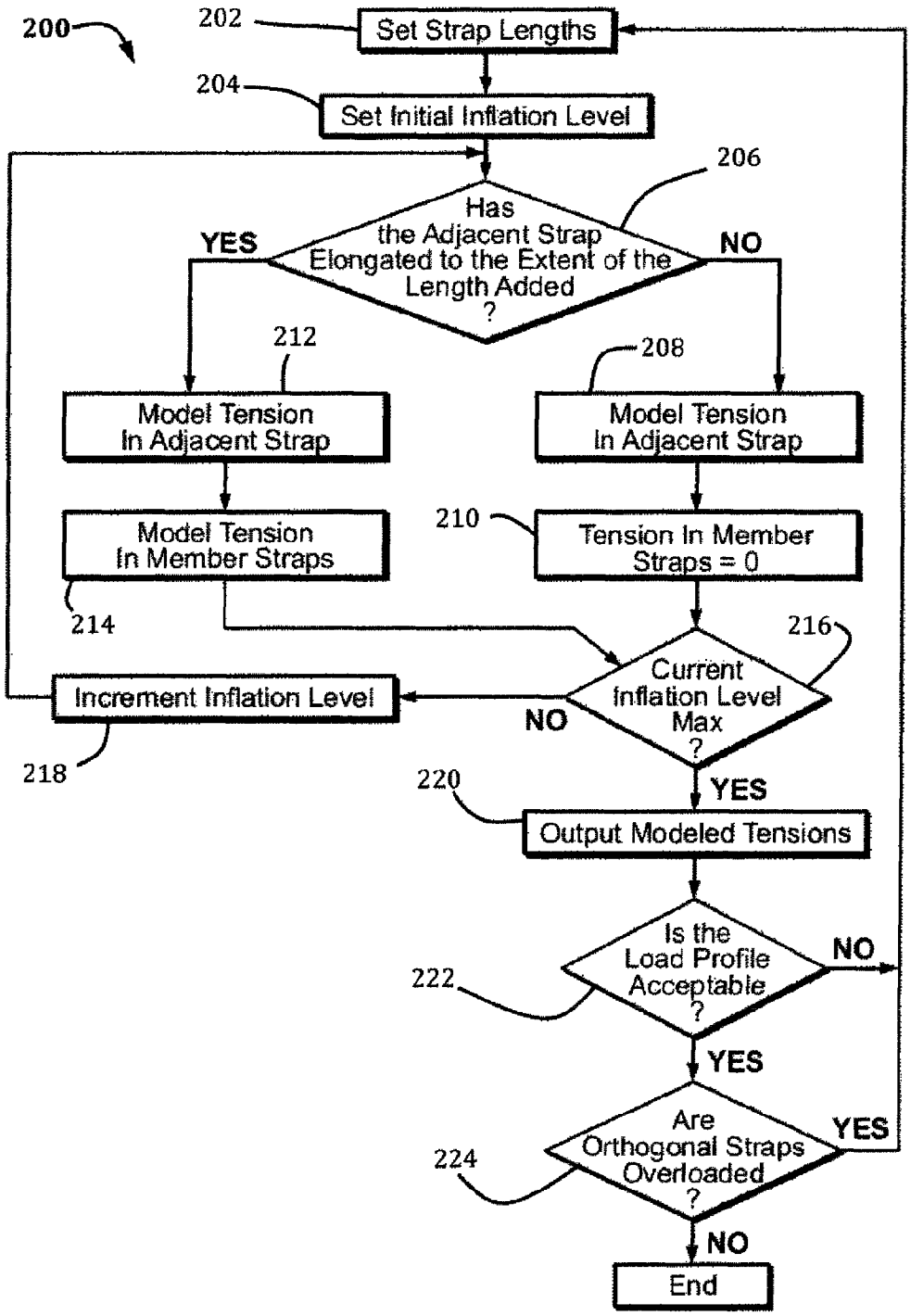

200
202
Set Strap Lengths
204
Set Initial Inflation Level
206
Has the Adjacent Strap Elongated to the Extent of the Length Added ?
YES
NO
212
Model Tension In Adjacent Strap
208
Model Tension In Adjacent Strap
Model Tension In Member Straps
210
Tension In Member Straps = 0
214
216
Current Inflation Level Max ?
Increment Inflation Level
NO
218
YES
220
Output Modeled Tensions
Is the Load Profile Acceptable ?
NO
222
YES
Are Orthogonal Straps Overloaded ?
YES
224
NO
End

FIG. 7

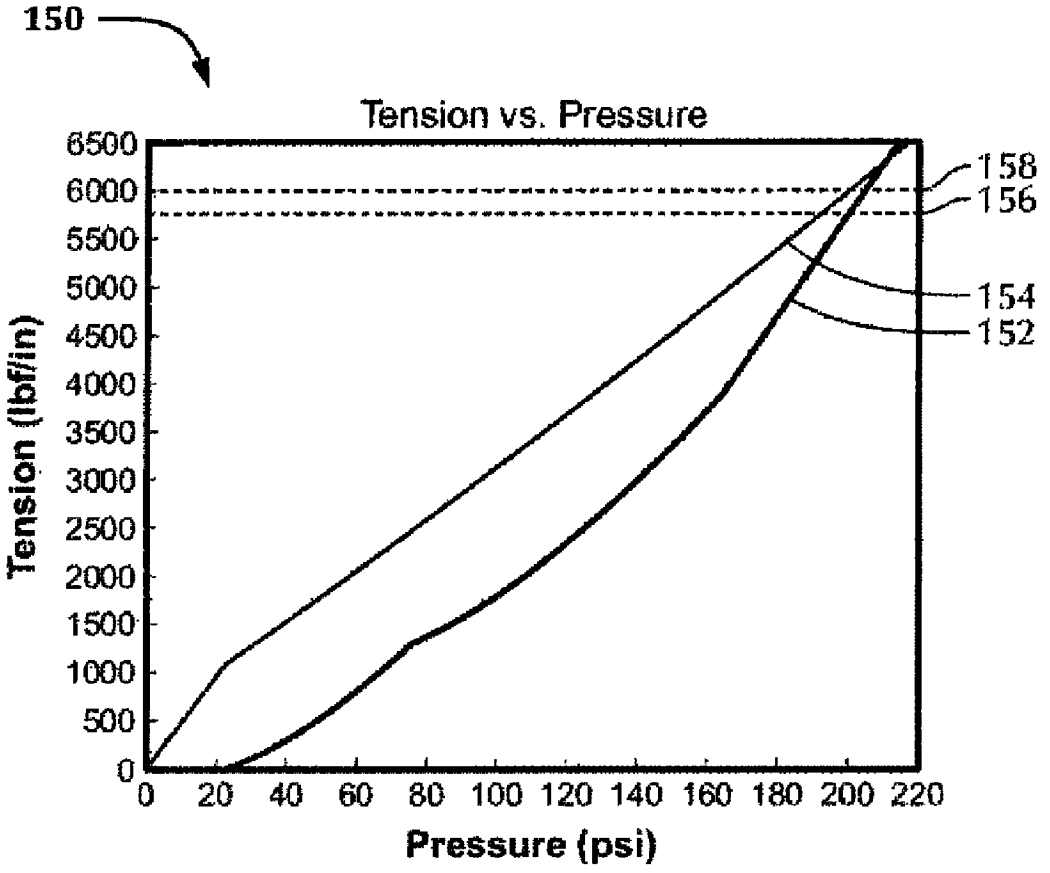

150
Tension vs. Pressure
Tension (lbf/in)
6500
6000
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0 20 40 60 80 100 120 140 160 180 200 220
Pressure (psi)
158
156
154
152

FIG. 8

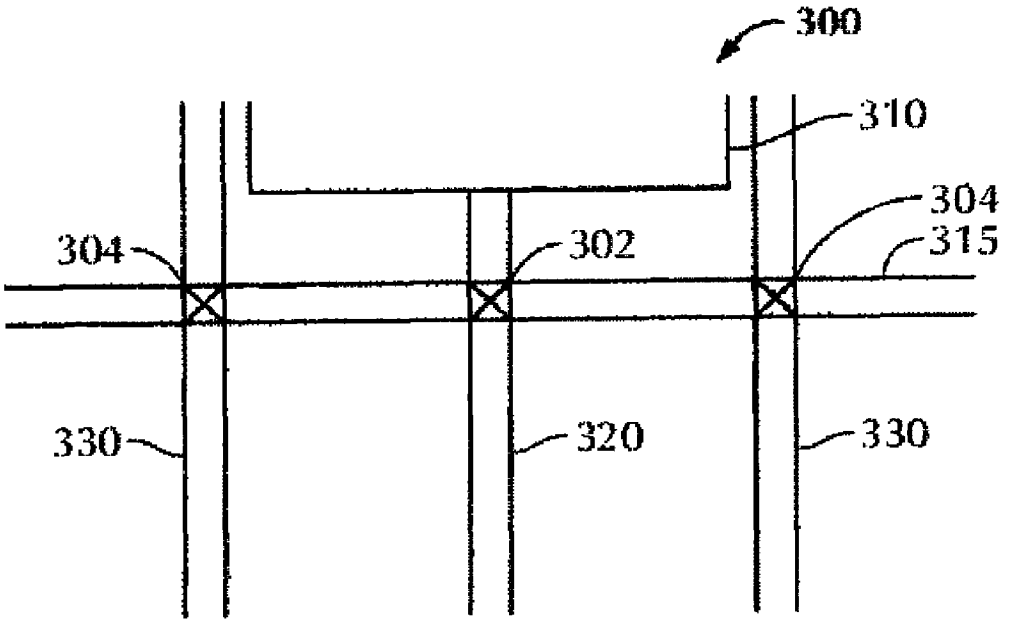

300
310
304
315
304
302
330
320
330

FIG. 9A

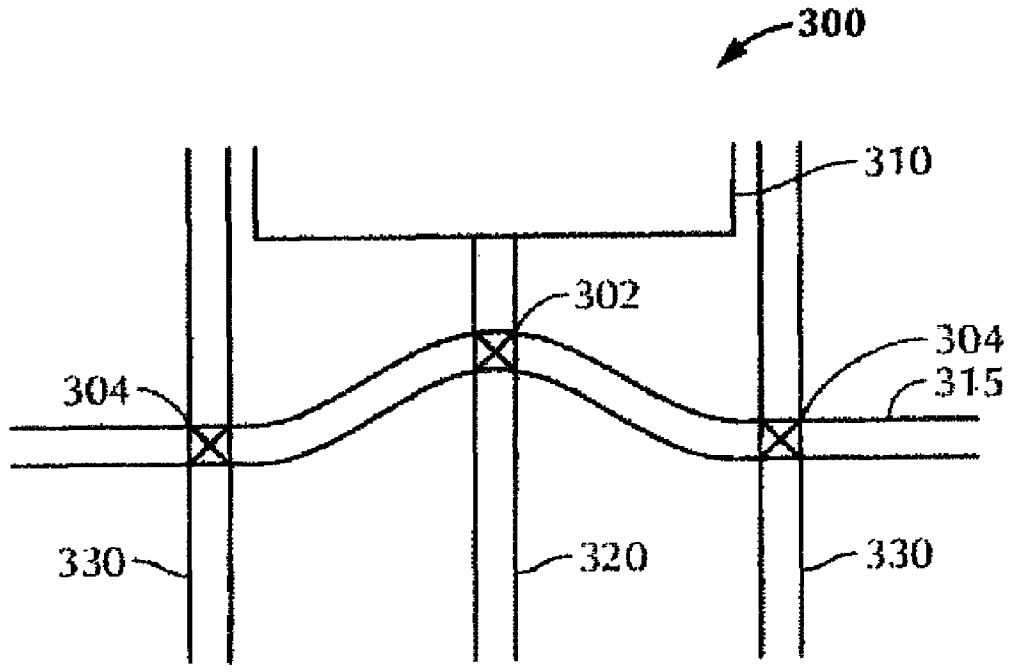

300
310
302
304
315
304
330
320
330

FIG. 9B

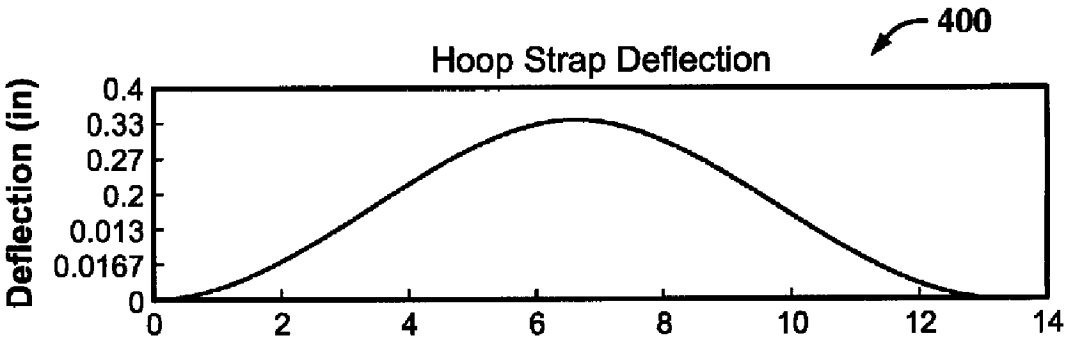

400
Hoop Strap Deflection
Deflection (in)
0.4
0.33
0.27
0.2
0.013
0.0167
0
0
2
4
6
8
10
12
14

FIG. 9C

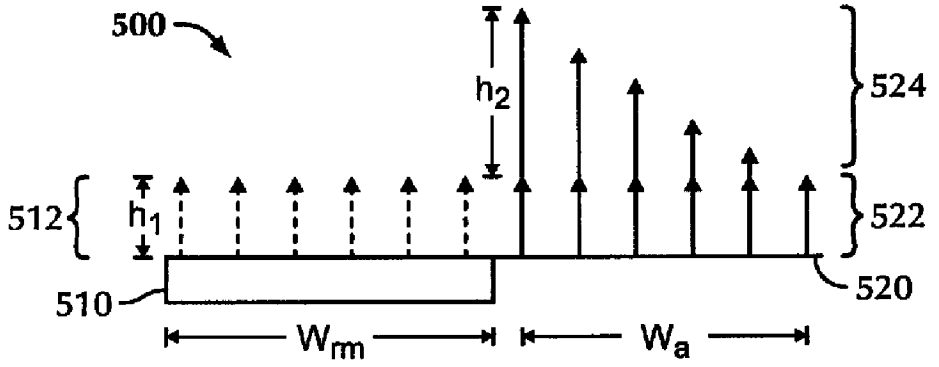

500
h2
524
512
h1
522
520
510
Wm
Wa

FIG. 10

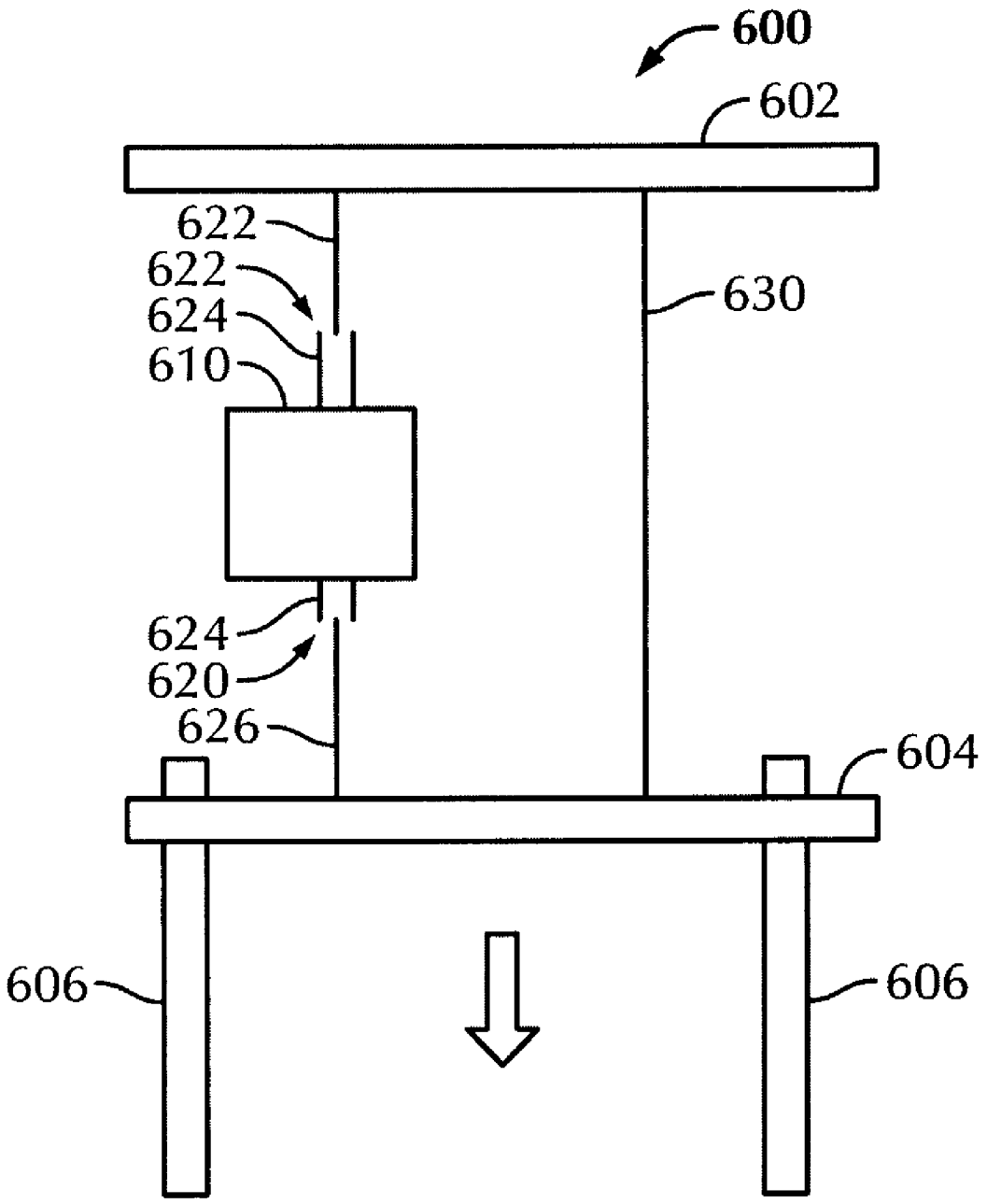


FIG. 11

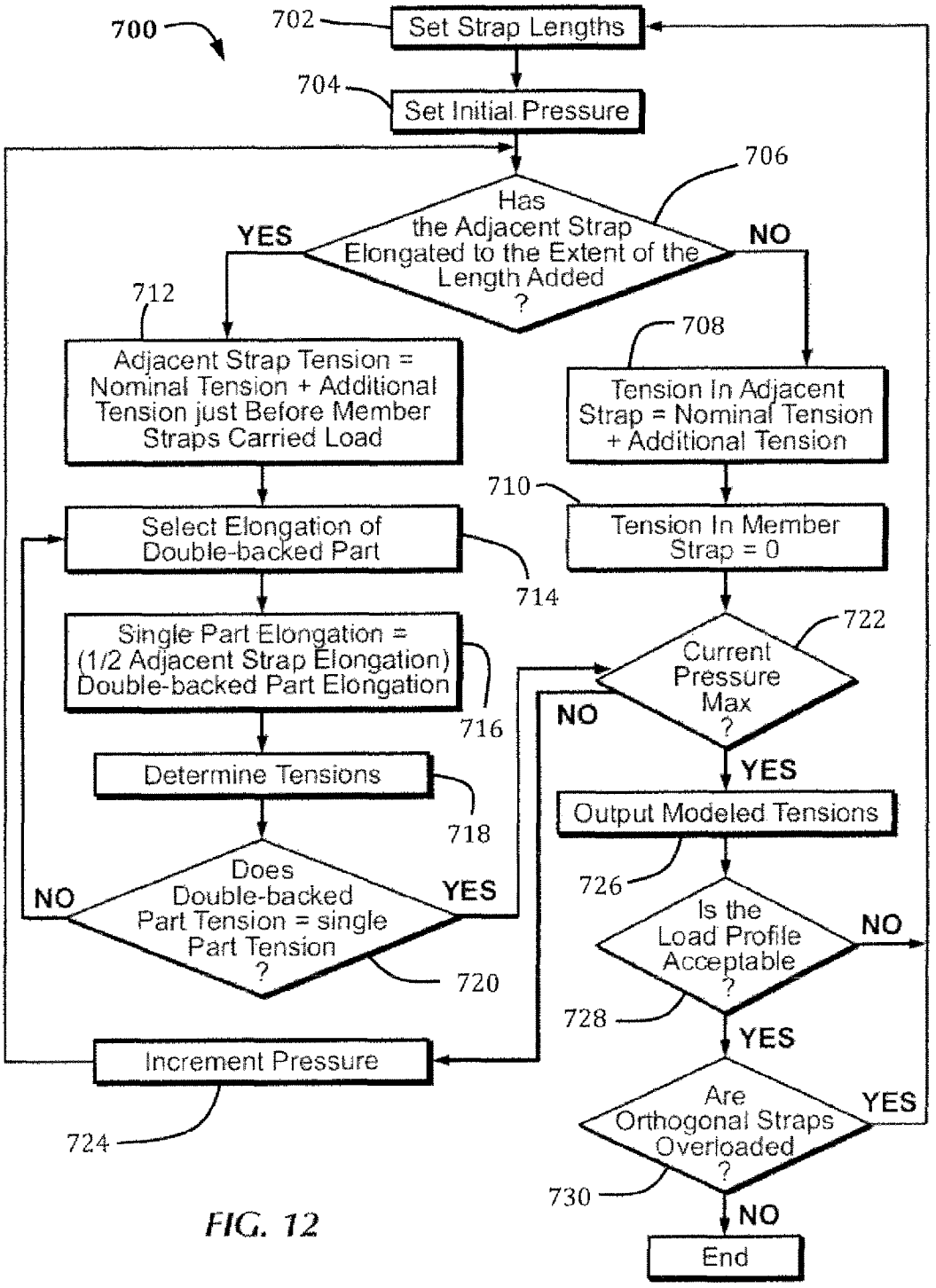

700
702
Set Strap Lengths
704
Set Initial Pressure
706
Has the Adjacent Strap Elongated to the Extent of the Length Added ?
YES
NO
712
Adjacent Strap Tension = Nominal Tension + Additional Tension just Before Member Straps Carried Load
708
Tension In Adjacent Strap = Nominal Tension + Additional Tension
710
Tension In Member Strap = 0
Select Elongation of Double-backed Part
714
Single Part Elongation = (1/2 Adjacent Strap Elongation) Double-backed Part Elongation
716
Determine Tensions
718
Does Double-backed Part Tension = single Part Tension ?
NO
YES
720
Increment Pressure
724
722
Current Pressure Max ?
NO
YES
Output Modeled Tensions
726
Is the Load Profile Acceptable ?
NO
728
YES
Are Orthogonal Straps Overloaded ?
YES
730
NO
End

FIG. 12

SYSTEM AND METHOD OF DESIGNING A LOAD BEARING LAYER THAT INTERFACES TO A STRUCTURAL PASS-THROUGH OF AN INFLATABLE VESSEL

ORIGIN OF THE INVENTION

The invention described herein was made by employee(s) of the United States Government and may be manufactured and used by or for the Government of the United States of America for governmental purposes without the payment of any royalties thereon or therefor.

BACKGROUND

1. Field

Embodiments of the present invention generally relate to inflatable modules.

2. Background Art

Inflatable modules are well known in the art, as disclosed in U.S. Pat. No. 6,547,189 (hereinafter "Raboin") assigned to the assignee of the present invention, which is hereby incorporated by reference in its entirety. Typically, an inflatable module is lightweight, collapsible, and compact prior to deployment, and is capable of being subsequently inflated to provide relatively large volume for storage, containment, human habitation, shelter, or work, as well as for space flight.

FIG. **1** shows a typical inflatable module **10**, which may withhold a relatively high pressure of an internal fluid, such as air or other gas or liquid, and may be made to any desired shape and size. The inflatable module **10** is shown in its inflated configuration and includes a rigid core **12** and an inflatable shell. The inflatable module **10** may also include a structural pass-through **14** (hereinafter "rigid member") disposed in the inflatable shell, such as a window, fluid port, hatch, connecting tunnel, etc. In the embodiment shown, the rigid member **14** is shown as a window.

The inflatable shell has two primary components: a restraint layer and a bladder. The restraint layer is the primary load bearing layer of the inflatable module **10** and reacts as a membrane to the entire pressure load. The restraint layer is typically fabricated from various high strength flexible materials. FIG. **2** shows a portion of the restraint layer **20** of the inflatable module **10**. The restraint layer **20** is made up of high-strength fabric straps, which may be formed from a Kevlar, Vectran, or PBO narrow webbing material. More specifically, the restraint layer **20** has a woven webbing design, with both longitudinal straps **22** and hoop straps **24** orthogonal to the longitudinal straps **22**. The longitudinal straps **22** and the hoop straps **24** are woven together.

Additionally, indexing stitches **26** secure the longitudinal straps **22** and hoop straps **24** together, and series of these indexing stitches form longitudinal stitch seams **27** and hoop stitch seams **28**. Each indexing stitch **26** secures one hoop strap **24** to one longitudinal strap **22**. Accordingly, the restraint layer **20** may be woven into a desired cylindrical, toroidal, or other inflatable module shape.

FIG. **2** also shows the rigid member **14** disposed in the restraint layer **20**. Longitudinal straps **22** and hoop straps **24** intersecting the rigid member **14** are connected to a frame of the rigid member **14**. The straps **22**, **24** may be connected in any way known in the art. For example, connecting straps to a rigid member may include wrapping a strap around a smooth round slot or boss on the rigid member. The strap may then be woven or sewn back into the restraint layer. In one or more embodiments, a strap may be wrapped around the slot or boss and sewn back on itself to form a loop. Alternatively, the straps may be connected to the rigid member using a clevis and roller arrangement, as disclosed in Raboin.

Although including rigid members in inflatable modules is known in the art, incorporating a rigid member into an inflatable module without affecting the strength of the inflatable module is an extremely difficult engineering challenge. Because high-strength straps typically exhibit non-linear properties when stretched under load, the restraint layer of an inflatable module stretches non-linearly when an internal pressure is applied to the module (e.g., during pressurization). Furthermore, the rigid member typically exhibits a negligible amount of elongation when loaded as compared to the elongation of the restraint layer. Thus, it is difficult to analyze and predict the loads and elongation that occur in this non-linear system.

SUMMARY

In one aspect, embodiments of the invention relate to a method for determining a design of an inflatable module comprising a rigid member disposed in a restraint layer, wherein the restraint layer comprises orthogonal straps. The method includes modeling a strap adjacent to the rigid member and a strap connected to the rigid member, wherein the adjacent strap and the member strap extend in a first direction, selecting a first length of the member strap such that the adjacent strap carries load before the member strap during pressurization of the inflatable module, modeling tensions in the member strap with the first length and the adjacent strap during pressurization of the inflatable model, and outputting the modeled tensions in the member strap with the first length and the adjacent strap.

In one aspect, embodiments of the invention relate to an inflatable module, including a restraint layer comprising orthogonal straps and a rigid member disposed in and connected to the restraint layer. The straps include a member strap connected to the rigid member and extending in a first direction, and an adjacent strap adjacent to the rigid member and extending in the first direction. The member strap has a length such that the adjacent strap carries load before the member strap during pressurization of the inflatable module.

Other aspects of the invention will be apparent from the following description and the appended claims.

BRIEF DESCRIPTION OF DRAWINGS

FIG. **1** shows a typical inflatable module.

FIG. **2** shows a portion of the restraint layer of the inflatable module of FIG. **1**.

FIG. **3** shows a typical computer system.

FIG. **4** shows a model of an inflatable module in accordance with one or more embodiments of the present invention.

FIG. **5**A shows a percent elongation vs. pressure curve for a strap in accordance with one or more embodiments of the present invention.

FIG. **5**B shows a plot of longitudinal tension vs. strain in accordance with one or more embodiments of the present invention.

FIG. **6** shows a plot of nominal tension vs. pressure in accordance with one or more embodiments of the present invention.

FIG. **7** shows a method for determining the lengths of straps of an inflatable module in accordance with one or more embodiments of the present invention.

FIG. **8** shows an example of a tension vs. pressure plot in accordance with one or more embodiments of the present invention.

FIG. **9**A shows an orthogonal strap model before pressurization in accordance with one or more embodiments of the present invention.

FIG. **9**B shows the orthogonal strap model of FIG. **9**A during pressurization.

FIG. **9**C shows a plot of orthogonal strap deflection in accordance with one or more embodiments of the present invention.

FIG. **10** shows a model of the load carried by a plurality of straps in accordance with one or more embodiments of the present invention.

FIG. **11** shows another model of an inflatable module in accordance with one or more embodiments of the present invention.

FIG. **12** shows another method for determining the lengths of straps of an inflatable module in accordance with one or more embodiments of the present invention.

DETAILED DESCRIPTION

Specific embodiments of the present invention will now be described in detail with reference to the accompanying figures. Like elements in the various figures may be denoted by like reference numerals for consistency.

In the following detailed description of embodiments of the present invention, numerous specific details are set forth in order to provide a more thorough understanding of the invention. However, it will be apparent to one of ordinary skill in the art that the present invention may be practiced without these specific details. In other instances, well-known features have not been described in detail to avoid unnecessarily complicating the description.

In general, embodiments of the present invention relate to methods and apparatus for designing an inflatable module having one or more rigid members. One or more embodiments of the present invention may provide a repeatable process that can be used to design the restraint layer of an inflatable module. Methods of the present invention may be performed, at least in part, using a computer system, such as the computer system **50** shown in FIG. **3**. The computer system **50** includes a processor **52**, associated memory **54**, a storage device **56**, and numerous other elements and functionalities typical of modern computers (not shown). The computer **50** may also include input means, such as a keyboard **57** and a mouse **58**, and output means, such as a monitor **59**. Furthermore, one or more embodiments of the present invention may be implemented in software stored on, for example, the storage device **56** or a computer-readable medium.

Referring back to FIG. **2**, it can be seen that a first longitudinal strap **30** is connected to a top part of the rigid member **14**, and a second longitudinal strap **31** is connected to bottom part of the rigid member **14** directly below the first strap **30**. Furthermore, a third longitudinal strap **32** runs adjacent to the rigid member **14**. During pressurization of the inflatable module **10**, all three straps **30**, **31**, **32** elongate under load created by the internal pressure. However, the elongation of the rigid member **14** is negligible compared to, or at least is substantially less than, the elongation of the straps **30**, **31**, **32**. Thus, the first and second straps **30**, **31** have a greater percent elongation (greater strain) than the third strap **32** to account for the lack of elongation of the rigid member **14**. This results in a greater amount of tension in the first and second straps **30**, **31** connected to the rigid member **14** than in the third strap **32** adjacent to the rigid member **14**.

Furthermore, the first and second straps **30**, **31** connected to the rigid member **14** may be connected by passing the straps **30**, **31** through a slot in the rigid member **14** and sewing the straps **30**, **31** back onto themselves to form a loop. Thus, the doubled-back straps **30**, **31** may have an increased stiffness than that of other straps, e.g., the fold may result in a portion having twice the stiffness of an unfolded strap. Because of these factors, straps connected to a rigid member may load up to a higher tension than straps not connected to the rigid member. This situation may result in overloading of the straps and/or the rigid member.

Accordingly, one or more embodiments of the present invention take into account such differences in elongation such that the lengths of longitudinal and/or hoop straps may be determined to achieve a desired load profile in the restraint layer of an inflatable module. For example, in one or more embodiments, extra length may be added to the straps connected to the rigid member. Thus, during pressurization, straps adjacent to the rigid member carry load before the straps connected to the rigid member, which may ultimately result in a more desirable load profile. However, determining the amount of extra length to add, and, thus, the lengths of the straps needed to achieve a desired load profile, can be difficult. Accordingly, one or more embodiments of the present invention provide methods and apparatus to determine the lengths of longitudinal and/or hoop straps needed to achieve a desired load profile.

FIG. **4** shows a representative model **100** of an inflatable module in accordance with one or more embodiments of the present invention. Models of inflatable modules may be used as a basis to determine the lengths of longitudinal and/or hoops straps needed to achieve a desired load profile. For example, models of inflatable modules may be used as a basis for software used to perform methods of the present invention. The model **100** is only one example of such models, and any representative model of an inflatable module may be used to determine the lengths of the straps to achieve a desired load profile. Furthermore, the model **100** is used to model longitudinal straps, not hoop straps. However, a similar model may be constructed to model hoop straps, or both longitudinal and hoop straps.

In the model **100**, it can be estimated that the straps elongate during pressurization as if the straps are connected to an infinitely stiff beam that travels along two sliders, thereby simulating that the circumference and/or the height of the inflatable module increases uniformly throughout. Accordingly, the model **100** includes a horizontal static beam **102** and a horizontal slidable beam **104**, each assumed to be infinitely stiff. The slidable beam **104** is mounted on sliders **106** and travels downward, as indicated by the arrow, during pressurization. Simulating that the circumference and/or the height of the inflatable module increases uniformly throughout may be modeled in any way known in the art.

A rigid member **110**, such as a window, is centrally disposed between the beams **102**, **104** and is assumed to have no elongation when loaded. A first member strap **120** is connected between the rigid member **110** and the slidable beam **104**, and a second member strap **122** is connected between the rigid member **110** and the static beam **102**. In the model **100**, the first and second member straps **120**, **122** are assumed to have identical lengths and properties. Additionally, an adjacent strap **130** is connected between the static beam **102** and the slidable beam **104** and adjacent to the rigid member **110**. Furthermore, the member straps **120**, **122** and the adjacent strap **130** run orthogonal to the beams **102**, **104**.

Numerous changes may be made to the model **100** to simulate the design of various inflatable modules. For example, more than one rigid member may be disposed between the beams **102**, **104**. In such an embodiment, a second rigid member may be disposed between the rigid member **110** and the static beam **102**. Then, three member straps may be disposed between the beams **102**, **104** and the rigid members. In other embodiments, the rigid member may not be centrally disposed, but rather disposed closer to one of the static beam **102** or the slidable beam **104**. As such, the first and second member straps **120**, **122** may have different lengths and/or properties.

Moreover, the straps **120**, **122**, **130** may be modeled as being composed of multiple sections. For example, the first member strap **120** may be modeled as having a first section that is of different strength than a second section, e.g., if a double backed loop to connect to the rigid member **110** is included in the first section, and the second section is a singular strap. However, in this embodiment, the straps **120**, **122**, **130** are assumed to be uniform.

Furthermore, in the model **100**, the rigid member **110** is centrally disposed, and the first and second member straps **120**, **122** have the same lengths and properties. Thus, in simulating the model **100**, the member straps **120**, **122** each elongate an amount equivalent to one half of the total elongation of the adjacent strap **130**. However, if the lengths or properties of the first and second member straps **120**, **122** differ, then such differences may be taken into account in determining the appropriate elongation. Additionally, because the first and second member straps **120**, **122** are identical in the model **100**, it may only be necessary to simulate and output results for one of the first and second member straps **120**, **122**. In other models, it may be necessary to simulate and output results for both member straps **120**, **122**.

The model **100** may be implemented in software, and settings of, or changes to, the model **100** may be achieved through user input or on the basis of a particular inflatable module design. Such settings may include the dimensions and properties of the inflatable module, rigid member **110**, and straps **120**, **122**, **130**. The settings may be used to run a simulation or to determine resultant strains and tensions in the straps due to pressure. In one or more embodiments of the present invention, the strains and tensions in longitudinal straps differ from those in hoop straps due to the geometry of the inflatable module. Thus, determining the resultant strains and tensions may also depend on the geometry of the inflatable module. Accordingly, the geometry of the inflatable module may also be a required setting.

In one or more embodiments of the present invention, the properties of straps may be provided, for example, as stress-strain curves, tension vs. pressure data, etc. Alternatively, such data may be calculated. From this data, the strain and tension in a strap at a given pressure can be determined. For example, in accordance with one or more embodiments of the present invention, FIG. **5**A shows a percent elongation vs. pressure curve for a strap and FIG. **5**B shows a plot of longitudinal tension vs. strain. During pressurization, as the pressure increases, the strain, or elongation, in the strap also increases. The strain results in tension in the strap, and the tension may be determined from the tension vs. strain plot, for example.

The tension resulting from the strain in the strap in a module without a structural pass-through and at a user-defined pressure is the nominal tension. A plot of the nominal tension vs. pressure is shown in FIG. **6** in accordance with one or more embodiments of the present invention. In one or more embodiments of the present invention, the nominal tension may be used in models of inflatable modules to determine the overall tension in the straps, and the nominal tension may be determined in any way known in the art. For example, the nominal tension may be determined based on experimental data, determined from strain, or calculated as the average tension per strap in an inflatable module without a rigid member.

FIG. **7** shows a method **200** for determining the lengths of the member straps **120**, **122** and the adjacent strap **130** to achieve a desired load profile in accordance with one or more embodiments of the present invention. Because the first and second member straps **120**, **122** of the model **100** have the same length, only the first member strap is modeled in the method **200**. However, those skilled in the art will appreciate that a similar method may be used to determine the lengths of straps in any other model, and in such methods, it may be necessary to model all member straps. In one or more embodiments of the present invention, the method **200** is an iterative process in that strap lengths are simulated until strap lengths that achieve the desired load profile are found.

In accordance with the method **200**, the lengths of the member straps **120**, **122** and the adjacent strap **130** are set such that the adjacent strap **130** carries load before the member straps **120**, **122** during pressurization of the inflatable module (step **202**). The lengths of the straps **120**, **122**, **130** may be based on a design of the inflatable module, or they may be input by a user. For example, the lengths of the straps **120**, **122**, **130** may be preset according to the design of the inflatable module, and a user may input the extra length of the member straps **120**, **122** such that the adjacent strap **130** carries load before the member straps **120**, **122**. According to the model **100**, the extra length is equally added to each member strap **120**, **122**.

Next, an initial level of inflation of the inflatable module is set (step **204**), and the method **200** models the tensions in the member straps **120**, **122** and the adjacent strap **130** over a range of inflation levels. Because the member straps **120**, **122** are similar, it is only necessary to model the tension in the first member strap **120**. Furthermore, the level of inflation may be, for example, a pressure, and the initial level and range of inflation levels may be automatically generated or set by a user. In this embodiment, the method **200** begins at a pressure of zero psi, which relates to the internal pressure of the inflatable module during pressurization.

Because the member straps **120**, **122** have extra length, the member straps **120**, **122** are initially slack while the adjacent strap **130** is taut and elongates under the load due to pressurization. Thus, for each pressure level, it is determined whether the adjacent strap **130** has elongated to the extent of the total extra length added to the member straps **120**, **122** (i.e., such that the member straps **120**, **122** are taut and carry load) (step **206**).

If the adjacent strap **130** has not elongated to the extent of the extra length, then the tension in the adjacent strap **130** is determined at the current pressure level (step **208**). For example, the tension in the adjacent strap **130** may be determined to be the nominal tension in the adjacent strap **130** plus the additional tension in the adjacent strap **130** due to the member straps **120**, **122** not carrying load. The additional load may be determined in any way known in the art, such as calculated by software, determined based on the nominal load of the adjacent strap **130**, and/or based on a setting of the model **100** or user input. Furthermore, the tension in the first member strap **120** is determined to be zero because the first member strap **120** is slack (step **210**).

If the adjacent strap **130** has elongated to the extent of the extra length added to the member straps **120**, **122**, then the

member straps **120**, **122** may begin to carry load. Thus, the tensions in the adjacent strap **130** (step **212**) and the first member strap **120** (step **214**) are determined. The tension in the adjacent strap **130** may be determined to be the nominal tension in the adjacent strap **130** plus the additional tension in the adjacent strap **130** just before the member straps **120**, **122** began to carry load. That is, because the member straps **120**, **122** now carry load, the additional load carried by the adjacent strap **130** will not increase, but instead will stay constant at the total amount of additional load at the point the member straps **120**, **122** began carrying load. Furthermore, the tension in the first member strap **120** may be determined as the nominal tension in the first member strap **120** based on elongation of the first member strap **120**.

Once the tensions in the first member strap **120** and the adjacent strap **130** have been determined, it is determined whether the current inflation level is the maximum inflation level as set by the range of inflation levels or end conditions (step **216**). If the maximum inflation level has not yet been met, then the inflation level is increased by a set increment (step **218**), and the method returns to step **206**. Otherwise, if the maximum inflation level has been met, then the tensions in the first member strap **120** and the adjacent strap **130** have been determined over the desired range of inflation levels. The resulting tensions in the straps **120**, **130**, or the load profile, may then be output (step **220**). For example, the tensions in the straps **120**, **130** may be plotted or output as data.

FIG. **8** shows an example of a tension vs. pressure plot **150** in accordance with one or more embodiments of the present invention. The plot **150** shows the tension in the first member strap **120** (indicated as **152**) and the tension in the adjacent strap **130** (indicated as **154**). Furthermore, the plot **150** shows the maximum tension before failure in the longitudinal straps **120**, **130** (indicated by **158**) and the maximum tension before failure of the rigid member **110** (indicated by **156**). A plot similar to the plot **150** of FIG. **8** may be used to determine if the load profile is acceptable.

Accordingly, from the output of the method **200**, it may be determined whether the load profile is acceptable or meets design standards or criteria (step **222**). The determination of whether the load profile is acceptable may be performed by a user or may be automatically determined by software. If the load profile is not acceptable, then the method returns to step **202**, where different values are selected for the lengths of the member straps **120**, **122**, and/or the adjacent strap **130**. For example, based on the output load profile, a user or software may select another value for the extra length added to the member straps **120**, **122**.

If the load profile is acceptable, then it may be determined whether the member straps **120**, **122** and the adjacent strap **130** overload straps orthogonal to the member straps **120**, **122** and the adjacent strap **130** (step **224**). That is, because of the different elongations of the member straps **120**, **122** and the adjacent strap **130**, the straps **120**, **122**, **130** have different relative motions during pressurization of the inflatable module. Furthermore, the orthogonal straps may be indexed to the member straps **120**, **122**, and the adjacent strap **130**. Thus, different relative movements of the straps **120**, **122**, **130** may impart load and strain to the orthogonal straps.

FIG. **9**A shows an orthogonal strap model **300** before pressurization in accordance with one or more embodiments of the present invention. The orthogonal strap model **300** is similar to the model **100**, and may be used with the model **100** and the method **200**. The model **300** includes a rigid member **310**, a first member strap **320** connected to the rigid member, and two adjacent straps **330** adjacent to the rigid member **310**. The first member strap **320** and the adjacent straps **330** extend longitudinally. Furthermore, the model **300** includes an orthogonal strap **315** orthogonal to the first member strap **320** and the adjacent straps **330**. A first indexing stitch **302** secures the orthogonal strap **315** to the first member strap **320**, and second indexing stitches **304** secure the orthogonal strap **315** to the adjacent straps **330**. As shown in FIG. **9**A, before pressurization, the first and second stitches **302**, **304** are positioned along the same horizontal line.

FIG. **9**B shows the orthogonal strap model **300** during pressurization in accordance with one or more embodiments of the present invention. During pressurization of the inflatable module, the first member strap **320** and the adjacent straps **330** elongate. However, because member strap **320** is stiffer, because the member strap **320** is shorter, doubled upon itself, and attached to the rigid member, the relative displacement of the adjacent **330** is greater than the member strap **320**. This relative movement generates strain in the orthogonal strap **315**, resulting in tension in the orthogonal strap **315**. Those skilled in the art will appreciate that the relative movement does not occur until all of the slack of member strap **320** has been taken up.

The tension in the orthogonal strap **315** may be determined in any way known in the art, and, further, may be based on determined elongations from the method **200**. For example, in one or more embodiments of the present invention, a sine distribution of the relative motion of the first member strap **120** and the adjacent straps **130** may be assumed. FIG. **9**C shows a plot **400** of the orthogonal strap **315** deflection in accordance with one or more embodiments of the present invention. The plot **400** shows the deflection of the orthogonal strap **315** along a horizontal length of the rigid member **110**. The left side of the x-axis represents the intersection of the orthogonal strap **315** and the adjacent strap **130** to the left of the rigid member **110**, and the right side represents the intersection of the orthogonal strap **315** and the adjacent strap **130** to the right of the rigid member **110**. Thus, the deflection of the orthogonal strap **315** is assumed to be greater towards the center of the rigid member **110**.

Furthermore, the strain in the orthogonal strap **315** may be determined using the plot **400** of the orthogonal strap **315** deflection. For example, the strain may be determined as the change in the length of the orthogonal strap **315** divided by the length of the orthogonal strap **315** along the horizontal length of the rigid member **110**. Then, given properties of the orthogonal strap **315**, the resulting tension may be determined.

Referring back to the method **200** of FIG. **7**, the resulting tension in the orthogonal strap **315** may be determined and taken into account when determining the lengths of the member straps **120**, **122** and the adjacent strap **130**. If the orthogonal strap is overloaded, then the method **200** returns back to step **202**. Then, different values for the member straps **120**, **122** and/or the adjacent strap **130** are selected. Otherwise, if the orthogonal strap **315** is not overloaded, the lengths of the member straps **120**, **122** and the adjacent strap **130** may be determined to be acceptable.

Accordingly, the lengths of the longitudinal straps of an inflatable module necessary to achieve a desired load profile may be determined from the model **100**, the method **200**, and the orthogonal strap model **300**. Additionally, similar models and methods may be used to determine the lengths of the hoop straps of an inflatable module necessary to achieve a desired load profile. It is well within the ability of those skilled in the art to derive such models and methods for hoop straps from the models and methods presented herein.

In embodiments of the present invention, the additional load carried by an adjacent strap due to member straps not carrying load may be determined in any way known in the art. For example, FIG. **10** shows a model **500** of the load carried by a plurality of straps in accordance with one or more embodiments of the present invention. In the model **500**, it is assumed that the plurality of straps of an inflatable module are disposed very close to one another. In accordance with the model **500**, and for simplicity, the straps connected to a rigid member are modeled as a rigid member surface **510**, and straps adjacent to the rigid member are modeled as an adjacent surface **520**. Furthermore, the rigid member surface **510** has a width w_{rm} equal to one half of the width of the modeled rigid member, and the adjacent surface **520** has a width w_a.

The load that the rigid member surface **510** would normally carry is shown as a rectangular area having a height h_1 indicated as **512**. However, because member straps are initially slack, the rigid member surface **510** does not actually carry the load, and, thus, the load is shown using dashed lines. Furthermore, the nominal load of the adjacent surface **520** is shown as a rectangular area. The nominal load has the same height h_1 indicated as **522** because the two surfaces **510**, **520** are assumed to have equal loads per unit of width.

The additional load on the adjacent surface **520** is shown as a triangular area with a height h_2 indicated as **524** distributed over the width w_a of the adjacent surface **520**. A triangular area is used in the model **500** because it is assumed straps nearer the rigid member would carry more of the additional load than straps farther from the rigid member. The additional load is equal to the load not carried by the rigid member surface **510**, which may be expressed as

$$w_{rm} \cdot h_1 = \frac{1}{2} w_a \cdot h_2. \tag{1}$$

Furthermore, it is assumed that the additional load on the adjacent surface **520** due to the rigid member surface **510** not carrying load is distributed over a width equal to the rigid member surface **510**. Accordingly,

$$w_{rm}=w_a \tag{2}$$

Then, the total load on the adjacent surface **520**, nominal plus additional, may be expressed as

$$w_a \cdot h_1 + w_{rm} \cdot h_1 = w_a \cdot h_1 + \frac{1}{2} w_a \cdot h_2. \tag{3}$$

Then, using the assumption that the widths are equal, Eq. 3 may be simplified to

$$h_2=2h_1 \tag{4}$$

Thus, the height of the triangular area representing the additional load is twice the height of the rectangular surface representing the nominal load. According to the model **500**, a strap immediately adjacent to a rigid member would carry an additional load equal to twice the nominal load the adjacent strap carries. In other words, the adjacent strap carries three times its nominal load.

The determination of the additional load in an adjacent strap based on its nominal load from model **500** may be used with, for example, the model **100** and the method **200** of determining the lengths of member straps and the adjacent strap to achieve a desired load profile. Furthermore, the model **500** is only one example of a model that may be used to determine the additional load of an adjacent strap. It is well within the ability of those skilled in the art to derive other models using other assumptions. For example, other models may be derived for inflatable modules having other spacings of straps or distributions of load.

FIG. **11** shows another model **600** of an inflatable module in accordance with one or more embodiments of the present invention. The model **600** is similar to the model **100** of FIG. **4**. Specifically, the model **600** includes a horizontal static beam **602** and a horizontal slidable beam **604**, each assumed to be infinitely stiff. The slidable beam **604** is mounted on sliders **606** and travels downward, as indicated by the arrow, during pressurization. This simulates that the circumference and/or the height of the inflatable module increases uniformly throughout.

Furthermore, the model **600** includes a window **610** (one type of rigid member), a first member strap **620**, a second member strap **622**, and an adjacent strap **630**, all of which are disposed in a manner similar to the model **100**. However, in the model **600**, each of the member straps **620**, **622** are composed of two parts: a double-backed part **624** and a single part **626**. That is, each member strap **620**, **622** is passed through a slot on the window **610**, doubled-back, and sewn onto itself, thus creating a loop. Accordingly, each part **624**, **626** must be taken into account in modeling the member straps **620**, **622**. Additionally, in the model **600**, the additional load carried by the adjacent strap **630** is determined according to the model **500** of FIG. **10**.

FIG. **12** shows a method **700** for determining the lengths of the member straps **620**, **622** and the adjacent strap **630** to achieve a desired load profile in accordance with one or more embodiments of the present invention. Before executing the method **700**, a user may input any information the method **700** requires. For example, the user may input dimensions and properties of the window **610** and the straps **620**, **622**, **630**, and the geometry of the inflatable module. Furthermore, the user may input start conditions and end conditions (e.g., start/stop pressure, pressure increments, and max tension). Additionally, the user may input the additional load on the adjacent strap **630** as a percent of the nominal load. In this case, and based on the model **500** of FIG. **10**, the additional load is 200% of the nominal load.

In accordance with the method **700**, the lengths of the member straps **620**, **622** and the adjacent strap **630** are set such that the adjacent strap **630** carries load before the member straps **620**, **622** during pressurization of the inflatable module (step **702**). Furthermore, extra length added to the member straps **620**, **622** is added to the double-backed part **624** of the member straps **620**, **622**. Next, the start pressure for inflation of the inflatable module is set (step **704**), for example, at zero psi. Then, the tensions in the member straps **620**, **622** and the adjacent strap **630** are modeled over the set range of pressures. Because the member straps **620**, **622** are similar, it is only necessary to model the tension in one of the member straps **620**, **622**. In this embodiment, the tension in the first member strap **620** is determined.

For each pressure level it is determined whether the adjacent strap **630** has elongated to the extent of the total extra length added to the member straps **620**, **622** (i.e., such that the member straps **620**, **622** are taut and carry load) (step **706**). In this embodiment, the elongation of the adjacent strap **630** at the current pressure level is determined from the stress-strain plot of FIG. **5**A. This elongation is compared to the extra length added to the member straps **620**, **622**.

If the adjacent strap **630** has not elongated to the extent of the extra length, then the tension in the adjacent strap **630** is determined at the current pressure level (step **708**). The ten-

sion in the adjacent strap **630** is determined to be the nominal tension in the adjacent strap **630** plus the additional tension in the adjacent strap **630** due to the member straps **620**, **622** not carrying load. The nominal tension in the adjacent strap is determined from the tension vs. strain plot of FIG. **5**B based on the elongation determined from the stress-strain plot of FIG. **5**A. Then, the additional tension is determined to be twice the nominal tension. Additionally, the tension in the first member strap **620** is determined to be zero because the first member strap **620** is slack (step **710**).

If the adjacent strap **630** has elongated to the extent of the extra length added to the member straps **620**, **622**, then the member straps **620**, **622** begin to carry load. Thus, the tensions in the adjacent strap **630** and the first member strap **620** are determined. The tension in the adjacent strap **630** is determined in the manner discussed above as the nominal tension in the adjacent strap **630** plus the additional tension in the adjacent strap **630** just before the member straps **620**, **622** began to carry load (step **712**).

The tension in the first member strap **620** is determined as the nominal tension in the first member strap **620** based on elongation of the first member strap **620**. However, the double-backed part **624** and the single part **626** of the first member strap **620** carry the same load, and, thus, have the same tension, but elongate at different rates. Accordingly, the elongation of each part **624**, **626** must be determined to determine the tension in the first member strap **620**.

In one or more embodiments, the tension in the first member strap **620** may be determined through an iterative process. For example, a value for the elongation of the double-backed part **624** is selected (step **714**). Then, the elongation of the single part **626** is determined to be half of the elongation of the adjacent strap **630** less the selected elongation of the double-backed part **624** (step **716**). Based on the elongations of the two parts **624**, **626**, the tension in each part may be determined (step **718**). Finally, if the tension in each of the two parts **624**, **626** is equal (step **720**), the selected elongation of the first part **624** is correct. Thus, the tension has been determined. Otherwise, another value for the elongation of the double-backed part **624** is selected, and the process repeats.

Once the tensions in the first member strap **620** and the adjacent strap **630** have been determined, it is determined whether the current pressure is the maximum pressure (step **722**). If the maximum pressure has not yet been met, then the pressure is increased by a set increment (step **724**), and the method **700** returns to step **706**. Otherwise, if the maximum pressure has been met, then the tension in the first member strap **620** and the adjacent strap **630** has been determined over the desired range of pressures. The resulting tension in the straps **620**, **630**, or the load profile, may then be output (step **726**). For example, the tension in the straps **620**, **630** may be plotted or output as data, as shown in FIG. **8**.

Accordingly, from the output of the method **700**, it may be determined whether the load profile is acceptable or meets design standards or criteria (step **728**). If the load profile is not acceptable, then the method returns to step **702**, where different values are selected for the lengths of the member straps **620**, **622**, and/or the adjacent strap **630**. If the load profile is acceptable, then it may be determined whether the member straps **620**, **622** and the adjacent strap **630** overload orthogonal straps in the manner discussed with reference to FIGS. **9**A-**9**C (step **730**).

Furthermore, the resulting tension in orthogonal straps may be determined and taken into account when determining the lengths of the member straps **620**, **622** and the adjacent strap **630**. If the orthogonal strap **315** is overloaded, then the method **700** returns back to step **702**. Then, different values for the member straps **620**, **622** and/or the adjacent strap **630** are selected. Otherwise, if the orthogonal strap **315** is not overloaded, the lengths of the member straps **620**, **622** and the adjacent strap **630** may be determined to be acceptable.

Accordingly, the lengths of the longitudinal straps of an inflatable module necessary to achieve a desired load profile may be determined from the model **600** and the method **700**. Additionally, similar models and methods may be used to determine the lengths of the hoop straps of an inflatable module necessary to achieve a desired load profile. It is well within the ability of those skilled in the art to derive such models and methods for hoop straps from the models and methods presented herein.

In accordance with embodiments of the present invention, an inflatable module having one or more rigid members, such as the inflatable module of FIG. **1**, may be designed to achieve a desired load profile. Thus, the inflatable module may be designed to carry loads due to pressurization of the inflatable module, as well as any other loads on the inflatable module. More specifically, referring back to FIG. **2**, the lengths of the straps of the inflatable module, whether connected to the rigid member or not, may be determined to achieve a desired load profile.

Embodiments of the present invention may provide one or more of the following advantages. Inflatable modules having one or more rigid members may be designed to withstand the loads of pressurization, as well as other loads. Furthermore, the lengths of straps of an inflatable module may be determined to achieve a desired profile. One or more embodiments of the present invention provide repeatable processes by which the lengths of straps of an inflatable module may be determined. Even further, inflatable modules having one or more rigid members may be analyzed based on the length of straps of the inflatable modules. Additionally, inflatable modules may be constructed based on a determined design.

While the invention has been described with respect to a limited number of embodiments, those skilled in the art, having benefit of this disclosure, will appreciate that other embodiments can be devised which do not depart from the scope of the invention as disclosed herein. Accordingly, the scope of the invention should be limited only by the attached claims.

What is claimed is:

1. A method for determining a design of an inflatable module comprising a rigid member disposed in a restraint layer, wherein the restraint layer comprises orthogonal straps, the method comprising:

modeling an adjacent strap, a member strap, and the rigid member in accordance with pressurization of the inflatable module to achieve a predetermined load profile, wherein the adjacent strap is comprised of a first strap adjacent to the rigid member but not connected to the rigid member and the member strap is comprised of a second strap connected to the rigid member, wherein the adjacent strap and the member strap are modeled to extend in a first direction;

selecting a first length of the member strap such that, in accordance to the predetermined load profile, the adjacent strap is modeled to carry load before the member strap during pressurization of the inflatable module;

modeling tensions in the member strap with the first length and the adjacent strap during pressurization of the inflatable model at predetermined pressure level increments over a predetermined pressure range; and

outputting the modeled tensions in the member strap with the first length and the adjacent strap at a predetermined maximum pressure level,

wherein the step of modeling the adjacent strap, the member strap, and the rigid member comprises modeling an elongation of the adjacent strap and the member strap in accordance with pressurization of the inflatable module at the predetermined pressure level increments, and

wherein the rigid member exhibits substantially no elongation when loaded.

2. The method of claim **1**, further comprising determining whether the modeled tensions in the member strap and the adjacent strap are acceptable in accordance with the predetermined load profile.

3. The method of claim **2**, further comprising:

if the modeled tensions are not acceptable in accordance with the predetermined load profile, substituting the first length of the member strap with a second length of the member strap such that the adjacent strap is modeled to carry load before the member strap during pressurization of the inflatable module;

modeling tensions in the member strap with the second length and the adjacent strap during pressurization of the inflatable model at the predetermined pressure level increments over the predetermined pressure range; and

outputting the modeled tensions in the member strap with the second length and the adjacent strap at the predetermined maximum pressure level.

4. The method of claim **1**, wherein the step of modeling tensions in the member strap with the first length and the adjacent strap comprises determining whether the adjacent strap has elongated to the extent that the member strap also carries load.

5. The method of claim **4**, wherein if the adjacent strap has not elongated to the extent that the member strap also carries load, then the step of modeling tensions in the member strap with the first length and the adjacent strap further comprises modeling the tension in the member strap as zero, and modeling the tension in the adjacent strap as a nominal tension plus an additional tension for the entire predetermined pressure range.

6. The method of claim **5**, wherein the nominal tension is modeled based on the elongation of the adjacent strap.

7. The method of claim **5**, wherein the additional tension is modeled based on the nominal tension.

8. The method of claim **7**, wherein the additional tension is set as twice the nominal tension.

9. The method of claim **4**, wherein if the adjacent strap has elongated to the extent that the member strap also carries load, then the step of modeling tensions in the member strap with the first length and the adjacent strap further comprises modeling the tension in the adjacent strap as a nominal tension plus an additional tension for the entire predetermined pressure range.

10. The method of claim **9**, wherein the nominal tension is modeled based on the elongation of the adjacent strap.

11. The method of claim **9**, wherein the additional tension is set as a constant equal to the value of the additional tension at the highest pressure level increment in which the tension in the member strap is zero.

12. The method of claim **10**, wherein the additional tension is a predetermined constant value for subsequent pressure level increments after the member strap carries load.

13. The method of claim **9**, wherein the tension in the member strap is modeled based on the elongation of the member strap.

14. The method of claim **13**, wherein the member strap with the first length comprises a first section and a second section, and wherein the step of modeling tensions in the member strap with the first length and the adjacent strap comprises:

selecting a first value of elongation for the first section;

determining a second value of elongation for the second section based on the selected first value of elongation and the elongation of the adjacent strap; and

determining the tensions in the first section and the second section.

15. The method of claim **14**, wherein the step of modeling tensions in the member strap with the first length and the adjacent strap further comprises selecting a third value of elongation for the first section and replacing the third value of elongation for the first value of elongation if the tension in the first section does not equal the tension in the second section.

16. The method of claim **14**, wherein one of the first section and the second section is doubled-backed forming a loop to connect to the rigid member, and the other of the first section and the second section is not double-backed thereby remaining a singular strap.

17. The method of claim **1**, wherein the step of modeling the adjacent strap, the member strap, and the rigid member comprises providing predetermined properties of the adjacent strap and the member strap.

18. The method of claim **1**, further comprising:

modeling a second adjacent strap and a second member strap in accordance with pressurization of the inflatable module to achieve the predetermined load profile, wherein the second adjacent strap is comprised of a third strap adjacent to the rigid member but not connected to the rigid member and the second member strap is comprised of a fourth strap connected to the rigid member, wherein the second adjacent strap and the second member strap are modeled to extend in a second direction;

selecting a third length of the second member strap such that the second adjacent strap is modeled to carry load before the second member strap during pressurization of the inflatable module;

modeling tensions in the second member strap and the second adjacent strap during pressurization of the inflatable model at the predetermined pressure level increments over the predetermined pressure range; and

outputting the modeled tensions in the second member strap and the second adjacent strap at the predetermined maximum pressure.

19. The method of claim **18**, wherein the second direction is orthogonal to the first direction.

20. The method of claim **18**, further comprising determining whether the modeled tensions in the second member strap and the second adjacent strap are acceptable in accordance with the predetermined load profile.

21. The method of claim **2**, further comprising:

modeling an orthogonal strap in accordance with pressurization of the inflatable module to achieve the predetermined load profile, wherein the orthogonal strap is modeled to extend in a third direction orthogonal to the first direction; and

modeling tension in the orthogonal strap at the predetermined pressure level increments over the predetermined pressure range.

22. The method of claim **21**, wherein the orthogonal strap is attached to the member strap and the adjacent strap, wherein relative movement between the member strap and the adjacent strap causes displacement in the orthogonal strap, and wherein the step of modeling the tension in the

orthogonal strap comprises modeling the tension in the orthogonal strap due to the displacement of the orthogonal strap.

23. The method of claim **1**, further comprising determining whether the modeled tension in the orthogonal strap is acceptable in accordance with the predetermined load profile.

24. The method of claim **2**, further comprising providing the design of the inflatable module.

25. The method of claim **2**, further comprising providing the inflatable module based on the design of the inflatable module.

26. The method of claim **1**, wherein the rigid member is selected from a group consisting of a window, a hatch, a fluid port, and a connecting tunnel.

27. An inflatable module, comprising:

a restraint layer comprising orthogonal straps; and

a rigid member disposed in and connected to the restraint layer,

wherein the straps include a member strap connected to the rigid member extending in a first direction, and an adjacent strap not connected to the rigid member and adjacent to the rigid member extending in the first direction,

wherein the rigid member exhibits substantially no elongation when loaded, and

wherein the member strap has a length such that the adjacent strap carries load before the member strap during pressurization of the inflatable module.

28. The inflatable module of claim **27**, wherein the length of the member strap is determined by:

modeling the adjacent strap and the member strap;

selecting a first length of the member strap such that the adjacent strap carries load before the member strap during pressurization of the inflatable module;

modeling tensions in the member strap with the first length and the adjacent strap during pressurization of the inflatable model; and

outputting the modeled tensions in the member strap with the first length and the adjacent strap.

29. The inflatable module of claim **27**, wherein the orthogonal straps are interwoven.

* * * * *