ABSTRACT

A sandwich beam including in one example first and second spaced walls, a core configured to maintain a predetermined spacing between the walls when the core is filled with pressurized gas and to resist shear when the beam is loaded in bending and a port for filling the core with gas biasing both walls in tension. The tension tends to increase in the second wall and decrease and cause a compression load in the first wall in response to a sufficiently large applied bending load. A compression element is fixed only with respect to the first wall and is configured (a) to support the compression load so that the beam is stronger at a given gas pressure and (b) to flex sufficiently to allow the beam to be rolled up when the gas is emptied from the core via the port.
FIG. 11
Load Diagram of an Un-Reinforced Inflatable Beam

F

FIG. 12
End-View Cross-Section of a Reinforced Inflatable Beam with Angled Threads

40

Angled Threads

Floq=0
FIG. 14A
Pre-Sewing Fabric Baffles to the Top Surface

FIG. 14B
Sewing Fabric Baffles to the Bottom Surface
Partial Cross-Section of Reinforced Beam with Mated/Joined Tubular Baffles and Tensile Reinforcement of the Bottom Surface

FIG. 20

Inflatable Sheet-Reinforced Airfoil with Foam Core

FIG. 21
FIG. 24
Cross-Section of a Beam Reinforced with Rods

40°

FIG. 25
Cross-Section of a Beam with Tape-Springs and Coarsely Spaced Baffles

40°
FIG. 26
Cross-Section of a Beam with Top and Bottom Skins Spanning Convex Ridges

FIG. 27
Partial Cross-Section of a Beam with Hinged-Strip Compression Elements
FIG. 30

Beam with Two-Layer Structural Element and Edge Seals
FIG. 31

Partial Cross-Section of Beam with Tape Springs in Sleeves

FIG. 32

Partial Cross-Section of Beam with Multi-Layer Tape Springs in Sleeves
ROLL-UP INFLATABLE BEAM STRUCTURE

RELATED APPLICATIONS

[0001] This application claims the benefit of and priority to U.S. Provisional Application Ser. No. 60/965,670, filed Aug. 21, 2007, which is incorporated herein by reference.

FIELD OF THE INVENTION

[0002] This subject invention relates to inflatable structures.

BACKGROUND OF THE INVENTION

[0003] Inflatable structures such as the surfboard discussed in U.S. Patent No. 2,743,510 (incorporated herein by reference) are becoming increasingly popular. U.S. Patent No. 2,743,510 discloses an inflatable structure with top and bottom walls made of fabric and drop stitches securing the top and bottom walls together to hold them in a desired shape when the structure is inflated. See also U.S. Patent No. 6,066,016 also incorporated herein by reference.

[0004] Such inflatable structures are generally weak in buckling owing to the fact that the top and bottom walls must be sufficiently flexible so that the structure can be rolled up when deflated for transport and storage.

[0005] For example, an inflatable surfboard in accordance with U.S. Patent No. 2,743,510, when inflated to 15 psi and placed across two saw horses, could not support 170 lbs. Adding additional air pressure so the surfboard can sustain greater loads is both difficult in the field and can be dangerous and/or result in severe stress on the components of the inflated surfboard.

[0006] U.S. Patent No. 2,743,510 discloses a coating on the top and bottom fabric plies but solely for gas imperviousness. U.S. Patent Application No. 2003/0153221 also discloses overlays of "flexible" material to increase "strength or durability" of the board, however, "flexible" material is defined as being an elastomer or elastomer-coated fabric as are typically used for inflatable boats. These overlays add puncture resistance and tensile stiffness, but have minimal resistance to buckling.

[0007] While it is common knowledge that an inflatable beam can be stiffened by adding batons (e.g. shock-corded aluminum tubes used on the Feathercraft Gemini kayak), this method is time consuming to assemble and provides only a small increase in strength and stiffness.

BRIEF SUMMARY OF THE INVENTION

[0008] It is therefore an object of this invention to provide a stronger inflatable structure.

[0009] It is a further object of this invention to provide such an inflatable structure which better withstands buckling loads.

[0010] It is a further object of this invention to provide such an inflatable structure which better withstands buckling loads without the need to increase the inflation pressure.

[0011] It is a further object of this invention to provide such an inflatable structure which can still be easily deflated and rolled up for transport and/or storage.

[0012] It is a further object of this invention to provide such an inflatable structure which is easily manufactured.

[0013] The subject invention results from the realization that the problem of an inflated sandwich structure buckling upon the application of a bending load is solved by understanding that buckling occurs when one wall of the sandwich structure is no longer in tension and the solution is to add a compression element which can withstand the in-plane compressive load and which, at the same time, is sufficiently compliant so that the sandwich structure can still be rolled up for transport and/or storage. A further realization is that for most beam-like applications, the compression element is needed on only one side, and that by allowing buckling of the other side, the deflated beam can be rolled up easily.

[0014] The subject invention features a sandwich beam comprising first and second walls and a core configured to maintain a predetermined spacing between the walls when the core is filled with pressurized gas and to resist shear when the beam is loaded in bending. A port is provided for filling the core with gas which biases both walls in tension. In response to a bending load, the tension increases in the second wall and decreases in the first wall. If the load is sufficiently large, the first wall goes into compression. A compression element is fixed only with respect to the first wall and is configured (a) to support the compression load so that the beam is stronger at a given gas pressure and (b) to flex sufficiently to allow the beam to be rolled up when the gas is emptied from the core via the port.

[0015] The typical beam has a load capacity X without the compression element and a load capacity of N times X when the compression element is added to the beam. In one example, N is greater than 1.5. The typical beam is also approximately N times X stronger when loaded in the intended direction than when loaded in the reverse direction; the intended direction being that which tends to cause in-plane compression of the first wall.

[0016] The compression element may be a sheet of material secured to the outer surface of the first wall. Typically, the first and second walls include fabric. One core construction includes a plurality of drop-stitches between the first and second walls. The drop-stitches may be angled. In one variation, the compression element is between ¼ and ⅛ inches thick. The compression element may include fiber reinforced polymers, polymer films, polymer sheets, metals, wood, and wood-based products. In one example, the compression element is flat. But, the compression element may also be curved concave or curved convex. The core may include baffles. The baffles may be angled and/or intersecting. The baffles may be tube shaped. Another core includes foam.

[0017] In some embodiments, there are a plurality of compression elements. Each compression element may be a flat strip. The compression elements may be rods. In other embodiments, the compression elements are tape springs. There may be a skin over the compression element.

[0018] In one particular example, the core includes baffles and there is a compression element associated with select baffles each including a top leaf hinged to a side leaf. There may be a vacuum pocket about the compression element. In one example, the compression element includes multiple plies that are clamped together by pressure or vacuum force, but are allowed to slide when the beam is deflated, thus allowing the beam to be rolled up more easily.

[0019] One waterboard in accordance with the subject invention features upper and lower walls, a core configured to maintain a predetermined spacing between the walls when the core is filled with gas and to resist shear when the waterboard is loaded in bending, a port for filling the core with gas, thus biasing both walls in tension until the upper wall expe-
riences compression due to a sufficiently large bending load, and a compression sheet secured about the upper wall and configured to support the compression on the upper wall and to flex sufficiently to allow the waterboard to be rolled up when the gas is emptied from the core via the port.

[0020] One method of making a sandwich beam in accordance with the subject invention includes securing a first wall to a second wall via a core configured to maintain a predetermined spacing between the walls when the core is filled with gas and to resist shear when the beam is loaded in bending. A compression element is applied only to and fixed with respect to the first wall. The compression element is configured to support the compression load on the first wall so that the beam is stronger at a given gas pressure and configured to flex sufficiently to allow the beam to be rolled up when the gas is emptied from the core via the port.

[0021] One sandwich beam in accordance with the subject invention includes first and second spaced walls, a core configured to maintain predetermined spacing between the walls when the core is filled with pressurized gas and to resist shear when the beam is loaded in bending, a port for filling the core with gas, and narrow compression elements fixed to both walls and configured (a) to support compression loads in the first or second walls due to bending loads applied to the beam in either direction (b) to flex sufficiently to allow the beam to be rolled up when the gas is emptied from the core via the port, and (c) to nest when deflated to allow each compression element to bend about its neutral axis.

[0022] The subject invention, however, in other embodiments, need not achieve all these objectives and the claims thereof should not be limited to structures or methods capable of achieving these objectives.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

[0023] Other objects, features and advantages will occur to those skilled in the art from the following description of a preferred embodiment and the accompanying drawings, in which:

[0024] FIG. 1 is a schematic three-dimensional top view showing an inflatable surfboard in accordance with the prior art;

[0025] FIG. 2 is a cross-sectional view showing the surfboard of FIG. 1 under a load;

[0026] FIG. 3 is a highly schematic three-dimensional top view of an inflatable surfboard in accordance with the subject invention;

[0027] FIG. 4 is a schematic cross-sectional view showing the inflatable surfboard of FIG. 3 in its partially rolled up configuration;

[0028] FIG. 5 is a cross-sectional end view showing an example of an inflatable beam in accordance with the subject invention with a cone compression element;

[0029] FIG. 6 is a schematic cross-sectional end view of an inflatable beam in accordance with the subject invention with a convex compression element;

[0030] FIG. 7 is a schematic cross-sectional end view of an inflatable beam in accordance with the subject invention with a corrugated compression element;

[0031] FIG. 8 is a schematic cross-sectional end view of a drop-stitched inflatable beam in accordance with the subject invention including a compression element;

[0032] FIG. 9 is a schematic cross-sectional side view showing a portion of a drop-stitched reinforced inflatable beam in accordance with the subject invention;

[0033] FIG. 10 is a schematic cross-sectional side view showing a portion of a reinforced inflatable beam with angled threads in accordance with the subject invention;

[0034] FIG. 11 is a load diagram for an unreinforced inflatable beam in accordance with the prior art;

[0035] FIG. 12 is a cross-sectional end view of a reinforced inflatable beam with angled threads in accordance with the subject invention;

[0036] FIG. 13 is a cross-sectional end view of an inflated beam with stitched baffles in accordance with the subject invention;

[0037] FIG. 14A is a highly schematic view showing baffles being pre-sewn to the top surface of an inflatable beam in accordance with the subject invention;

[0038] FIG. 14B is a highly schematic depiction showing baffles being sewn to the bottom surface of an inflatable beam in accordance with the subject invention;

[0039] FIG. 15A is a schematic front view showing a fabric strip including biased fibers;

[0040] FIG. 15B is a schematic front view showing a fabric strip including zero and ninety degree fibers;

[0041] FIG. 15C is a schematic front view showing a two-ply baffle strip including biased fibers and fibers at zero and ninety degrees;

[0042] FIG. 16 is a schematic cross-sectional end view showing a reinforced inflated beam with angled baffles in accordance with the subject invention;

[0043] FIG. 17 is a schematic cross-sectional end view showing a reinforced inflated beam in accordance with the subject invention including angled/intersecting baffles;

[0044] FIG. 18 is a schematic cross-sectional end view showing a reinforced inflated beam having tubular baffles in accordance with the subject invention;

[0045] FIG. 19 is a schematic cross-sectional end view showing a portion of a reinforced inflated beam with mated/ joined tubular baffles in accordance with the subject invention;

[0046] FIG. 20 is a schematic cross-sectional end view showing a portion of a sheet inflated beam with mated/ joined tubular baffles and tensile reinforcement of the bottom surface;

[0047] FIG. 21 is a schematic cross-sectional end view of an inflatable airfoil with a foam core including a compression element on the top surface of the airfoil in accordance with the subject invention;

[0048] FIG. 22 is a schematic cross-sectional side view of a portion of a reinforced beam with a random fibrous core in accordance with the subject invention;

[0049] FIG. 23 is a schematic cross-sectional end view of an inflated beam reinforced with flat compression elements strips in accordance with the subject invention;

[0050] FIG. 24 is a schematic cross-sectional end view showing an example of an inflated beam reinforced with compression element rods in accordance with the subject invention;

[0051] FIG. 25 is a schematic cross-sectional end view showing an inflated beam with compression elements in the form of tape springs;

[0052] FIG. 26 is a schematic cross-sectional end view of an inflated beam with top and bottom skins in accordance with the subject invention;
FIG. 27 is a schematic cross-sectional end view showing a portion of an inflated beam in accordance with the subject invention with hinged-strip compression elements;

FIG. 28 is a schematic cross-sectional end view of an inflated beam in accordance with the subject invention with narrow compression elements on both sides;

FIG. 29 is a schematic cross-sectional end view showing an example of a beam with a two layer structural sheet in accordance with the subject invention;

FIG. 30 is a schematic cross-sectional end view showing an example of a beam with a two layer structural sheet and edge seals in accordance with the subject invention;

FIG. 31 is a schematic cross-sectional end view showing a portion of a beam with tape spring compression elements residing in sleeves in accordance with the subject invention; and

FIG. 32 is a schematic cross-sectional end view showing a portion of a beam with multi-layer tape springs residing in sleeves in accordance with the subject invention.

DETAILED DESCRIPTION OF THE INVENTION

Aside from the preferred embodiment or embodiments disclosed below, this invention is capable of other embodiments and of being practiced or being carried out in various ways. Thus, it is to be understood that the invention is not limited in its application to the details of construction and the arrangements of components set forth in the following description or illustrated in the drawings. If only one embodiment is described herein, the claims hereof are not to be limited to that embodiment. Moreover, the claims hereof are not to be read restrictively unless there is clear and convincing evidence manifesting a certain exclusion, restriction, or disclaimer.

FIG. 1 shows a prior art inflatable surfboard 10 with top wall 12, bottom wall 14, and side wall 16. Inflating port 18 is for filling the interior core of the surfboard with compressed air. FIG. 2, also prior art, shows core 20 including drop-stitches 22 extending between top wall 12 and bottom wall 14 to maintain a predetermined spacing between walls 12 and 14.

Inflation pressure causes tension in the drop-stitches 22, as well as planar (X and Y) tension in the top wall 12 and bottom wall 14. The planar tension results from the pressure acting on the sidewalls 16. When surfboard 10 is loaded in bending as shown by the surfer’s weight at 24 and buoyant force 25 in FIG. 2, this results in a decrease in the X-axis tension in the top wall 12 (shown at 26), and an increase in tension in the bottom wall (shown at 27). The changes in X-axis tension cause the surfboard to bend concave up, as does the tendency of the beam to "rack" as in a parallelogram. The "racking" effect causes horizontal shear, i.e., the tendency of the bottom wall 14 to move inward relative to the top wall 12, as shown at 28. Shear is resisted by the sidewalls, and by a small component of the tension in the drop-stitches 22 acting in-line with the top and bottom walls.

In the prior art, the walls of the surfboard are typically made of elastomer-coated polyester or nylon fabric. These materials are very flexible in bending and thus buckle easily when the top wall tension 26 goes to zero. The typical way to increase the load capacity is to increase the inflation pressure, but this increases the inflation time and effort, requires more expensive pump and valving, makes the surfboard more likely to leak, requires heavier materials, and creates an explosion hazard.

FIG. 3 shows reinforced surfboard 10' having compression element 40 fixed on top wall 12. When loaded as in FIG. 2, the load capacity of the reinforced surfboard 10' is not limited by the tension 26 in the top wall going to zero, in fact, the compression element 40 can sustain significant in-plane compressive force without buckling. Compression element 40 is preferably stiff and strong in tension and compression, but can still be flexible in bending, for example, it may be a very thin (e.g., 0.031 inches thick) layer of G10 fiberglass-epoxy laminate (a common circuit board material). The buckling strength of compression element 40 is greatly enhanced by the stabilizing effect of the inflated structure. When the surfboard 10' is deflated, it can be rolled up for storage and/or transport as shown in FIG. 4. Preferably, the surfboard is turned upside down before rolling.

In testing, at 2.7 times increase of load carrying capacity was realized as was a 2.3 times increase in bending stiffness holding pressure constant at 15 psi. Alternatively, the reinforced surfboard could support more load at an inflation pressure of 5 psi than the un reinforced surfboard at 15 psi. In this way, the problem of an inflated sandwich structure of any type buckling upon the application of a large load is solved by understanding that buckling occurs when one wall of the sandwich structure is no longer in tension and cannot withstand the resulting compressive load. The solution is to include a compression element which can withstand the compressive load and which at the same time is sufficiently compliant so that the inflated sandwich structure can be rolled up for transport and/or storage. The result is an inflated beam with increased bending strength and stiffness and the ability to reduce the inflation pressure, the size, or the overall weight of the beam. The advantage is more compact storage and fast deployment or repacking. Reduction of the inflation pressure is advantageous since it reduces the inflation time, the leak rate, and the risk of an explosion and/or damage to the surfboard.

The method of the subject invention can be applied to all inflatable beams and plates, but is especially applicable to beams that are relatively long or wide compared to their thickness and have a simple curvature on their compression side. Example applications include the surfboard example discussed above, as well as the following: other waterboards such as paddleboards, rescue boards, sailboards, boogie-boards and sit-on-top kayaks; floor panels for kayaks and Zodiac boats, watercraft such as car ferries, barges and the like; floating devices such as docks, bridges and runways; airfoils, e.g., for aircraft, kites, sails or wind power generation; ramps and bridges; and other beam structures such as tables, stretchers, floor panels, walls, roofs, tent supports, masts, towers, helipads, and the like.

FIG. 4 shows a cross-section of a partially rolled-up beam similar to that of FIG. 3. The bottom wall has no compression elements and is therefore able to compress, buckle, and wrinkle in order to absorb the difference in arc/length between the outside and inside of the roll.

In general, when a sandwich structure is rolled, the outer wall (of the roll) goes into tension, the inner wall into compression, and the core and sidewalls go into shear. To facilitate rolling, the possibilities are to allow stretch of the outer surface, allow compression or buckling of the inner wall, and/or allow shear of the core and sidewalls. However, in an inflated structure, e.g., a drop-stitched surfboard, the sidewalls tend to have significant resistance to shear, and the top and bottom walls are preferably stiff, at least in tension.
One aspect of the subject invention is that the compression element (e.g., sheet) is fixed only on the top side. By allowing compression or buckling of the bottom side, the surfboard (or other beam) can be easily rolled up. This solution also allows the use of high-tensile fibers in the bottom wall and sidewalls. When inflated, the surfboard has high bending stiffness which improves controllability and reduces hydrodynamic drag.

In this specification, the terms “top” and “bottom” of the beam are illustrative, and should not be considered limiting. The term “top” or “top wall” is used to describe the side of the beam or plate that goes into compression in response to the predominant bending moment. This terminology is literally correct for a surfboard, ramp, bridge, or wing (while flying). However, there are other applications where the compression side is on the bottom (e.g., a see-saw).

The compression element is preferably made of a low-density, high strength, high-modulus material in sheet form. The sheet should be as stiff as possible without being too difficult to roll up to the desired stowed size. For best results, the sheet should have a minimum bend diameter significantly smaller than the desired rolled-up diameter. In the 0.031 inch G10 example, the minimum bend diameter is about 1.4 inches but the rolled up diameter is about 12 inches. A small minimum bend radius can also allow the inflated beam to be overloaded (i.e., buckled) without causing permanent damage.

Other candidate materials for the compression element include, but are not limited to, the following: fiber reinforced polymers (FRP) such as fiberglass, Kevlar, Spectra, Vectran, carbon fiber in a matrix of epoxy, polyester, or PEEK; polymer films such as Vectran, PBO, Mylar, Ultlem, Kapton; polymer sheets such as ABS, nylon, acetal, PEEK; alloys of aluminum, iron, copper, titanium; and woods such as bamboo, hickory, etc. The structural sheet can also be thin sandwich, e.g., two layers of FRP or film bonded to a thin core of foam, balsa wood, or honeycomb material.

The structural sheet can also be formed by laying up high-modulus fibers (e.g., cloth or roving) directly on an air-beam structure (e.g., a drop-stitched beam). Conventional methods such as squeegees and/or vacuum bagging can be used to impregnate the fibers with a polymer resin such as epoxy or polyester.

Increased bending capacity can be achieved by making the compression element curved or wavy in the direction transverse to the direction of maximum compression. FIGS. 5-7 show cross-sections of inflatable beams having a concave, convex and corrugated sheet respectively. In all cases, the compression element 40 is attached to the compression-side of the beam (e.g., the top of a surfboard). The curvature increases the bending stiffness of the compression element, thus increasing buckling resistance. When the beam is deflated and rolled, the curvature tends to flatten out and has only a small effect on the resistance to rolling and diameter of the roll.

FIGS. 5-7 show an approximately constant beam thickness but this should not be considered limiting: the beam can have variable thickness transversely or along its length as determined by the sidewalls, baffles and/or threads connecting the top and bottom walls.

In the surfboard example, and other beams having non-circular cross-sections, a collapsible core is needed to control the spacing between the top and bottom walls. The collapsible core can include fibers, threads, fabric, foam, or any combination thereof. An especially convenient construction is shown in FIGS. 8 and 9. FIG. 8 is an end-view cross-section of a drop-stitched inflatable beam with a structural sheet attached on the top side. FIG. 9 is a partial side-view cross-section of the same beam. This construction is consistent with the reinforced surfboard 10 of FIG. 3.

Drop-stitching is a manufacturing process in which two layers of fabric are stitched together leaving slack threads between the two layers. The fabric layers are typically impregnated and/or coated with an airtight elastomer such as PVC, urethane or Hypalon. To make an inflatable panel or beam, the drop-stitched material is cut and the edges are sealed around the perimeter using one or more strips of coated fabric. The edge strips are typically bonded with contact adhesive or welded using heat, ultrasound, RF, or a solvent.

When inflated, the beam assumes the shape as shown in FIGS. 8 and 9. Typically, drop-stitch material is made with constant-length threads oriented substantially parallel to each other. The density of stitches is typically on the order of 10 per square inch.

Having the fibers oriented in the thickness, or Z direction, is simpler to achieve, but results in lower beam stiffness since the core provides little resistance to horizontal shear until there is significant deflection. In FIG. 2 note the angle of the threads relative to the top and bottom surfaces. Only a small component of the thread tension resists shear between the top and bottom layers.

For greater shear stiffness, the threads may be angled, e.g., as in FIG. 10. Angled drop-stitched material is commercially available, however, the angle with respect to the Z-axis is typically much smaller than would be optimal for the present invention. There are two reasons for this. Firstly, the existing techniques for angled drop-stitching limit the angle to +/-half the arc tangent of the pitch spacing divided by the thread length. For example, a 3° thick drop-stitched panel with 0.3 inch thread spacing would have thread angles of +/-2.9°. The second reason is that the optimal thread angle for an un-reinforced inflatable drop-stitch beam is, in fact, very small.

FIG. 11 shows a load diagram for a cantilever unreinforced inflatable beam having length L, thickness T, inflation pressure P, thread angle +/-θ, and applied load F. There are two main “failure” modes: buckling of the top surface at the fixed end (left), and slack in the left-leaning threads. The latter does not actually cause failure, but leads to larger deflections. The “optimal” thread angle θ is that which avoids slack threads up to the point where the top wall buckles. Resolving the various forces and stresses, and neglecting strain in the top and bottom surfaces, results in the following equation:

$$\theta = \tan^{-1}\left(\frac{\frac{T}{2L} + F}{P}\right)$$

(1)

For example, a 3 inch thick un-reinforced drop-stitched surfboard spanning a 6 foot gap between two waves will have an “optimal” drop-stitch angle of +/-2.3°. The pressure P required to support load F is given by the following equation (where W is the width of the beam):
\[ p = F \frac{2L + T}{W \cdot T^2} \]  

(2)

[0081] In the surfboard example, assuming a width of 20”, a pressure of approximately 41.7 psi would be needed to support a 200 lb rider, assuming a 6 foot span.

[0082] With a structural sheet attached to the top wall of an angled drop-stitched inflatable beam, the resulting “reinforced” beam can support many times greater load. Whereas the improvement in load capacity was 2.7x adding a 0.031 inch G10 sheet to a straight drop-stitched surfboard, the improvement would be approximately 4-5x using the same sheet to reinforce an angled drop-stitched surfboard. The angled drop-stitch reduces deflection of the beam which reduces the curvature of the top wall near the point of maximum compressive stress. With less curvature, the top wall has a higher buckling load.

[0083] The preferred drop-stitch angle for a reinforced inflatable beam is described by the following equation:

\[ \theta = \tan^{-1} \left( \frac{F}{p \cdot W - T} \right) \]  

(3)

[0084] In the surfboard example above, the pressure requirement can be reduced to about 10 psi, and the preferred thread angle is about \( +/-10^\circ \). This angle provides just enough shear resistance to avoid “racking” up to the load capacity of the beam. Larger thread angles are typically undesirable since a component of the thread angle tends to reduce the pretension in the bottom wall, thus reducing beam strength in the non-dominant direction of loading. In the surfboard application, a reversal of the typical direction of loading can occur for example when a wave momentarily supports the middle of a surfboard while the rider has one foot forward and one aft.

[0085] In the surfboard example, the beam is relatively long compared to its width and it is most important to angle the threads as viewed from the side (see FIG. 10). For better bi-axial (i.e., plate-like) stiffness, the threads can also be angled as viewed from the end, e.g., as in FIG. 12. This will reduce deflection due to shear in the Y/Z plane.

[0086] Another source of compliance in a drop-stitched beam is the stretch of the fabric. If, in accordance with the present invention, the top wall is reinforced with a structural sheet, the resulting beam will be much stiffer. Further stiffness improvement is possible by adding tensile material to the bottom wall of the beam. The tensile material is preferably made of a high-strength, high-modulus material which can sustain repeated buckling and wrinkling as is likely to occur when the beam is rolled up. Example materials include fabrics, sailcloth, elastomer-coated fabric, mat, unidirectional ribbons, flat braid or cord made of polyester, Nylon, Kevlar, Vectran, fiberglass, Spectra or PBO fiber. At least some of the fibers should be aligned substantially in the direction of greatest tension (typically the long, or X-direction). To allow for buckling and wrinkling, the fibers should be embedded in a low-modulus matrix (e.g., an elastomer), or have voids where the fibers are not impregnated and are therefore allowed to shear. The tension element(s) can be bonded or welded to the bottom wall of the drop-stitch panel over the full mating surface area, or can be attached at more localized areas. The latter method is less likely to kink and damage the fibers, but also creates pockets between the tensile element(s) and the bottom surface which may be undesirable in some applications.

[0087] The tensile material can also be a polymer film. Desired properties are high-modulus, high strength, low creep, high elongation to failure, and good fatigue and tear resistance. Example film materials are Mylar, PEEK, Ultem, and Vectran. Metal films such as stainless steel or aluminum could also be used.

[0088] In accordance with the invention, the variations described above relating to fiber angles in the core and tensile reinforcement of the bottom wall also apply to other core constructions. For instance, the drop-stitch threads could instead be small wires or filaments and could be attached directly to a top structural sheet and bottom tensile film. The threads can also be replaced by baffles made of fabric or a collapsible film.

[0089] FIGS. 5-7 showed three examples of a core construction using baffles. FIG. 13 shows a more detailed view. In this variation, the top and bottom walls, sidewalls and baffles are made of fabric and are joined by sewing. An example of a sewing method is shown in FIGS. 14A and 14B. The last sewing operation (not shown) would be to sew the edges of the top and bottom walls together, thus forming the sidewalls.

[0090] Outer walls can be sealed by coating with an air-tight elastomer to form an inflatable sealed volume. Alternatively, each compartment can be inflated with a separate bladder. Additional layers of bias fabric (e.g., having fiber angles \( +/-45^\circ \) when viewed in the Y/Z plane) can be bonded to the top and/or bottom walls to better transfer horizontal shear from the baffles to the top and bottom walls, and to improve the torsion stiffness of the beam.

[0091] To stiffen the beam against shear loads in the X/Z plane, the baffles preferably have fibers that are angled when viewed from the side. Since most fabric is produced with angles 0 and 90\(^\circ\), one solution would be cut fabric on the bias to make strips having fiber angles \( +/-45^\circ \), however, when inflated, the tension in the fibers needed to resist the outward pressure force produces an equal force tending to contract the beam lengthwise. In effect, the pressure forces in X and Z cancel, resulting in essentially zero pre-tension in the top and bottom surface assemblies. This has little effect on the bending capacity in the preferred direction (i.e., the structural sheet in compression), but it greatly reduces bending capacity in the opposite direction. Applications such as surfboards, kayaks, wings etc, tend to have much greater bending load in one direction, but the same strength in the opposite direction is still needed.

[0092] In accordance with the invention, one solution when using fabric baffles is to bond or sew strips of 0\(^\circ\)/90\(^\circ\) fabric 50, FIG. 15B, to bias-cut strips 52, FIG. 15A, thus producing 0\(^\circ\)/45\(^\circ\)/45\(^\circ\) two-ply baffle material 54, FIG. 15C. Outward pressure is directly resisted by the Z-oriented fibers, thus minimizing the contractile force in the X-direction.

[0093] Alternately, the baffles, sidewalls, bottom wall and/or top wall can be made from a film material such as Mylar, PEEK, Ultem or Vectran. The parts could be bonded or welded. If the latter, a method can be used similar to that shown in FIGS. 14A and 14B, but replacing the sewing assembly with a device that pinches the layers together and uses heat, ultrasound, RF or other method to weld the layers together.
For improved bi-axial shear stiffness, the baffles can be angled in the Y/Z plane as shown in FIG. 16. An intersecting pattern of baffles can also be achieved e.g., by sewing, bonding or welding the intersection points shown in FIG. 17. This allows for smoother top and bottom surfaces (i.e., more closely spaced baffles) and/or greater baffle angle Φ.

In another variation, the baffles are made from fabric or film tubes, e.g., as shown in FIG. 18. The tubes can be spaced apart, or mated and joined together as in FIG. 19. If joined, the bottom of the tubes can form the bottom wall of the beam, or to reduce peel forces in the corners of the tubes, an additional tensile film or fabric can be added to the bottom wall as in FIG. 20. The latter approach is advantageous in that the tubes need not be airtight or as abrasion/penetration resistant. This allows the use of thinner/lighter tubes to make the baffles. Note that in accordance with the invention, the bottom surface assembly is sufficiently thin and flexible to allow it to buckle and/or wrinkle when the beam is deflated and rolled-up.

In accordance with the invention, the core of the beam can also be made from open-cell foam, e.g., the airfoil of FIG. 21. The foam is preferably made from a high-tensile strength, high-modulus polymer having relatively large cells and thin connecting struts or webs. The foam should be easily collapsible, but have high tensile stiffness and strength when the beam is inflated. The foam may be blown into a female mold in which the top and bottom walls, front “side-walls” and/or structural sheet are held in place, e.g., by vacuum. Alternately, the foam can be cut or molded, and then bonded to the structural sheet and bottom tensile film.

In another variation of the invention, the core is made from randomly oriented fibers as shown in FIG. 22. This type of construction can be achieved for example by bonding the top and bottom walls to fibrous batting, as taught by U.S. Pat. No. 5,552,205 incorporate herein by this reference.

In another variation, the inflatable beam or panel is placed inside a female mold and inflated while subjected to heating, e.g., by the introduction of hot air internally or externally. Thermoplastic elements of the top and bottom walls, structural sheet, side-walls and/or core are allowed to stretch or creep as the beam assumes the shape of the mold. This process allows for complex curvature of the beam surfaces, avoids wrinkles, and is a cost effective way to provide varying core thickness with high accuracy. If the core includes random fibers or foam, stretching the core will tend to orient the fibers or foam interconnections in the Z-direction. This tends to improve the load capacity of the beam since the structural sheet (or other compression element(s)) is better stabilized against buckling.

In additional variations, the compression elements attached to or integral with the top wall can include structural strips, tape-springs, hinged strips, rods, bars, tubes or other elongate structural elements. In accordance with the invention, the compression elements can be rolled up without damage and without disassembling them from the inflatable structure.

FIG. 23 shows a cross-sectional view of a beam with flat strips 40° attached to the top surface. The flat strips are preferably aligned in the direction of maximum compression (typically the long direction –X) due to the principal bending moment. Bending strength in this direction will be similar to that of a sheet-reinforced beam (of similar local bending resistance). Lateral bending strength will be lower since the gaps between strips do not support compression in the Y direction. Candidate materials for the strips are the same as for the structural sheet, as described above.

FIG. 24 shows a cross-sectional view of a beam reinforced with rods 40°. The rods are best stabilized against buckling if they are attached at the intersection of baffles and the top wall.

Curved strips 40°, FIG. 25 also known as “tape-springs”, are especially advantageous since the beams have high bending stiffness when curved, but are easy to roll up as they flatten out. Combined with a baffle-type beam construction, the inflation pressure helps maintain the curvature and further stabilize the tape-springs against buckling. In this case, coarser baffle spacing tends to improve the strength of the beam since it increases the Z-height of the tape springs. Preferred materials for making the tape springs are the same as for the structural sheet described above.

In many applications it will be desirable for the top and/or bottom surfaces to be smooth. This is especially important for airfoils where the accuracy of the surfaces has a major effect on the lift/drag ratio. For flat beams, such as that shown in FIG. 26, smooth surfaces can be achieved using a skin 60 to bridge between the convex ridges. In this case, the skin(s) can be thin, flexible membranes. The voids between the skins and the rest of the beam assembly are preferably held at or near the ambient pressure and/or filled with open-cell foam.

For airfoil applications, flat spots between the convex ridges may reduce lift or add drag. Possible solutions are to fill the voids with open-cell foam in a molding operation, or use skins with bending resistance in the lateral direction. To allow the beam to be rolled up, the skins can be made of a directional material such as FRP with most of the fibers oriented close to the Y-direction. This is especially important for the bottom skin since, in accordance with the invention it must compress and/or buckle as the beam is rolled up.

When rolled, the top skin will experience tension in the X-direction. For ease of rolling, it should be allowed to stretch in this direction, but to smooth between the convex ridges, lateral bending stiffness is desirable. As with the bottom skin, orienting the fibers close to the Y-direction is one way to achieve the desired effect. Use of a top-skin with bi-axial stiffness (e.g., G10, polymer or metal sheet, etc) is also possible, but will increase the bending resistance and/or require thinner tape springs.

Another way to provide high compression strength but preserve the ability to be rolled-up, is to use hinged strips 40° as shown in FIG. 27. Each hinged strip includes a top leaf 70 attached to the top wall 12 of the beam, a side leaf 72 attached to a baffle, and a hinge. The hinge can be a pinned hinge (e.g., piano hinge), a thinned part (e.g., flexure or “plastic hinge”), or can be achieved by bonding the hinge to a flexible element such as thin metal, Nitinol superelastic material, polymer, elastomer, or fabric. The hinge can also be achieved by having the material (e.g., fabric or film) of the top wall and baffles act as the hinge.

When inflated, the leaves of the hinge form an L shape which provides a high moment of inertia. When deflated, the hinged strips lay flat and can be rolled-up. For easiest rolling, the width of each pair of hinged strips is less than width between baffles. This allows the strips to all lie in-plane, and avoids a build-up of horizontal shear.

FIG. 28 presents an embodiment of the invention wherein narrow compression elements 40° (e.g., rods, strips,
etc) are attached to the top and bottom walls, thus providing bi-directional bending strength. When deflated, the compression elements are allowed to lie in-plane for easy rolling. The “compression elements” in fact provide tensile strength and stiffness (as well as compressive) depending on the direction of the bending load. This reduces the need for high tensile stiffness in the film or fabric of the top and bottom walls, and can result in higher beam stiffness and lower overall weight.

To clarify the terminology used in this specification, the primary function of the “top wall” and “bottom wall” is to resist the Z-axis inflation force, and transfer this force to the baffles, threads or other core material. The two walls may or may not have an airtight coating, since internal bladders can also be used. The two walls also may or may not provide the primary tensile elements resisting bending of the beam, since this function can be provided by adding tensile elements (such as banded high-modulus cord) or “compression elements” such as rods.

In this specification, when compression elements or tension elements are said to be “attached” to the top or bottom wall, this includes the case where the compression or tension elements are attached to the baffles, threads or other shear-resistant core material in close proximity to the top or bottom walls. For example, the rods of FIG. 28 can be “attached” to the top and bottom walls, by bonding them to baffles near the connection of the baffles and the top or bottom wall.

In one embodiment, compression elements are shear-locked to one or both of the top and bottom core, or sidewalls of the inflatable structure by friction, using pressure or vacuum to supply the normal force. In the inflated state, one or more of the compression elements are allowed to slide, which allows the beam to be rolled-up much more easily. The compression elements can also be made of multiple thin layers. When clamped together by pressure forces, the compression elements have effectively greater thickness. This increases the local bending resistance and results in greater beam stiffness and greater tolerance of contact forces (i.e., local Z-axis pressure by a surfer’s foot).

An example of this embodiment is shown in FIG. 29. In this case, the top wall is reinforced by two structural sheets 40a and 40b which are “attached” to the top wall by pulling a vacuum on the vacuum pocket. The two sheets are constrained in a vacuum pocket 80 by sleeve material 82. When the vacuum is applied, the sleeve material 82 collapses on the sheets 40a and 40b and applies a normal force up to atmospheric pressure (e.g. 14.7 psi). Friction clamps the two sheets together and clamps the inner sheet to the “top wall” of the beam.

The vacuum pressure required to prevent slippage between the inner compression element and the top surface is given by the following equation (where V is the vertical shear force, W is the beam width, T is the thickness and f is the friction coefficient):

\[ P = \frac{V}{W \cdot T \cdot f} \]  

[0114] In the surfing example, the vertical shear is half the rider’s weight (~100 lb), and the beam dimensions (WxT) were 20”x3”. Assuming a friction coefficient of 0.5, the required vacuum pressure is 3.3 psi. For greater load capacity or safety factor, the vacuum can be increased and/or the friction coefficient can be enhanced, e.g., using coatings, films, particles, surface texture, or mating features such as bumps and pockets or ridges engaging troughs.

Multi-layer compression elements are advantageous since bending stiffness (when shear-locked) scales with thickness cubed, but when shear is allowed (i.e., when rolling-up the beam), the bending stiffness scales linearly with thickness (i.e., the number of layers). For a given stowed diameter and bending moment (i.e., resistance to rolling), the multi-layer type of compression element will provide greater local bending stiffness, greater resistance to buckling, higher beam load capacity and greater tolerance of contact forces.

FIG. 30 shows another variation of the embodiment which avoids the need for a sleeve. Instead, outer sheet 40b is sealed to the top wall 12 or sidewalls of the beam by an edge seal around the perimeter of the sheet. One or more inner sheets 40a are allowed to “float” inside the vacuum pocket 80, but when vacuum is applied to the vacuum port, the sheets are all clamped to each other and to the top wall of the beam.

To make sure the vacuum pocket gets fully evacuated, the surfaces of the sheets can be textured or roughened or additional porous “breather” material can be used between the layers and/or around the perimeter of the sheet(s). The breather material preferably should have high shear stiffness and a high coefficient of friction.

In another variation of this embodiment, the beam inflation pressure is used to preload the compression elements against the bottom and/or top walls. In FIG. 31, the compression elements are tape springs 40a. As shown, the top tape springs are bonded to the top wall, but those on the bottom are constrained in sleeves 96. The beam is inflated using inflation bladders, and the inflation force presses the bottom tape springs against the bottom wall. As in the previous example, shear is inhibited by friction.

As shown, the sleeve material is needed primarily to keep the bottom tape springs in place when the beam is deflated and rolled up. For best results, the sleeve should have excess lateral (Y-direction) slack so that the full pressure force is applied to the bottom tape springs, and the bottom wall bears the Y-axis tension resulting from the inflation pressure. The sleeves can also be formed by using a series of threads or bands to hold the compression elements in position.

As shown, the sleeve material, baffles, and top and bottom walls are preferably air-permeable, however, it is also possible to avoid the need for the inflation bladders if the sleeve material and top, bottom and side walls are impermeable.

In another variation, both the sleeve material and the bottom wall are impermeable, and the sleeve pockets are plumbed to a port. If the port is blocked during inflation of the beam, the air trapped in the sleeve pockets will prevent shear-locking of the bottom tape springs. Once full pressure is reached, the port can be vented to the atmosphere (e.g., by opening a valve). The air trapped in the sleeves will be driven out and the tape springs will be shear-locked. This procedure can result in a more accurate final shape of the beam than if shear-locking occurs during partial inflation. A passive version of this process is also possible if the sleeve and/or bottom wall are very slightly permeable. During inflation the air in the sleeves will take some time to leak out, thus delaying the clamping and shear-locking of the bottom tape springs. This variation does not require a port or valve.

As shown in FIG. 32, the principle of using internal pressure and friction to cause shear-locking can also be
applied to multi-layer compression elements, in this case tape springs. This example also avoids the use of bladders by using impermeable material for the sleeves and sidewalls.

[0123] In both FIGS. 31 and 32, the topmost tape spring was bonded to the top surface. This is beneficial to avoid wrinkles in the top wall as the beam is inflated, but wrinkles can also be avoided by delaying the expulsion of air from the sleeves. In accordance with the invention, it is also acceptable for the topmost tape spring, or other compression element to be slid ingly accepted by the sleeve.

[0124] The above examples are not to be considered limiting. The tape springs or sheet may be replaced by any other rollable compression element such as rods, strips, bars, etc. The compression elements may be single layer or multi-layer and may be disposed on the top wall or bottom wall of the beam, and any combination of pressure or vacuum may be used to clamp and shear-lock the compression elements to the top and bottom walls or to the baffles.

[0125] In one embodiment, the compression elements are pre-stressed so as to make the beam roll-up automatically or with reduced effort when the beam is deflated. The pre-stress can be imparted either prior to after attaching to the air-beam structure. If the compression elements are sufficiently ductile (e.g., metal) pre-stress can be achieved by rolling the material or the final assembly through a sheet metal roll, or wrapping it around a mandrel that is significantly smaller than the desired stowed diameter. If the compression elements are made of FRP, pre-stress can be achieved, for example by wrapping on a mandrel prior to final curing (e.g., using time, elevated temperature or UV). FRP can also be wrapped on a mandrel and stress-relieved, by raising the temperature above the stress-deflection temperature. This is most effective if the polymer is a thermoplastic.

[0126] For best results, the tendency of the compression elements to roll-up, i.e., the bending moment, should be greatest at the end of the beam farthest from the inflation port. This will tend to cause the beam to roll up more neatly. The rolled-up beam can be further compacted by twisting the inside of the roll while holding the outside. When inflated, the beam will un-roll like a party favor.

[0127] Although specific features of the invention are shown in some drawings and not in others, this is for convenience only as each feature may be combined with any or all of the other features in accordance with the invention. The words “including”, “comprising”, “having”, and “with” as used herein are to be interpreted broadly and comprehensively and are not limited to any physical interconnection. Moreover, any embodiments disclosed in the subject application are not to be taken as the only possible embodiments. Other embodiments will occur to those skilled in the art and are within the following claims.

[0128] In addition, any amendment presented during the prosecution of the patent application for this patent is not a disclaimer of any claim element presented in the application as filed: those skilled in the art cannot reasonably be expected to draft a claim that would literally encompass all possible equivalents, many equivalents will be unforeseeable at the time of the amendment and are beyond a fair interpretation of what is to be surrendered (if anything), the rationale underlying the amendment may bear no more than a tangential relation to many equivalents, and/or there are many other reasons the applicant can not be expected to describe certain insubstantial substitutes for any claim element amended.

What is claimed is:
1. A sandwich beam comprising:

   a core configured to maintain a predetermined spacing between the walls when the core is filled with gas and to resist shear when the beam is loaded in bending;

   a port for filling the core with gas, said gas biasing both walls in tension, said tension tending to increase in the second wall and decrease and cause a compression load in the first wall in response to a sufficiently large applied bending load; and

   a compression element fixed only with respect to the first wall and configured (a) to support the compression load so that the beam is stronger at a given gas pressure and (b) to flex sufficiently to allow the beam to be rolled up when the gas is emptied from the core via the port.

2. The sandwich beam of claim 1 in which the beam has a load capacity X without the compression element and a load capacity of N times X when the compression element is added to the beam.

3. The sandwich beam of claim 2 in which N is greater than 1.5.

4. The sandwich beam of claim 1 in which the beam is at least 1.5x weaker when loaded in the reverse direction.

5. The sandwich beam of claim 1 in which the compression element is a sheet of material secured to the outer surface of the first wall.

6. The sandwich beam of claim 1 in which the first and second walls are fabric.

7. The sandwich beam of claim 1 in which the core includes a plurality of drop-stitches between the first and second walls.

8. The sandwich beam of claim 6 in which the drop-stitches are angled.

9. The sandwich beam of claim 1 in which the compression element is between \( \frac{1}{16} \) and \( \frac{1}{8} \) inches thick.

10. The sandwich beam of claim 1 in which the compression element is selected from materials including fiber reinforced polymers, polymer films, polymer sheets, metals, wood, and wood-based products.

11. The sandwich beam of claim 1 in which the compression element is flat.

12. The sandwich beam of claim 1 in which the compression element is curved concave.

13. The sandwich beam of claim 1 in which the compression element is curved convex.

14. The sandwich beam of claim 1 in which the core includes baffles.

15. The sandwich beam of claim 14 in which the baffles are angled.

16. The sandwich beam of claim 14 in which the baffles are angled and intersecting.

17. The sandwich beam of claim 14 in which the baffles are tube shaped.

18. The sandwich beam of claim 1 in which the core includes foam.

19. The sandwich beam of claim 1 in which there are a plurality of compression elements.

20. The sandwich beam of claim 19 in which each compression element is a flat strip.

21. The sandwich beam of claim 19 in which the compression elements are rods.

22. The sandwich beam of claim 19 in which the compression elements are tape springs.
23. The sandwich beam of claim 1 further including a skin over the compression element.

24. The sandwich beam of claim 1 in which the core includes baffles and there is a compression element associated with select baffles each including a top leaf hinged to a side leaf.

25. The sandwich beam of claim 1 in which there is a vacuum pocket about the compression element.

26. The sandwich beam of claim 1 in which the compression element includes multiple plies that are clamped together by pressure or vacuum force, but are allowed to slide when the beam is deflated, thus allowing the beam to be rolled up more easily.

27. A waterboard comprising:
   upper and lower walls;
   a core configured to maintain a predetermined spacing between the walls when the core is filled with gas and to resist shear when the waterboard is loaded in bending;
   a port for filling the core with gas, said gas biasing both walls in tension, said tension tending to increase in the lower wall and decrease and cause a compression load in the upper wall in response to a sufficiently large applied bending load; and
   a compression sheet secured about the upper wall and configured to support the compression load on the upper wall and to flex sufficiently to allow the waterboard to be rolled up when the gas is emptied from the core via the port.

28. A method of making a sandwich beam, the method comprising:
   securing a first wall to a second wall via a core configured to maintain a predetermined spacing between the walls when the core is filled with gas and to resist shear when the beam is loaded in bending; and
   applying a compression element only to and fixed with respect to the first wall, the compression element configured to support the compression load on the first wall resulting from bending so that the beam is stronger at a given gas pressure and configured to flex sufficiently to allow the beam to be rolled up when the gas is emptied from the core via the port.

29. The sandwich beam of claim 1 having one or more second compression elements received by one or more sleeve pockets attached to the second wall.

30. The sandwich beam of claim 1 in which the compression element is pre-curved such that the beam rolls up when deflated and unrolls when inflated.

31. A sandwich beam comprising:
   first and second spaced walls;
   a core configured to maintain a predetermined spacing between the walls when the core is filled with pressurized gas and to resist shear when the beam is loaded in bending;
   a port for filling the core with gas; and
   narrow compression elements fixed to both walls and configured (a) to support compression loads in the first and second walls due to bending loads applied to the beam in either direction (b) to flex sufficiently to allow the beam to be rolled up when the gas is emptied from the core via the port, and (c) to nest when deflated to allow each compression element to bend about its neutral axis.

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