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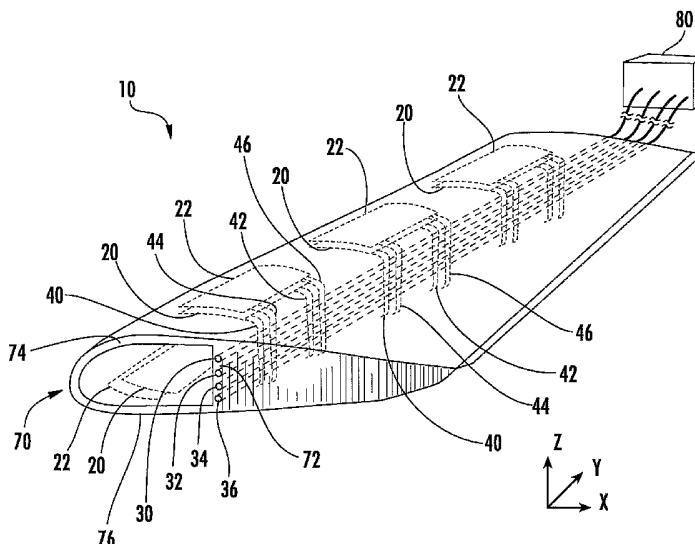
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[Continued on next page]

(54) Title: STRUCTURALLY INTEGRATED CIRCUIT AND ASSOCIATED METHOD



(57) Abstract: A composite structural member (10) with an integrated electrical circuit and an associated method of manufacture are provided. The structural member includes a plurality of layers (12, 14, 16) of structural reinforcement material, and two or more electrical devices (20, 22) are disposed at least partially between the layers with an intermediate layer (14) of the structural reinforcement material disposed between the electrical devices. At least one electrical bus (30, 32, 34, 36) is disposed in the structural member, and each electrical device is connected to the bus by a conductive electrode (40, 42, 44, 46). Thus, the electrodes (40, 42, 44, 46) can extend through the intermediate layer of the structural reinforcement material to connect each of the electrical devices to one or more of the buses (30, 32, 34, 36).

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STRUCTURALLY INTEGRATED CIRCUIT AND ASSOCIATED METHOD

FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

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BACKGROUND OF THE INVENTION

1) Field of the Invention

10 [0002] The present invention relates to a structural member with an integrated electrical
circuit and, in particular, to a structurally integrated circuit including multiple electrical devices
that are electrically connected by electrodes to one or more electrical buses.

2) Description of Related Art

[0003] Electrical devices are often used in conjunction with a structural member. For
15 example, electrical devices such as sensors and actuators can be embedded within, mounted on,
or otherwise structurally integrated with the structure of a vehicle such as an airplane, spacecraft,
land vehicle, ship, and the like. Other examples of electrical devices mounted in conjunction
with a structural member can include machinery, buildings, and the like. The sensors can be
used to detect temperature, motion, stress, strain, damage, and the like at different locations
20 throughout the structure. The actuators can be used to adjust various control portions of the
structure such as an elevator, rudder, aileron, helicopter rotor, door, or valve. Data generated by
the electrical devices is typically communicated via electrical wires from the devices to a
computer or other circuit device for processing. Similarly, control signals and electrical power
are typically transmitted via electrical wires from the computer, power supply, and/or other
25 circuit device to the actuators and sensors. Thus, a network of wires is often required for
controlling and monitoring the electrical devices. Each wire usually includes one or more
conductive strands, for example, copper strands, which are covered with an insulative jacket.
Parallel wires can be held in groups with bundle fasteners, such as cable tie straps or shrink
tubing. Fasteners such as clips, ties, and the like are often used to connect the wires or bundles
30 of wires to the structural member at successive locations along the length of the wires so that the
position of the wires is maintained. In some cases, an extensive and complex network of wires
may be required.

[0004] In some applications, however, it is difficult or impractical to connect the wires to
the structural member. For example, the structural member may not define any interior cavities

through which the wires can be passed, and the environmental conditions outside the structural member may be harsh, for example, excessively warm or cold or subject to mechanical stress, moisture, or corrosive agents. In addition, the weight and size of the wires may negatively affect the performance of the structural member. Further, in applications where the structural member
5 undergoes significant or repeated mechanical stress, the resulting strains in the wires can break the wires regardless of whether the wires are connected to the structural member.

[0005] One illustrative example is a blade of a helicopter rotor, which is rotated quickly around a hub of the rotor. In some cases, it may be desirable to provide wires that extend along the length of the blade, for example, to monitor sensors or control actuators in or on the blade.

10 The wires cannot be connected to the outside of the blade because of the external conditions, e.g., wind, moisture, and the like. Further, the blade undergoes significant stress due to centripetal force when rotated at high speeds. If the wires are not connected successively or continuously along the length of the blade, each wire will also be strained due to the centripetal force that results from the rotation. On the other hand, if the wires are connected to the blade,
15 the wires will be strained at the same rate as the blade. In either case, the stress that results in the wires can break or fatigue the wires, rendering the electrical devices ineffective.

[0006] Thus, there exists a need for a structurally integrated circuit that can be provided in a structural member for transmitting electrical signals or power. The circuit should be capable of functioning in harsh environmental conditions that include strain and temperature variations,
20 moisture, and corrosive agents. The structurally integrated circuit should also be adaptable to structural members that do not include internal passages for wiring. The circuit should be capable of providing a complex electrical network in which multiple electrical devices are connected to one or more buses. Further, the circuit should resist failure, even when the structural member is subjected to significant or repeated stresses.

BRIEF SUMMARY OF THE INVENTION

[0007] The present invention provides a composite structural member with an integrated electrical circuit. The member includes a plurality of layers of structural reinforcement material and first and second electrical devices that are disposed at least partially between the layers of
30 the structural reinforcement material. At least one intermediate layer of the structural reinforcement material is disposed between the electrical devices so that the electrical devices are disposed in different layers and directed toward opposite sides of the intermediate layer. Each of the layers can be formed of one or more composite laminate plies that are impregnated

with a matrix material. One or more electrical buses that are disposed at least partially between the layers of the structural reinforcement material extend along the structural member.

Electrodes extend between each of the electrical devices and one or more of the buses so that the electrical devices are electrically connected to the buses.

5 [0008] According to one embodiment of the present invention, the structural member includes at least two buses, which can be separated by spacers. First and second electrodes can connect each of the first and second electrodes to the first bus, and at least one electrode can connect the second bus to one or more of the electrical devices. Thus, the electrodes can extend through one or more of the layers of the reinforcement material, e.g., through apertures in one or
10 more of the layers. Further, the electrical devices can be configured in a plane that is nonparallel to a plane defined by the buses, and the electrodes can extend in a nonlinear configuration to connect the electrical devices to the buses.

[0009] Each electrode and bus can include one or more tows, each of which is formed of a plurality of reinforcement fibers, and which include a conductive material such as a metallic
15 coating on the fibers or tows.

[0010] According to another embodiment, the present invention provides a method of manufacturing a composite structural member with an integrated electrical circuit. The method includes providing a plurality of layers of structural reinforcement material and disposing first and second electrical devices at least partially between the layers of the structural reinforcement material with at least one intermediate layer therebetween. At least one electrical bus is disposed
20 between the layers of the structural reinforcement material so that the bus extends along the structural member. First and second electrodes are connected between the bus and the first and second electrical devices, thereby electrically connecting the electrical devices to the bus.

[0011] According to one aspect of the invention, multiple buses are disposed along the structural member, and the buses can be electrically isolated by placing one or more spacers therebetween. The first bus can be connected to each of the electrical devices, and the second bus can also be connected to one or more of the electrical devices. For example, one or more of
25 the electrodes can be disposed through the intermediate layer of reinforcement material.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

[0012] Having thus described the invention in general terms, reference will now be made to the accompanying drawings, which are not necessarily drawn to scale, and wherein:

[0013] Figure 1 is a perspective view schematically illustrating a structural member with a structurally integrated electrical circuit according to one embodiment of the present invention;

[0014] Figure 2 is a section view schematically illustrating the structural member of Figure 1;

[0015] Figure 3 is a plan view schematically illustrating one of the buses of the structural member of Figure 1;

[0016] Figure 3A is an enlarged view schematically illustrating a portion of the bus of Figure 3;

[0017] Figure 4 is a plan view schematically illustrating one of the electrodes of the structural member of Figure 1;

[0018] Figure 4A is a section view schematically illustrating the electrode of Figure 4, as seen along line 4A-4A of Figure 4;

[0019] Figures 5A-5F are perspective views schematically illustrating a portion of the structural member of Figure 1 during various stages of manufacture according to one embodiment of the present invention;

[0020] Figure 6 is a perspective view schematically illustrating a portion of the structural member of Figure 1 being cured between a tool and an inflatable bladder according to one embodiment of the present invention;

[0021] Figure 7 is a perspective view schematically illustrating a portion of a structural member during manufacture according to another embodiment of the present invention; and

[0022] Figure 8 is a section view schematically illustrating a portion of the structural member of Figure 7 during manufacture.

DETAILED DESCRIPTION OF THE INVENTION

[0023] The present invention now will be described more fully hereinafter with reference to the accompanying drawings, in which some, but not all embodiments of the invention are shown. Indeed, this invention may be embodied in many different forms and should not be construed as limited to the embodiments set forth herein; rather, these embodiments are provided so that this disclosure will satisfy applicable legal requirements. Like numbers refer to like elements throughout.

[0024] Referring now to the figures, and in particular to Figure 1, there is shown a structural member **10** with a structurally integrated electrical circuit according to one embodiment of the present invention. The term “structural member” is not meant to be limiting, and the structural member **10** can be a single component or multiple assembled members, for example, building components or machinery. Further, the structural member **10** can be used in any type of structure including vehicles such as aerospace vehicles, aircraft, marine vehicles, automobiles and other land vehicles, and the like. For example, as shown in Figure 1, the structural member **10** is a helicopter rotor blade with four wire buses **30, 32, 34, 36** extending along the length of the member **10**. In particular, the structural member **10** of Figure 1 includes a closed-cell beam **70**, which can be generally D-shaped in cross-section, and is typically referred to as a “D-spar.” The D-spar **70** includes a web **72** and upper and lower flanges **74, 76**. The buses **30, 32, 34, 36** are disposed in the web **72** of the D-spar **70** along a longitudinal direction of the member **10**.

[0025] The structural member **10** illustrated in Figure 1 is formed of a composite material including a plurality of layers of laminate plies of reinforcement material that are impregnated with a matrix material. The layers are indicated by reference numerals **12, 14, 16**, though it is understood that any number of the layers **12, 14, 16** can be provided. For example, each illustrated layer **12, 14, 16** can include multiple individual layered members. The layers **12, 14, 16** can be formed of sheets or mats of reinforcement materials such as carbon fibers, sometimes referred to as graphite, fiberglass, or an aramid material such as Kevlar®, a registered trademark of E. I. du Pont de Nemours and Company. Alternatively, the layers **12, 14, 16** can be formed by disposing tows or filaments of the reinforcement material. In either case, the reinforcement material can be disposed separately from or in combination with the matrix material. For example, the reinforcement material can be preimpregnated with the matrix material, or the matrix material can be disposed as a distinct sheet of material. The matrix material, which can be formed of a thermoset or thermoplastic material such as a resin, is typically cured by subjecting the structural member **10** to heat and pressure so that the matrix material permeates the reinforcement material and hardens. The formation of composite materials using reinforcement and matrix materials is well known, and further explanation of such conventional formation techniques is unnecessary for an understanding of the present invention.

[0026] The structurally integrated electrical circuit is typically formed in the structural member **10** by disposing components of the circuit in the structural member **10** during the lay-up of materials of the structural member **10**, i.e., before curing the structural member **10**, which may

include procured assemblies. The circuit includes electrical devices **20, 22** that can be disposed within the structural member **10**. Each of the electrical devices **20, 22** can be any of a variety of active or passive electrical devices. For example, each electrical device **20, 22** can be an actuator such as a piezo-fiber actuator pack. When used in a helicopter rotor blade, as shown in Figure 1, actuator packs can be used in the upper and lower flanges **74, 76** to change the shape of the blade and thereby provide active aerodynamic control and vibration reduction. Alternatively, each of the electrical devices **20, 22** can be a sensor, such a strain gauge that senses deformation in the structural member **10**, a light-emitting device, a computer, a processor, a power supply, or any other circuit device. The structural member **10** can include any number of the electrical devices **20, 22**, each of which can be controlled independently or in combination.

[0027] The electrical circuit also includes a plurality of electrical communication devices for supplying power to, electrically grounding, communicating data with, and/or transmitting control signals to the electrical devices **20, 22**. In particular, the circuit includes the one or more electrical wire buses **30, 32, 34, 36** that extend along the structural member **10**, as well as a plurality of electrodes **40, 42, 44, 46** that connect each bus **30, 32, 34, 36** to the respective electrical devices **20, 22**. Thus, the buses **30, 32, 34, 36** and electrodes **40, 42, 44, 46** provide electrical connections to the electrical devices **20, 22** for such functions as monitoring, actuating, and/or powering the electrical devices **20, 22**.

[0028] The buses **30, 32, 34, 36** can be various types of electrical conductors, e.g., woven or braided conductive wires such as are described in U.S. Application No. 10/369,906, filed February 20, 2003, which application is assigned to the assignee of the present application, and which application is incorporated herein in its entirety by reference. Typically, each bus **30, 32, 34, 36** includes a plurality of tows, each tow being formed of a plurality of fibers. Some of the fibers can be nonconductive. For example, the fibers can be formed of Kevlar® or other conventional composite reinforcement materials. However, at least some of the fibers of each bus **30, 32, 34, 36** are electrically conductive. In this regard, the conductive fibers can be formed of an electrically conductive material such as metal. For example, Figures 3 and 3A illustrate the bus **30** according to one embodiment in which the bus **30** is formed of a plurality of braided tows **31**, each tow **31** including metallic fibers **33a** that are intertwined with nonconductive fibers **33b**. Alternatively, the conductive fibers can be formed of a nonconductive material that is coated with an electrically conductive material such as silver, copper, gold, and the like. In other embodiments of the present invention, the buses **30, 32, 34, 36** can be formed of conventional conductive wires, such as braided or monofilament copper wire. In any case, the buses **30, 32,**

34, 36 can extend longitudinally along the structural member 10 and from the structural member 10 to a circuit device such as a controller, computer, power source, or the like. For example, if the structural member 10 is a helicopter rotor blade, the buses 30, 32, 34, 36 can be electrically connected to a controller 80 mounted in the helicopter. That is, each bus 30, 32, 34, 36 can
5 extend from the structural member 10 to the circuit device, or an intermediate connection device such as a wire or other conductive element can be provided therebetween.

[0029] The term “longitudinal” is intended to indicate generally that the buses 30, 32, 34, 36 extend generally along a direction of the structural member 10 between two or more connection points or nodes of the circuit that are spaced apart, e.g., between the controller 80 and
10 the electrodes 40, 42, 44, 46. However, the particular path of the buses 30, 32, 34, 36 and electrodes 40, 42, 44, 46 need not be a straight or direct path. Instead, the components may be routed in a nonlinear configuration according to a variety of design factors that are particular to the structural member 10 including, for example, the shape of the structural member 10, the placement of the electrical devices 20, 22, the anticipated variation of stress and strain
15 throughout the structural member 10, and the like.

[0030] The electrodes 40, 42, 44, 46 can be formed of various types of electrical conductors. For example, each electrode 40, 42, 44, 46 can include one or more conductive tows that extend along a longitudinal direction of the electrode 40, 42, 44, 46. Figures 4 and 4A illustrate one exemplary electrode 40, which includes a conductive tow 41 that is sandwiched
20 between plies of dielectric material 43 and/or an adhesive material 43a. Each conductive tow 41 can be formed of a plurality of fibers that can be formed of materials including, but not limited to, carbon, nylon, fiberglass, and aramids such as Kevlar® fibers. A conductive coating can be provided on the tow 41, such as a coating of conductive material such as silver, nickel, gold, copper, beryllium, aluminum, and alloys thereof. The electrode 40, 42, 44, 46 can also include
25 contacts 45 at the opposite ends of the tow 41, such as electrically conductive pads formed of fabric plated with a conductive metal for connecting the electrode 40, 42, 44, 46 to one of the buses 30, 32, 34, 36, one of the electrical devices 20, 22, and the like.

[0031] Each of the dielectric plies 43 is configured to electrically insulate at least a portion of the tow 41. The plies 43 can be formed of a variety of dielectric materials, which can be
30 reinforced or non-reinforced. For example, the plies 43 can be formed of a flexible film, such as Kapton® polyimide film, a registered trademark of E. I. du Pont de Nemours and Company, or another non-reinforced or reinforced dielectric material. The plies 43 can be subjected to a curing operation before being integrated with the structural member 10, or the electrodes 40, 42,

44, 46 can be disposed in the structural member **10** in an uncured state and subsequently co-cured with the structural member **10**. Such electrodes are further described in U.S. Application No. _____, titled "STRUCTURALLY INTEGRABLE ELECTRODE AND ASSOCIATED ASSEMBLY AND FABRICATION METHOD," filed concurrently herewith, assigned to the assignee of the present application, and which application is incorporated herein in its entirety by reference. Alternatively, the electrodes **40, 42, 44, 46** can be formed of other electrically conductive members. For example, each electrode **40, 42, 44, 46** can have a structure similar to the buses **30, 32, 34, 36**, or the electrodes **40, 42, 44, 46** can be formed of conventional electrical wires or the like.

[0032] Figures 5A-5F illustrate a portion of the structural member **10** of Figure 1 during successive stages of manufacture according to one embodiment of the present invention. In particular, a portion of the web **72** and one of the flanges **74** of the D-spar portion **70** of the structural member **10** are illustrated in Figures 5A-5F. As shown in Figure 5A, the first layer **12** of the reinforcement material of the structural member **10** is disposed on a tool **50** that generally defines an inner mold line, or inner contour, of a space in the D-spar portion **70**. The first layer **12** can include one or more sheets of the reinforcement, dielectric material. (Alternatively, a conductive or semi-conductive reinforcement material can be placed alone or in combination with the second layer **14** of dielectric material to form an equivalent first layer **12**.) The first layer **12** can include one or more sheets of the reinforcement material. The first electrical device **20** is disposed on the first layer **12**, in a position corresponding to the upper flange **74** of the rotor blade. Electrodes **40, 42** are connected to the first electrical device **20**, either before or after electrical device **20** is disposed on the first layer **12**. The second layer **14** of the reinforcement material is disposed over the first electrical device **20**, and the second electrical device **22** is disposed on the second layer **14**, with the electrodes **44, 46** connected to the second electrical device **22**. The electrodes **44, 46** extending from the second electrical device **22** are typically offset relative to the electrodes **40, 42** of the first electrical device **20**, e.g., in the y-direction as illustrated, thereby improving the electrical isolation between the electrodes **40, 42, 44, 46** of the different electrical devices **20, 22**. Offsetting electrodes also offsets the actuator packs in the y-direction to provide a more smoothly tapering geometrical transition of the structural lay-up. As shown in Figure 5C, the third layer **16** of the reinforcement material is disposed over the second electrical device **22**.

[0033] Any number of the electrical devices **20, 22** can be disposed on the structural member **10**. For example, additional electrical devices can be disposed between the first and

second layers **12, 14** of the reinforcement material, e.g., at positions offset from the first electrical device **20** in the y-direction as illustrated in Figure 1. Further, additional electrical devices **20, 22** can be provided on the third layer **16**, with additional reinforcement layers disposed therebetween, to form a stacked configuration of three or more electrical devices **20, 22**. The second and third layers **14, 16** as well as any subsequent layers of the reinforcement material can define staggered edges **15, 17**, i.e., such that the layers **14, 16** extend to different positions in the x-direction, as shown in Figure 5C. A small offset may be imposed on layer **16** and subsequent layers to provide a smooth tapering geometrical transition of the structural lay-up.

[0034] As illustrated in Figure 5D, the first bus **30** is disposed on the first layer **12**, and a spacer **38** can be disposed with the first bus **30**. The spacer **38** can be formed of a rigid, dielectric material such as precured composite fiberglass, such that the spacer **38** can provide a rigid path along which the first bus **30** is disposed for supporting the first bus **30**. Some of the electrodes **40, 42, 44, 46** are selectively connected to the first bus **30**. That is, any of the electrodes **40, 42, 44, 46** from the electrical devices **20, 22** stacked in different layered positions can be bent into contact with the bus **30**. For example, one of the electrodes **40, 44** that are connected to each of the electrical devices **20, 22** can be connected to the first bus **30**. In some cases, each of the electrodes **40, 44** that are connected to the first bus **30** can define different lengths so that the electrodes **40, 44** extend from the respective electrical devices **20, 22** in the positions in the layers **12, 14, 16** of the reinforcement material to the bus **30** with sufficient overlap for forming a connection therebetween. That is, each of the electrodes **40, 42, 44, 46** extending from each electrical device **20, 22** can define a length that is sufficient for extending to the respective bus **30, 32**.

[0035] Thereafter, an additional portion **14a** of the second layer **14** of the reinforcement material is disposed over the first bus **30** and the connections between the first bus **30** and the electrodes **40, 44**. The additional portion **14a** may be a continuous extension of the first layer **14** or may be a separate piece that could have a different material and thickness than the rest of the first layer **14** and may or may not contact the rest of the first layer **14**. The second bus **32** is disposed generally parallel to the first bus **30** and opposite the spacer **38** from the first bus **30** such that the spacer **38** electrically isolates the two buses **30, 32**. In embodiments in which more than two buses **30, 32, 34, 36** extend along the structural member **10**, as illustrated in Figure 1, spacers **38** can be provided between each of the electrodes **40, 42, 44, 46**. For example, spacers **38** can be provided between the second and third buses **32, 34** or between the third and fourth

buses **34, 36** to electrically isolate the buses **30, 32, 34, 36**. Thus, the spacers **38** can separate the buses **30, 32, 34, 36** and also function to keep inner structural plies of the layers **14, 16** relatively straight and flat in the inner surface of the web **72** of the structural member **10**. Each spacers **38** can be formed of a number of layers of dielectric laminate that are stacked to approximately the same thickness of the buses **30, 32, 34** and **36**. The spacers **38** are compacted, cut, and cured. The spacers **38** can be pre-cured prior to being placed in the lay-up of the structural member **10** or they can be cured during the final cure of the structural member **10**.

[0036] As shown in Figure 5E, some of the electrodes **40, 42, 44, 46** are selectively connected to the second bus **32**. For example, one of the electrodes **42, 46** connected to each of the electrical devices **20, 22** can be connected to the second bus **32**, in a manner similar to the connections between the electrodes **40, 44** and the first bus **30** described above. The electrodes **42, 46** can define different lengths to accommodate the different distances from each electrical device **20, 22** to the second bus **32**. As shown in Figure 5F, an additional portion **16a** of the third layer **16** of the reinforcement material is disposed over the electrodes **42, 46** and the second bus **32**. The additional portion **16a** may be a continuous extension of the second layer **16** or may be a separate piece that could have a different material and thickness than the rest of the second layer **16** and may or may not contact the rest of the second layer **16**.

[0037] The connections between the electrodes **40, 42, 44, 46** and the electrical devices **20, 22** and between the electrodes **40, 42, 44, 46** and each bus **30, 32, 34, 36** can be formed by welding, adhering, or otherwise connecting the members. For example, a conductive epoxy can be disposed between each electrode **40, 42, 44, 46** and the respective electrical device **20, 22** or bus **30, 32, 34, 36**. In some cases, each connection can be a solder-like bond that is formed by heating and subsequently cooling the members, and such heating can be provided as part of the curing operation of the structural member **10** or separately before the structural member **10** is cured. Alternatively, the electrodes **40, 42, 44, 46** can be connected by other materials or by a device such as a mechanical connector.

[0038] Each of the layers **12, 14, 16** can be formed of the same or different reinforcement materials. Typically, each layer **12, 14, 16** disposed between members of the electrical circuit has sufficient electrical and dimensional properties to prevent electrical communication therethrough. For example, the second layer **14** can be sufficiently dielectric to prevent electrical conduction between the electrodes **40, 42, 44, 46** of the first and second electrical devices **20, 22**, even when the electrodes **40, 42, 44, 46** carry high voltages and/or high currents.

[0039] The electrodes **40, 42, 44, 46** can extend through one or more of the layers **12, 14, 16** to positions defined between any of the different layers **12, 14, 16**. For example, as illustrated in Figures 5C and 5E, the electrode **44** connected to the second electrical device **22** extends from the electrical device **22**, which is between the second and third layers **14, 16**, through the second layer **14** to the first bus **30**, which is between the first and second layers **12, 14**. The electrode **42** is connected to the first electrical device **20**, which is between the first and second layers **12, 14**, and extends through the second layer **14** to the second bus **32**, which is between the second and third layers **14, 16**. Similarly, other electrical devices **20, 22** can be disposed in any position among the stacked layers **12, 14, 16** of reinforcement material, and each electrical device **20, 22** can be connected to one or more buses **30, 32, 34, 36** that are disposed between the corresponding layers **12, 14, 16** or different layers of the reinforcement material. Each of the layers **12, 14, 16** can be disposed in multiple portions, e.g., as described above in connection with the second and third layers **14, 16** that include portions **14a, 16a**, respectively. Thus, each layer **12, 14, 16** can define one or more apertures **18** through which the electrodes **40, 42, 44, 46** can extend. The aperture **18** illustrated in Figure 5E is a continuous slit through the second layer **14** that completely separates portion **14a** from the rest of the layer **14**. Alternatively, the aperture can instead be a local, discrete hole through the layer **14** such that each of the layers **12, 14, 16** can be disposed as a single portion that defines one or more apertures through which the electrodes **40, 42, 44, 46** and/or the buses **30, 32, 34, 36** can extend.

[0040] With the structural member **10** assembled as shown in Figure 5F, the structural member **10** can be cured by heat and pressure to form the structural member **10** as a unified structure. For example, the structural member **10** can be cured in an autoclave according to a temperature and pressure schedule that is conventionally used for curing composite structures. In some cases, the structural member **10** can be disposed in a vacuum bag, i.e., a bag or bladder that is evacuated, during the curing process. Further, as shown in Figure 6, a pressurized bladder **52** can be placed inside the D-spar used to provide a compressive force on the interior of structural member **10**, e.g., by disposing the bladder **52** within the structural member **10** and inflating the bladder **52** to urge the structural member **10** outward against a rigid tool **54**. If any of the electrical devices **20, 22**, the buses **30, 32, 34, 36**, and/or the electrodes **40, 42, 44, 46** include curable components, these components can be cured before lay-up with the rest of the structural member **10**. Alternatively, any of the electrical devices **20, 22**, buses **30, 32, 34, 36**, and/or electrodes **40, 42, 44, 46** can be co-cured with the structural member **10**. Similarly, the

spacers **38** and select layers **12, 14, 16** of the reinforcement material can be pre-cured or partially pre-cured, or these members can be cured with the rest of the structural member **10**.

[0041] The structural member **10** can be cured while disposed on the tool **50**. In addition, or alternative, the structural member **10** can be cured on another tool that defines another surface of the member. For example, as illustrated in Figure 5F and 6, the structural member **10** defines inner and outer mold lines **60, 62** i.e., an inner contour surface **60** corresponding to the tool **50** and an outer contour surface **62** opposite thereto. After the structural member **10** is configured on the tool **50**, the tool **54** can be configured against the outer mold line **62** of the member **10** to urge the outer mold line **62** of the structural member **10** to a desired configuration during the curing operation. Further, in some cases, the structural member **10** can be transferred to the outer tool **54** and cured without the use of the inner tool **50**. For example, as shown in Figure 6, the first tool **50** can be replaced with the inflatable bladder **52** that is disposed against the inner mold line **60** of the structural member **10** and pressurized for the curing operation such that the structural member **10** is compressed during curing.

[0042] If the structural member **10** is to be compressed between a rigid tool and a non-rigid tool, such as the rigid outer tool **54** and the non-rigid bladder **52**, each of the electrodes **40, 42, 44, 46** can be disposed between the rigid tool **54** and the respective bus **30, 32, 34, 36** to which the electrode **40, 42, 44, 46** is connected. For example, as shown in Figures 5D and 5E, each electrode **40, 42, 44, 46** is connected to a respective one of the buses **30, 32, 34, 36** and disposed between the respective bus **30, 32, 34, 36** and the outer mold line **62**, where the rigid tool **54** is typically located. The structural member **10** is typically compressed throughout during curing. However, while compression proximate to the rigid tool **54** can be relatively uniform, compression proximate to the inflatable bladder **52** can be nonuniform, i.e., the amount of compression during curing can vary throughout the member **10**. For example, the relative incompressibility of the buses **30, 32, 34, 36** relative to the layers **12, 14, 16** of reinforcement material can cause the inner mold line **60** to change shape during compression. If each electrode **40, 42, 44, 46** is positioned between the respective bus **30, 32, 34, 36** and the rigid tool **54** at the outer mold line **62**, the rigid tool **54** tends to support the electrode **40, 42, 44, 46** during curing and prevent the electrode **40, 42, 44, 46** from being excessively or sharply bent during curing.

[0043] The tools **50, 54** can define a variety of contours according to the desired shape of the finished structural member **10**. Further, the tools **50, 54** can define contours to accommodate the difference in the number and thickness of the components layered between the inner and outer mold lines **60, 62** of the structural member **10** in different portions of the structural member

10. For example, the tool **50** can define contours at the inner mold line **60** corresponding to the placement of the buses **30, 32, 34, 36**. Tool **50** can define a contour such that after all plies have been placed and compacted, the outer definition of the plies will nearly conform to the inner mold line of tool **54**. This allows the minimization of movement in the plies and embedded wiring/electrodes when the internal bladder is inflated and puts pressure on the laminate layers, as the tool **54** constrains the opposite side.

[0044] According to one embodiment of the present invention, the layers **12, 14, 16** of reinforcement material of the structural member **10** are formed of a composite material including fibers or tows that are impregnated with a matrix of a cured resin. The fibers or tows can be disposed individually or as preformed laminar sheets of material. In any case, each of the electrical devices **20, 22**, the buses **30, 32, 34, 36**, and/or the electrodes **40, 42, 44, 46** can be structurally integrated with the structural member **10**. For example, each of the electrical devices **20, 22**, buses **30, 32, 34, 36**, and electrodes **40, 42, 44, 46** can be embedded between the reinforcement materials of a composite structural member **10** as illustrated in Figure 2.

Typically, the components are embedded into the structural member **10** before the composite material of the structural member **10** is cured so that as the structural member **10** is cured, each of the components is integrated with the structural member **10**. Further, in some cases, the components can include tows, curable resins, or other composite structural materials that can be compatible with the composite materials of the structural member **10** so that the components can form a continuous structure with the structural member **10**.

[0045] Thus, the electrodes **40, 42, 44, 46** and buses **30, 32, 34, 36** can be partially or completely embedded or encapsulated in the material of the structural member **10**, and during operation of the structural member **10**, the electrodes **40, 42, 44, 46** and buses **30, 32, 34, 36** can be subjected to substantially the same strains as the structural member **10**. Holes may be drilled into the structural member **10** and through or up to the electrodes **40, 42, 44, 46** and buses **30, 32, 34, 36** to gain electrical access. For access to the buses **30, 32, 34, 36** the holes can be drilled through the D-spar web at one end. Alternatively, the electrodes **40, 42, 44, 46** and buses **30, 32, 34, 36** can be gradually transitioned from fully embedded ply to the upper surface ply for external access to the electrical wiring. Typically, the tows or other components of the electrodes **40, 42, 44, 46** and buses **30, 32, 34, 36** are formed of a material that is strain-compatible with the reinforcement material of the structural member **10** so that the electrodes **40, 42, 44, 46** and buses **30, 32, 34, 36** are unlikely to break or otherwise fail during operation of the structural member **10**. For example, the electrodes **40, 42, 44, 46** and buses **30, 32, 34, 36** can be

formed of a material that is about as strong or compliant as, or stronger or more compliant than, the reinforcement material of the structural member **10**. In other embodiments, the components can be integrated with a structural member **10** formed of other conventional materials including polymers, metals, and the like. Further, the electrical devices **20, 22**, electrodes **40, 42, 44, 46**,
5 and buses **30, 32, 34, 36** can be secured to the structural member **10** in other alternative manners, such as by bonding the components thereto with adhesive, mechanical connectors, and the like.

[0046] Figures 7 illustrates the structural member **10** according to another embodiment of

the present invention in which three electrodes **40, 44, 47** extend from electrical devices (not shown) disposed between multiple layers **12, 14, 16, 19** of the structural material. The three

10 electrodes **40, 44, 47** are connected to the first bus **30**, and the first bus **30** is separated from the second bus **32** by one of the spacers **38**. Electrodes **42, 46, 48** also extend from the electrical

devices and are configured to be connected to the second bus **32**. For purposes of illustrative clarity, the electrodes **42, 46, 48** are positioned against the second bus **32** as the electrodes **42, 46, 48** would typically be configured for connection thereto. However, structural material such

15 as portions **14a, 16a** is typically disposed between the first bus **30** and the electrodes **42, 46, 48** before the electrodes **42, 46, 48** are connected to the second bus **32** to prevent electrical

communication between the first bus **30** and the electrodes **42, 46, 48**. As also shown in Figure 7, the structural member **10** can be disposed on the bladder **52**, with the tool **50** opposite thereto, such that the tool **50** can be removed and the bladder **52** inflated during the subsequent curing

20 operation. In addition, the edges of the layers **14, 16, 19** are spaced apart so that the thickness of the structural material tapers at the bend in the structural member **10**.

[0047] While only two of the buses **30, 32** are illustrated in Figure 7, it is understood that

the electrodes can be connected to any number of the buses. For example, as shown in Figure 8, the four buses **30, 32, 34, 36** are disposed on the first layer **12** of the structural material. Four

25 electrodes **40, 44, 47, 49** in each of the upper and lower flanges **74, 76** are disposed sequentially on the first, second, third, and fourth layers **12, 14, 16, 19** of the structural material, with each of the electrodes **40, 44, 47, 49** being connected to the first bus **30**. Additional electrodes (not

shown) can be connected to each of the second, third, and fourth buses **32, 34, 36**. Figure 8 also illustrates the contoured configuration of the inner mold line **60** as defined by the tool **50**. That

30 is, the tool **50** is contoured to define a recess or channel **61** so that the thickness of the buses **30, 32, 34, 36** and the spacers **38** can be accommodated in the web **72** without excessive bulging or otherwise undesired reconfiguring of the outer mold line **62**.

[0048] Many modifications and other embodiments of the invention set forth herein will come to mind to one skilled in the art to which this invention pertains having the benefit of the teachings presented in the foregoing descriptions and the associated drawings. Therefore, it is to be understood that the invention is not to be limited to the specific embodiments disclosed and
5 that modifications and other embodiments are intended to be included within the scope of the appended claims. Although specific terms are employed herein, they are used in a generic and descriptive sense only and not for purposes of limitation.

THAT WHICH IS CLAIMED:

1. A composite structural member with an integrated electrical circuit, the member comprising:

5 a plurality of layers of structural reinforcement material;
first and second electrical devices disposed at least partially between the layers of the structural reinforcement material, at least one intermediate layer of the structural reinforcement material being disposed between the electrical devices such that the electrical devices are directed toward opposite sides of the intermediate layer;

10 an electrical bus disposed at least partially between the layers of the structural reinforcement material and extending along the structural member;

a first electrode extending between the bus and the first electrical device and electrically connecting the first electrical device to the bus; and

15 a second electrode extending between the bus and the second electrical device and electrically connecting the second electrical device to the bus.

2. A member according to Claim 1 wherein first and second electrical buses extend along the structural member.

20 3. A member according to Claim 2 further comprising an elongate spacer disposed between the first and second buses and configured to electrically isolate the first and second buses.

4. A member according to Claim 2 wherein the first electrode extends between the first bus and the first electrical device and the second electrode extends between the first bus and the
25 second electrical device, and further comprising at least one electrode extending between the second bus and one of the electrical devices.

5. A member according to Claim 2 wherein the first and second buses are generally parallel along a longitudinal direction of the structural member.

30 6. A member according to Claim 2 wherein the intermediate layer of reinforcement material between the electrical devices defines at least one aperture, at least one of the electrodes being disposed through the aperture.

7. A member according to Claim 2 wherein the electrical devices are disposed generally parallel to a first plane and the buses generally define a second plane, the first and second planes being oblique and the electrodes extending in a curved path such that the first end of each
5 electrode is generally parallel to the electrical devices and the second end of each electrode is generally parallel to the buses.

8. A member according to Claim 1 wherein each of the electrodes comprises a tow formed of a plurality of reinforcement fibers and a conductive coating thereon.

10

9. A member according to Claim 1 wherein the bus comprises a plurality of nonlinear tows extending generally in a longitudinal direction, each tow including a plurality of fibers, at least some of the fibers including an electrically conductive metal.

15

10. A member according to Claim 1 wherein the first and second electrodes define different lengths.

11. A member according to Claim 1 wherein each of the layers of the structural reinforcement material is formed of a composite laminate ply impregnated with a matrix
20 material.

12. A method of manufacturing a composite structural member with an integrated electrical circuit, the method comprising:

providing a plurality of layers of structural reinforcement material;

25

disposing first and second electrical devices at least partially between the layers of the structural reinforcement material and directed toward opposite sides of at least one intermediate layer of the structural reinforcement material;

disposing an electrical bus at least partially between the layers of the structural reinforcement material and extending along the structural member;

30

connecting a first electrode to the bus and the first electrical device and thereby electrically connecting the first electrical device to the bus; and

connecting a second electrode to the bus and the second electrical device and thereby electrically connecting the second electrical device to the bus.

13. A method according to Claim 12 wherein said second disposing step comprises disposing first and second electrical buses along the structural member.

5 14. A method according to Claim 13 further comprising disposing an elongate spacer between the first and second buses and thereby electrically isolating the first and second buses.

15. A method according to Claim 13 wherein said first and second connecting steps comprise connecting the first bus to each of the first and second electrical devices, and further comprising
10 electrically connecting the second bus to at least one of the first and second electrical devices.

16. A method according to Claim 12 wherein said second disposing step comprises disposing the first and second buses generally parallel along a longitudinal direction of the structural member.

15 17. A method according to Claim 12 wherein at least one of said connecting steps comprises disposing at least one of the electrodes through the intermediate layer of reinforcement material.

18. A method according to Claim 12 wherein said first and second disposing steps comprise
20 disposing the electrical devices generally parallel to a first plane and disposing the buses generally in a second plane that is oblique to the first plane, and wherein said connecting steps comprise disposing the electrodes in a curved path such that a first end of each electrode is generally parallel to the electrical devices and a second end of each electrode is generally parallel to the second plane of the buses.

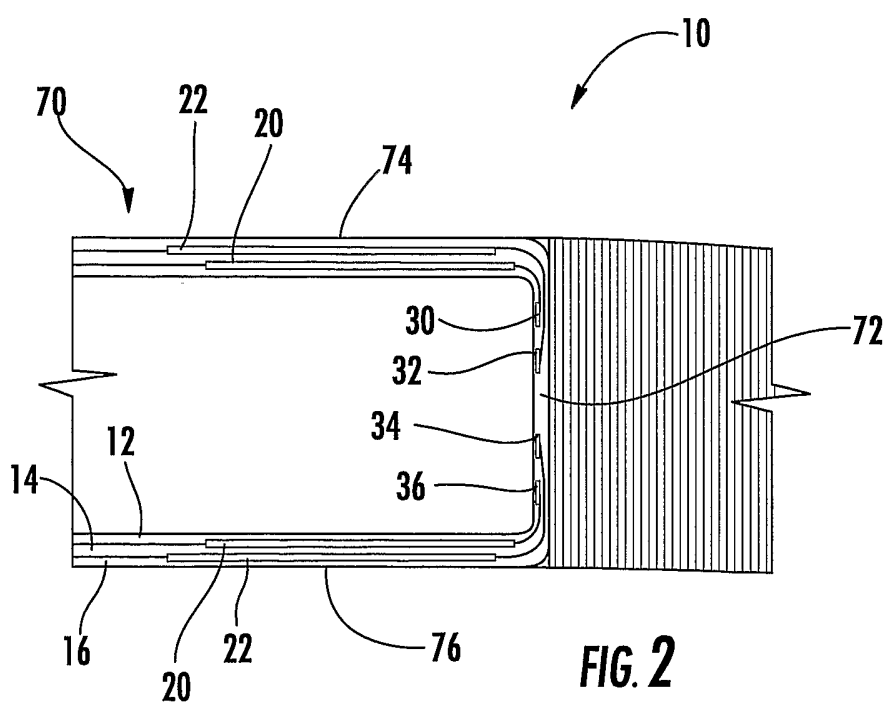
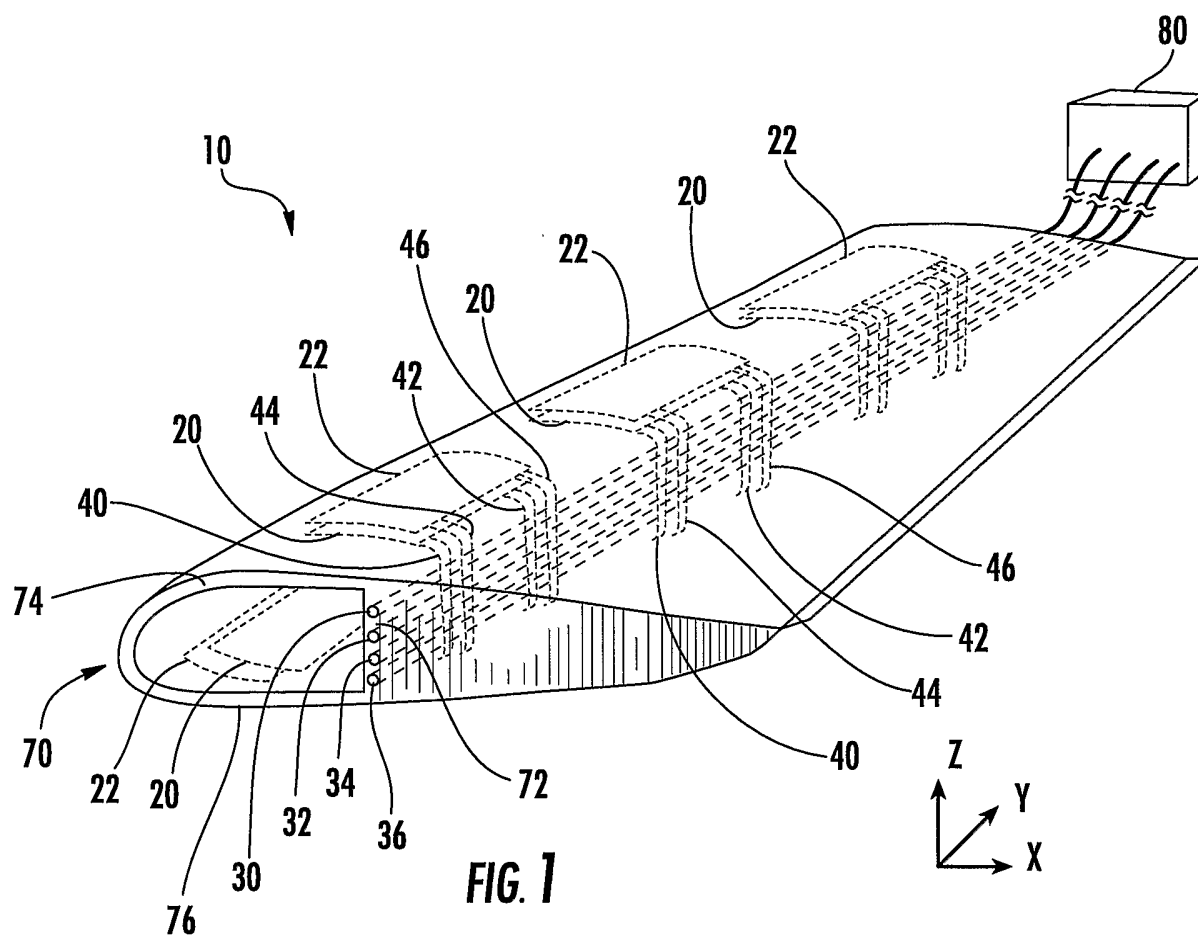
25 19. A method according to Claim 12 further comprising providing the electrodes, each electrode comprising a tow formed of a plurality of reinforcement fibers and a conductive coating thereon.

30 20. A method according to Claim 12 further comprising providing the bus, the bus comprising a plurality of nonlinear tows extending generally in a longitudinal direction, each tow including a plurality of fibers, at least some of the fibers including an electrically conductive metal.

21. A method according to Claim 12 further comprising providing the first and second electrodes defining different lengths.

- 5 22. A method according to Claim 12 wherein said providing step comprises disposing the layers of the structural reinforcement material as composite laminate plies with a matrix material.

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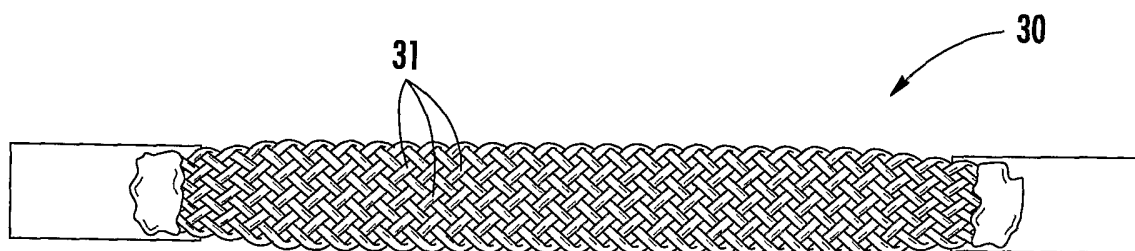


FIG. 3

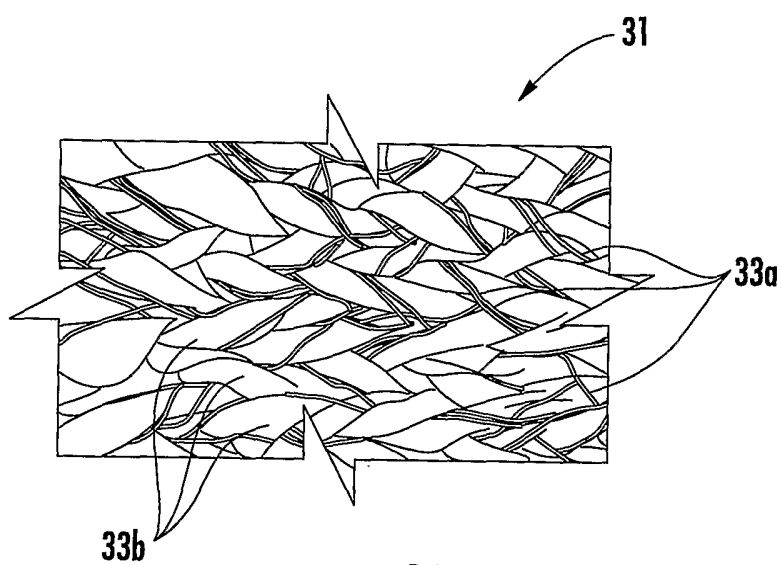


FIG. 3A

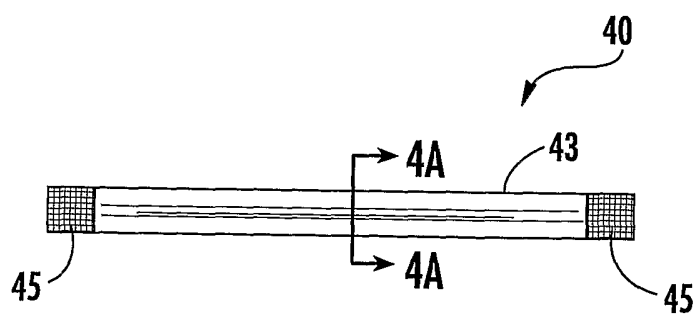


FIG. 4

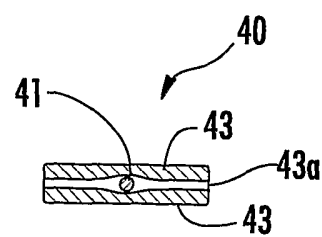
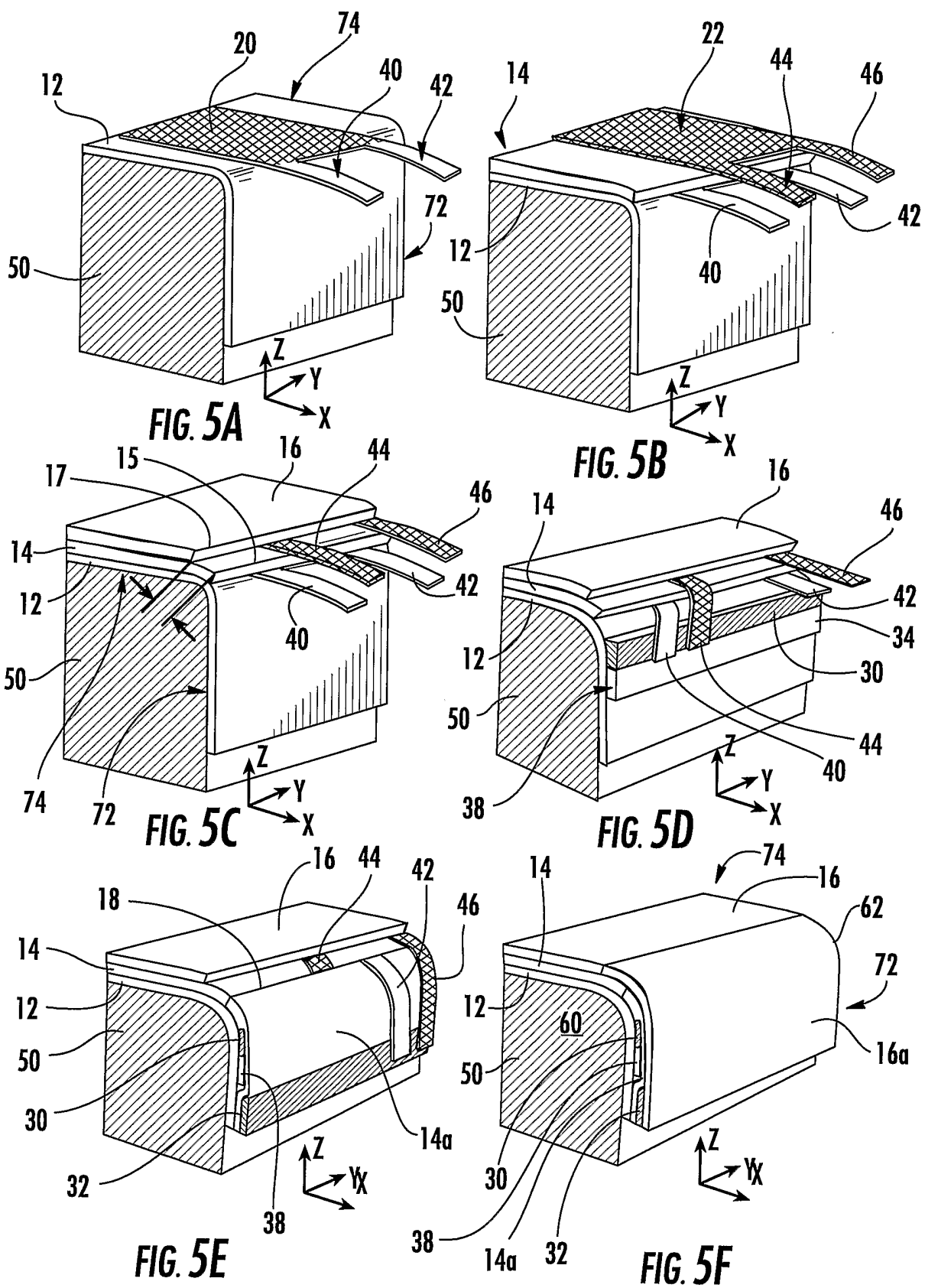
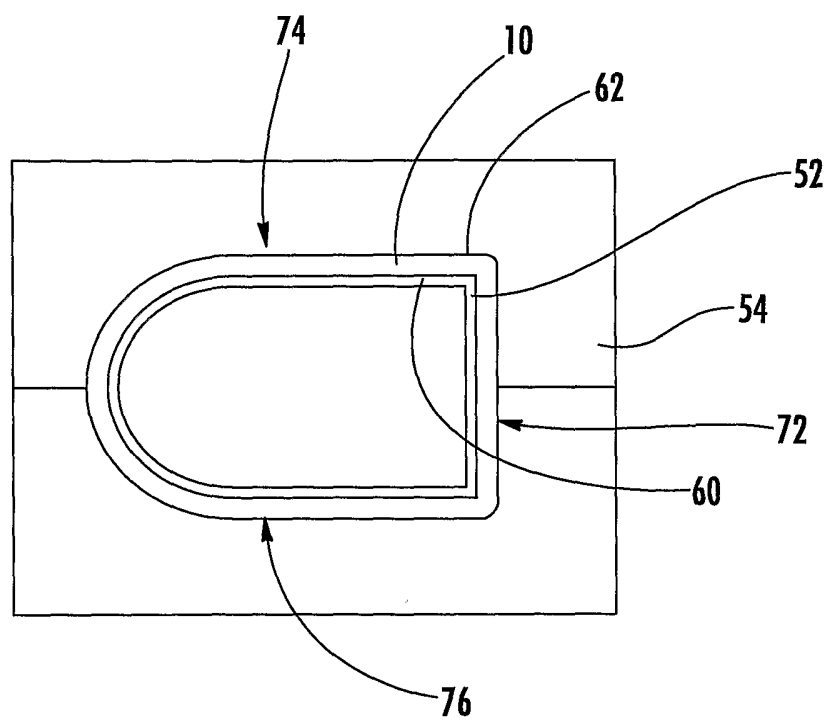
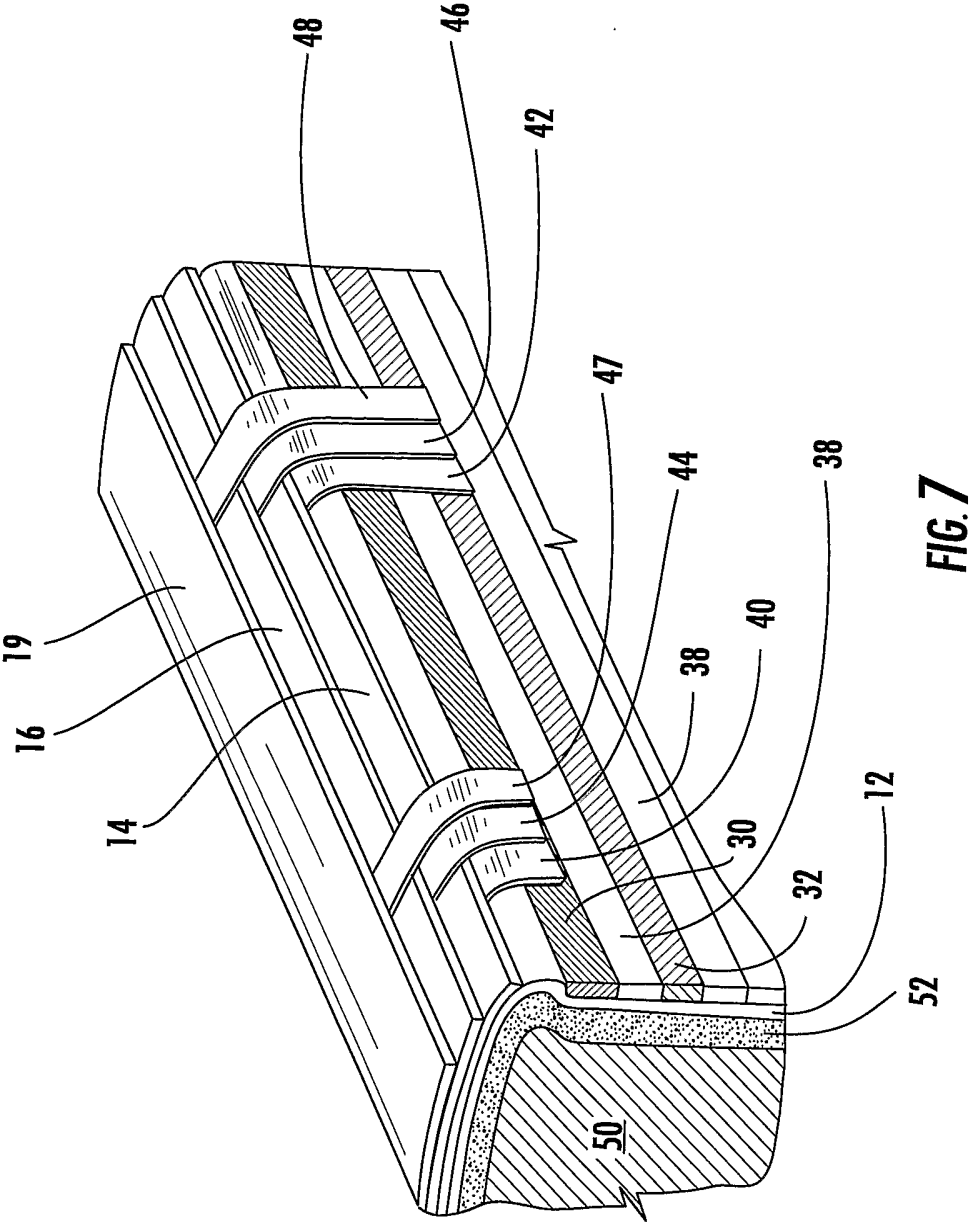


FIG. 4A



**FIG. 6**



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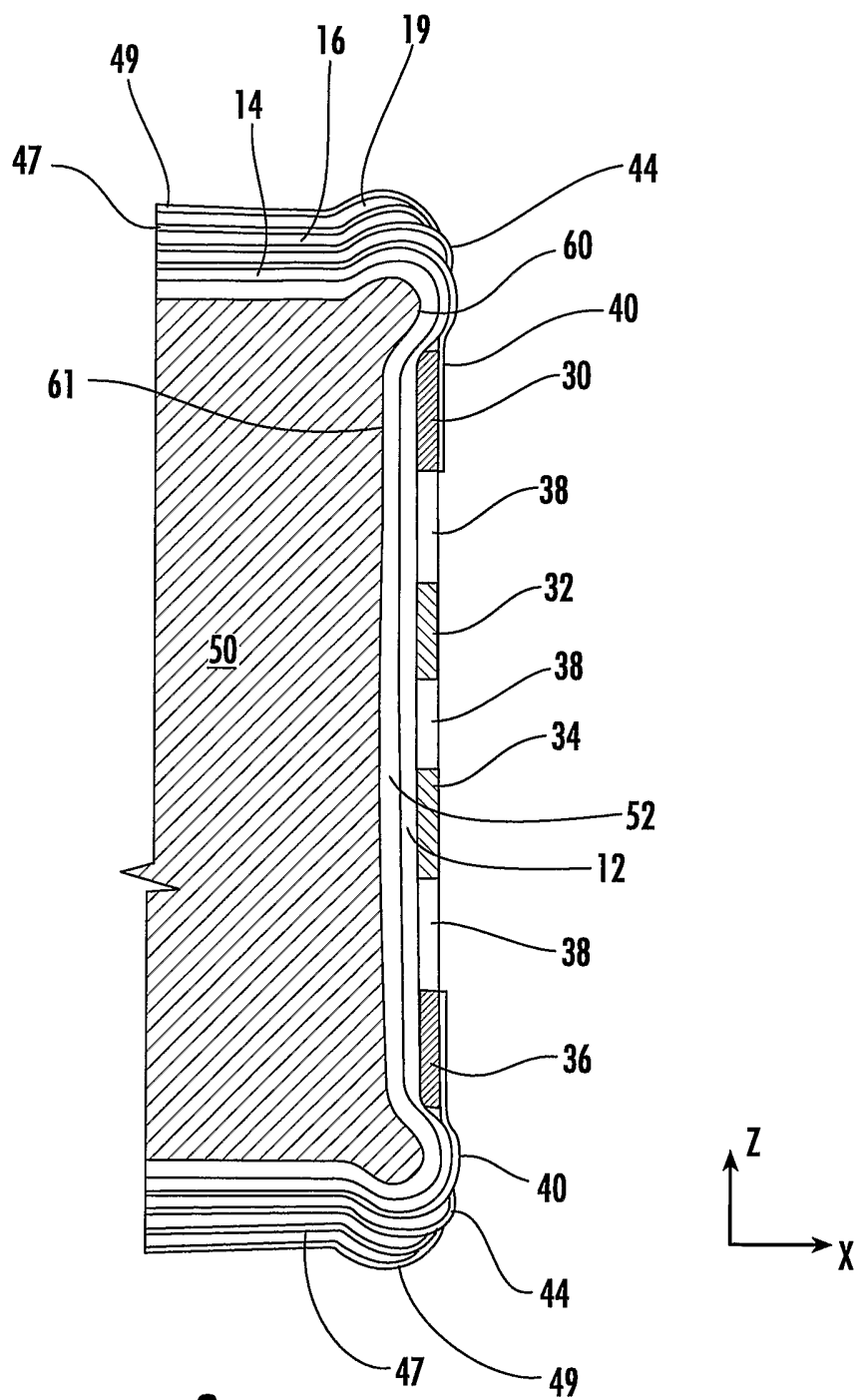


FIG. 8

INTERNATIONAL SEARCH REPORT

International Application No
PCT/US2005/016200

A. CLASSIFICATION OF SUBJECT MATTER

IPC 7 B29C70/88 B29C70/68 B29C70/86 H01B7/00 B64C27/473

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 7 B29C H01B B64C

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, PAJ, WPI Data, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	SCHMIDT M, HAGOOD N: "AIAA 00-1710: Design and Manufacturing of a Second-Generation Integral Twist-Actuated Rotor Blade" 41ST STRUCTURES, STRUCTURAL DYNAMICS, AND MATERIALS CONFERENCE & EXHIBIT, 3 April 2000 (2000-04-03), - 6 April 2000 (2000-04-06) XP008054848 Atlanta, GA, USA page 2, column 1, paragraph 2 - page 3, column 2, paragraph 3 ----- -/--	1,8, 10-12, 17-19, 21,22

☒ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

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"A" document defining the general state of the art which is not considered to be of particular relevance

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Date of the actual completion of the international search

28 October 2005

Date of mailing of the international search report

07/11/2005

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INTERNATIONAL SEARCH REPORT

International Application No

PCT/US2005/016200

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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