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GB 2558899 B

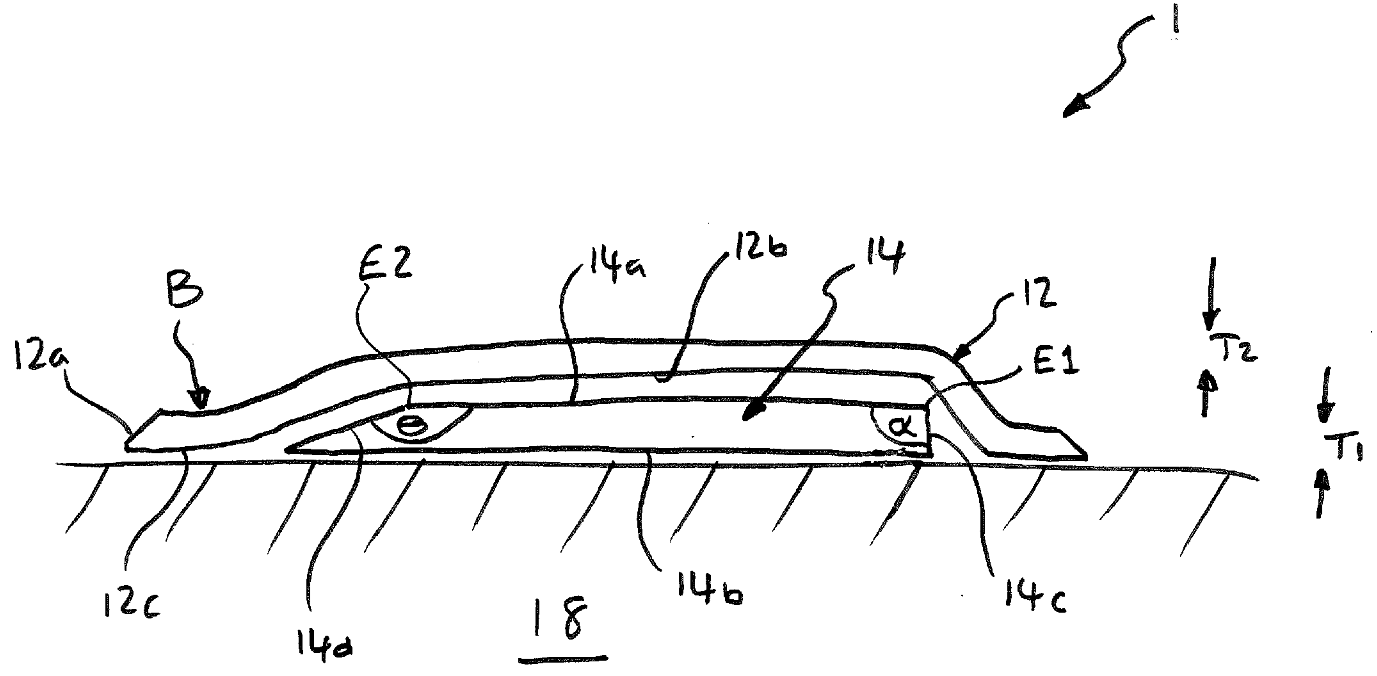

Figure 1a

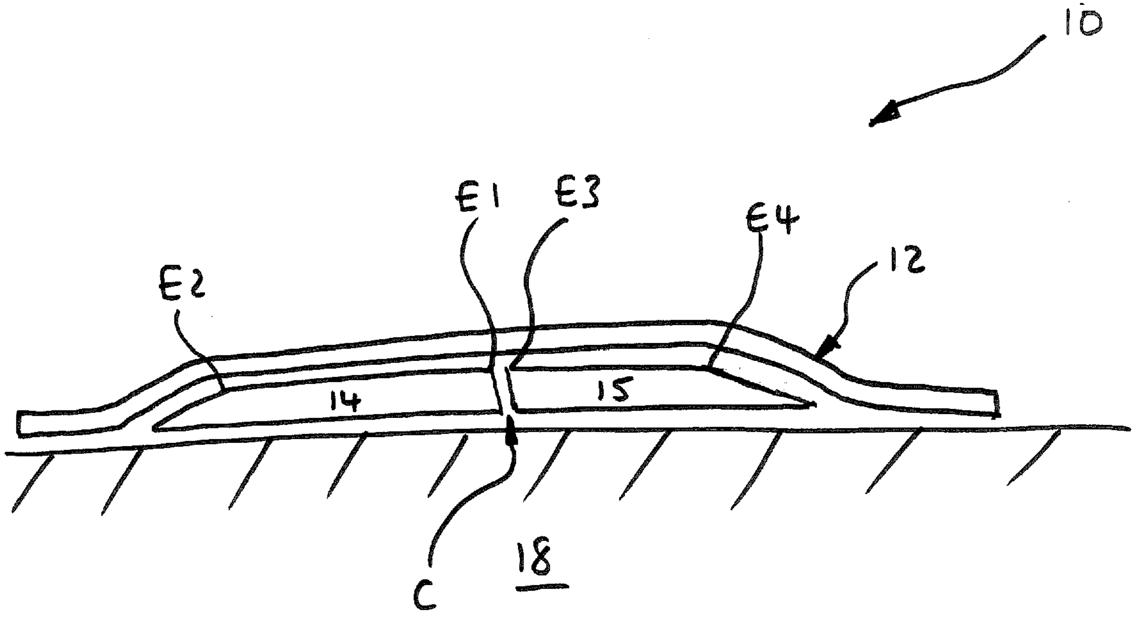

Figure 1b

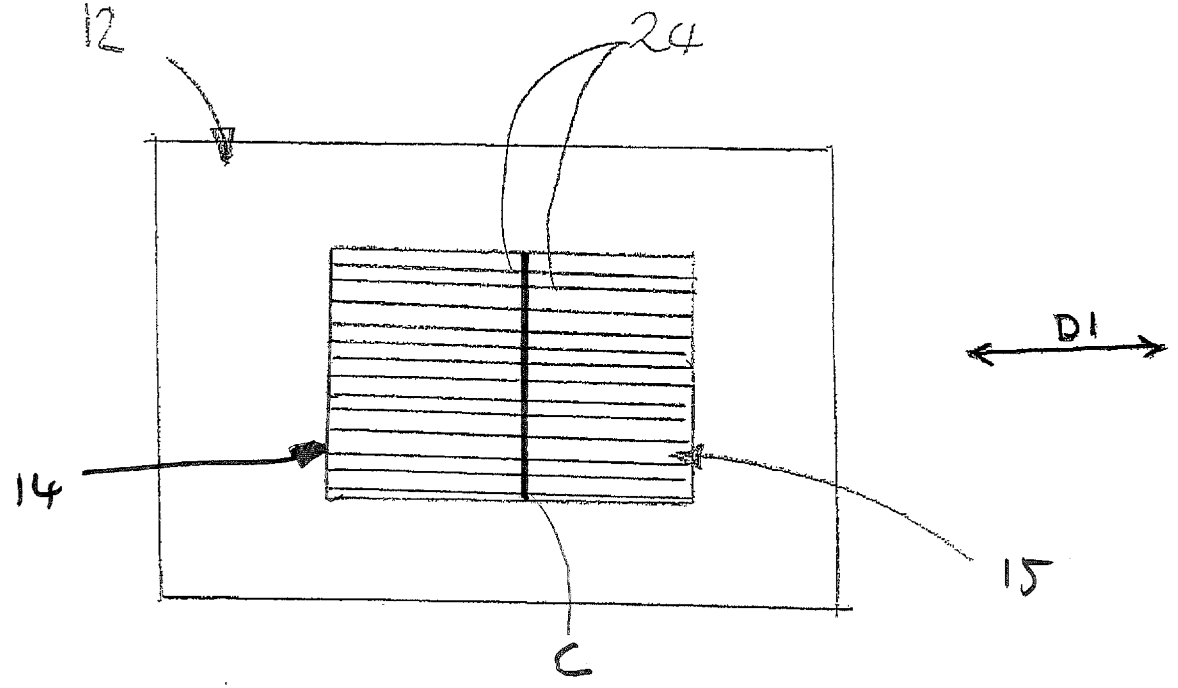

Figure 2

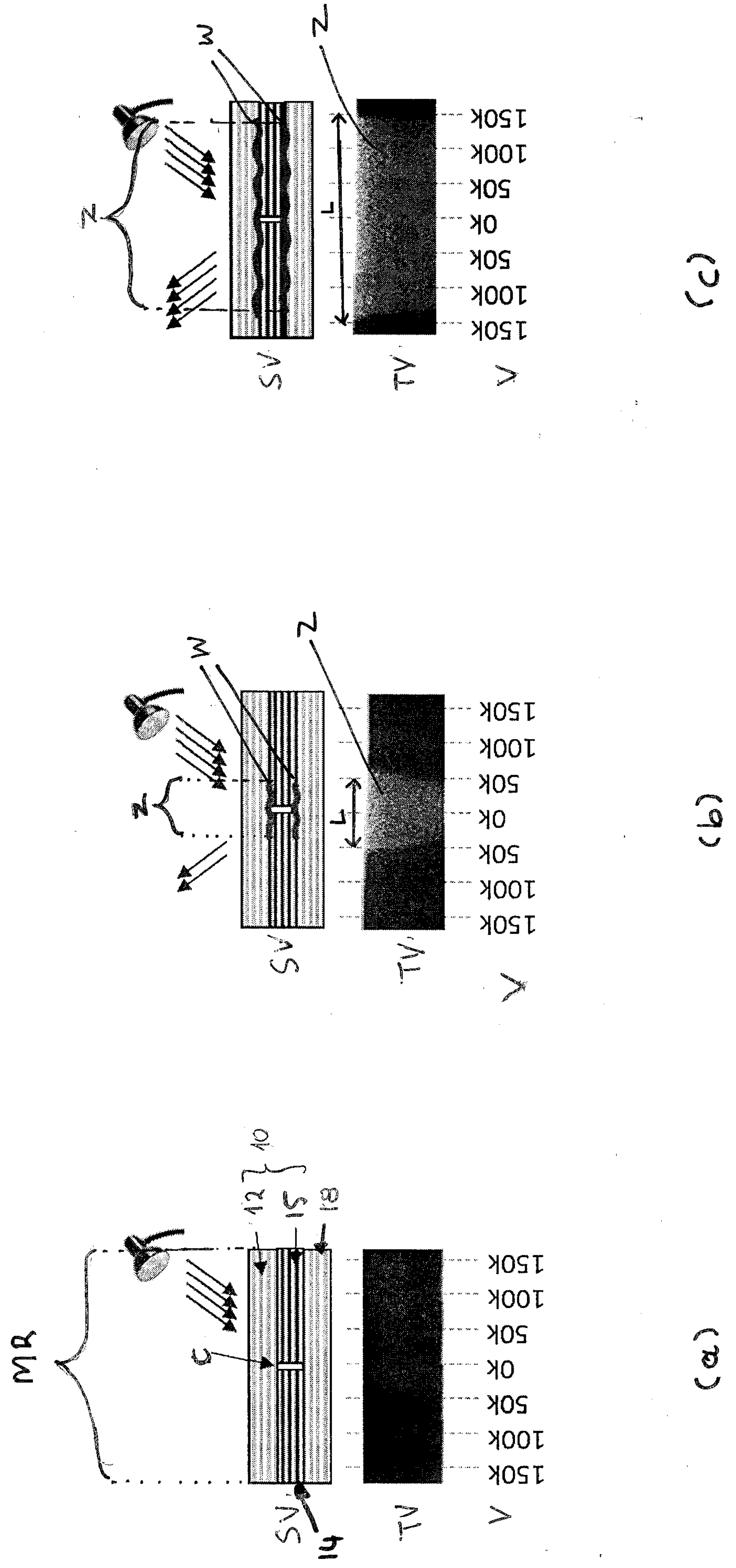
MR
C
12
15
18
10
14
SV
TV
V
150K
100K
50K
0K
50K
100K
150K
(a)
Z
W
L
SV
TV
V
150K
100K
50K
0K
50K
100K
150K
(b)
Z
W
L
SV
TV
V
150K
100K
50K
0K
50K
100K
150K
(c)

Figure 3

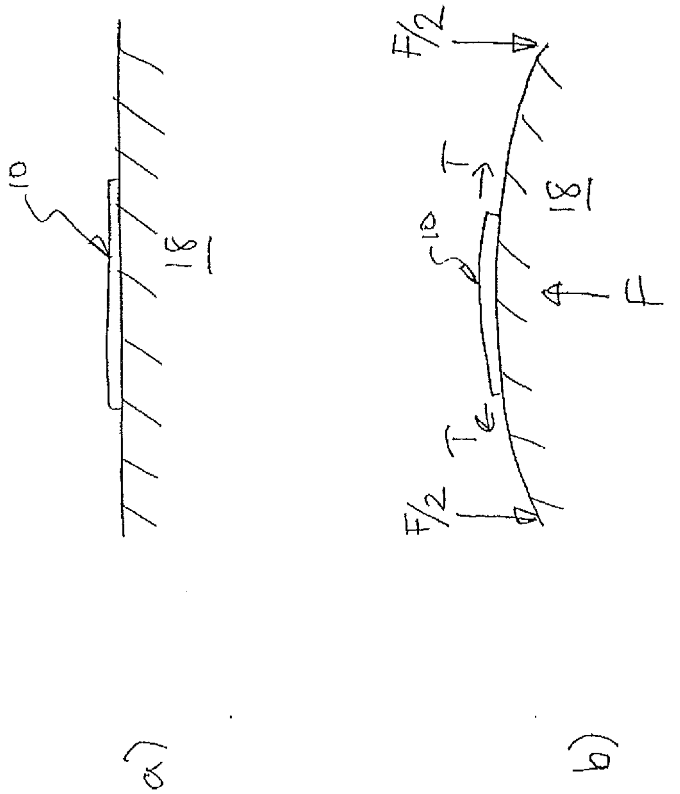

Figure 4

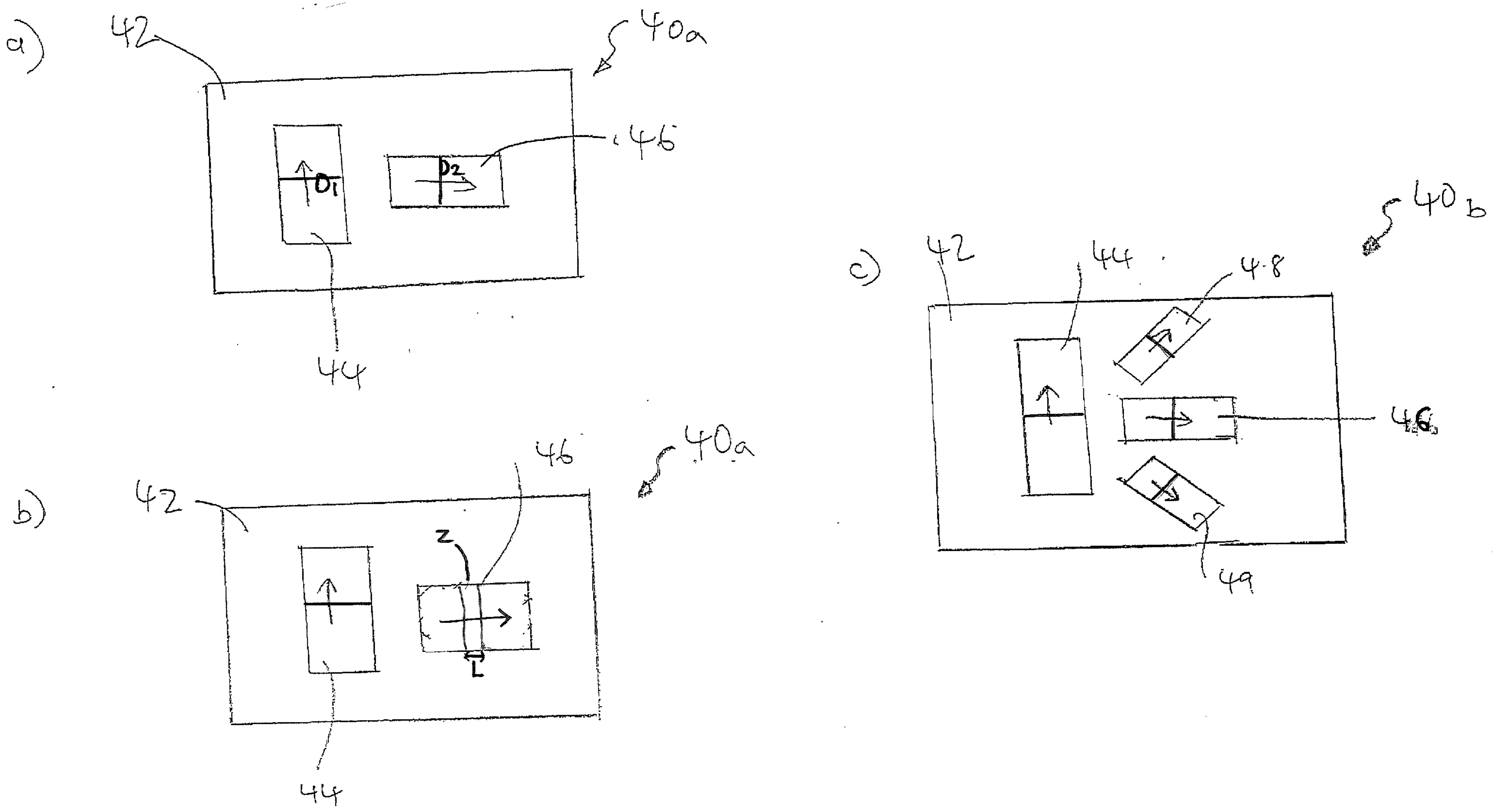

Figure 5

Sensor

Field of invention

The present invention relates to a sensor for indicating the number of loading cycles that a structure has been subjected to.

Background

Structures formed from composite or other materials are often required to be subjected to a number of loading cycles. Cycles of repeated loading and unloading result in material fatigue. Such loading cycles can cause structural damage and even the critical failure of the structure.

However, it can be difficult to identify the number of load cycles a structure has been subjected to and how many cycles are remaining until the end of the structure lifetime before a final failure.

Summary of invention

According to a first aspect of the present invention there is provided a sensor for indicating the number of loading cycles that a structure has been subjected to, the sensor comprising: a transparent layer; a first sensing element comprising a first surface and a second surface connected to the first surface by a first side so as to define a first edge of the first surface where the first surface meets the first side, the first surface being coupled to the transparent layer, the second surface being arranged to be secured to the structure via a coupling interface such that loading of the structure causes corresponding deformation of the first sensing element; and a measurement region including one or more first visual markers, the measurement region being positioned to include, or be in registration with, the first edge, each first visual marker indicating a distance from the first edge along a measurement axis which extends in a generally perpendicular manner with respect to the first edge, wherein loading of the structure causes the first edge to decouple from the transparent layer causing a first decoupled zone resulting in a visible change in the external appearance of the sensor, and further loading causes the first decoupled zone to propagate along the measurement axis in accordance with the number of the loading cycles to which the structure has been subjected to. At least the first surface and in some cases all of the sensing element is relatively opaque with respect to the transparent layer.

Thus, the first edge of the first sensing element serves as a delamination instigation line between the first sensing element and the transparent layer. When the structure is subjected to loading, the first edge of the sensing element decouples from the transparent layer to form a decoupled zone between the first sensing element and the transparent layer. The decoupled zone is visible through the transparent layer and has a different visual appearance in comparison to regions of the transparent layer that are still bonded to the sensing element(s). The visual markers, which can for example be printed on the transparent layer, can be used to measure the extent to which the decoupled zone propagates from the first edge to provide an indication of the number of loading cycles that the structure has been subjected to.

The sensor according to the first aspect of the invention therefore results in a simple, robust loading cycle gauge that can be cheap to manufacture and can be easily read without the need for special training. Such a sensor is particularly useful since the fatigue of a structure usually has no visible effect on a structure before a final failure occurs. The sensor can provide a visual indication before such final failure, allowing the user to know the number of loading cycles that the structure can be subjected to and the amount of loading cycles remaining before the end of the structure's lifetime. Sensors according to embodiments of the invention can be suitable for measuring variable and non-variable oscillatory loading cycles.

The ratio of the thickness of the sensing element to the thickness of the transparent layer can be such that the decoupled zone propagation rate, which is linearly proportional to the number of loading cycles, can cover the lifetime and the number of load cycles a structure is designed for.

The first surface and the second surface can be connected by a second side to define a second edge of the first surface where the first surface meets the second side, wherein a first internal angle between the first surface and the first side is closer to 90° than a second internal angle between the first surface and the second side, such that the second edge is relatively chamfered in comparison to the first edge. The chamfer angle of the second edge is chosen in a way to avoid delamination initiation from the transparent layer to form decoupled zones within the designated fatigue life of the structure. The side which is closer to 90° will decouple first, meaning that the measurement region can be positioned appropriately relative to the edge that will decouple first. It is preferred that the first angle is approximately 90° because this causes delamination to begin with the first load cycle. It is preferred that the second angle is approximately 45° to build a delay into the instigation of delamination at the second edge, so as to allow the first decoupled zone to propagate through a desired amount of the measurement zone without interference from delamination propagating from the second edge.

The number of loading cycles that the structure is subjected to during the delay of the instigation of delamination depends on the chamfer angle at the second edge and the configuration of the sensing element and the transparent layer.

The sensor can comprise a second sensing element having a third surface and a fourth surface connected by a third side to define a third edge of the third surface where the third surface meets the third side, the third surface being bonded to the transparent layer, the fourth surface being arranged to be secured to the structure via a coupling interface such that loading of the structure causes corresponding deformation of the second sensing element, wherein the measurement region includes one or more second visual markers, the measurement region being positioned to include or be in registration with the third edge, each second visual marker indicating a distance from the third edge along the measurement axis, wherein loading of the structure causes the third edge to decouple from the transparent layer causing a second decoupled zone resulting in a visible change in the external appearance of the sensor, and further loading causes the second decoupled zone to propagate along the measurement axis in accordance with the number of the loading cycles to which the structure has been subjected to.

The third surface and the fourth surface can be connected by a fourth side to define a fourth edge of the third surface where the third surface meets the fourth side, wherein a third internal angle between the third surface and the third side is closer to 90° than a fourth internal angle between the third surface and the fourth side, such that the fourth edge is relatively chamfered in comparison to the third edge. The comments made above in relation to the first and second angles apply analogously to the third and fourth angles.

The first and second sensing elements can be arranged in a side by side, parallel manner with the first edge adjacent to the third edge. This can be simply implemented by cutting through a single sensing element to form the first and second parallel layers.

The first and/or third sides and/or edges can extend across the respective sensing element(s) in a linear manner, preferably orthogonal to the longitudinal or measurement axis of the sensing element. Thus, the sensing direction must be parallel in relation to the measurement axis.

The second and/or fourth surfaces can be secured directly or indirectly to the structure. If the transparent layer is not capable of being directly coupled to the structure, then the sensing element can be bonded or otherwise directly coupled to the structure.

At least one of the visual markers can be positioned closer to the first edge of the first sensing element than the second edge of the first sensing element. At least one of the visual markers can be positioned closer to the third edge of the second sensing element than the fourth edge of the second sensing element.

The sensor can comprise a plurality of visual markers arranged in a regular spacing along the measurement axis of the, or each, sensing element and forming a linear scale.

The sensing element can have a portion of constant thickness which terminates as a boundary. The visual marker can be aligned with the boundary, such as the linear scale can be aligned with the constant thickness boundary. This is because delamination from the constant thickness boundary can be linear.

One or more of the visual markers can each comprise a line arranged generally perpendicular to the measurement axis of the, or each, sensing element.

One or more or each sensing element can be made out of any material with a linear elastic response at least up to strains of about 0.3%. One or more or each sensing element can be made out of fibrous composite materials, e.g. carbon/ epoxy composites, or metals, or polymers. The stiffness of one or more or each sensing element should generally be higher than the transparent layer. The higher such stiffness difference, the more sensitive the sensor to the number of loading cycles applied. The stiffness range of one or more or each sensing element can be between 50 GPa to 400 GPa.

The transparent layer can have linear elastic stress-strain curve at least up to 1% strains. The transparent layer stiffness can be between 10 GPa to 100 GPa.

One or more or each sensing element can comprise fibres, and in some cases unidirectional fibres.

One or more or each sensing element can comprise fibre reinforced composite material, such as a carbon fibre reinforced composite material.

One or more or each sensing element and/or the transparent layer can be made of fibre reinforced thermosetting polymer composite material. In this case, bonding of the first sensing element to the transparent layer can be achieved through co-curing the first sensing element and the transparent layer. Alternatively, bonding can be done through other means, for example using adhesive.

The first or each sensing element can comprise a first type of composite material and the transparent layer can comprise a second type of composite material which is distinct or different from the first type. Additionally, the first sensing element can comprise a plurality of different fibre types set within the matrix.

The transparent layer can be sized to have a larger footprint than the first or each sensing element so as to define a border region which can be used to secure the sensor to the structure.

The transparent layer can comprise glass fibre.

The sensor can further comprise a second layer on the opposite side of the first sensing element with respect to the transparent layer so as to encapsulate the first or each sensing element.

The first or each sensing element can have a sensing direction defined by the orientation of the first edge. The first edge may have a linear direction. The linear direction of the sensing edge may be perpendicular to the sensing direction.

The first or each sensing element can have a sensing direction defined by the intrinsic orientation of the fibres of the sensing element. The sensing direction of each sensing element can be parallel with respect to the measurement axis of each sensing element.

Where the sensor comprises a plurality of sensing elements, each sensing element can have a distinct sensing direction.

Two or more of the sensing directions can be perpendicular to each other.

The transparent layer can have chamfered edges to minimise the risk of premature de-bonding by reducing the stress concentration at the edges of the sensor.

According to a second aspect of the invention, there is provided an assembly comprising one or more sensors according to the first aspect.

One or more of the sensors can be integrally formed with the structure.

The assembly can comprise a single sensor that covers the majority of the surface area of the structure.

According to a third aspect of the invention, there is provided a method of forming an assembly comprising:

securing one or more sensors according to the first aspect to a structure; or

forming a structure with one or more integrally formed sensors according to the first aspect.

Brief description of the drawings

Embodiments of the invention will now be described, by way of example only, with reference to the accompanying drawings, in which:

Figures 1a and 1b show sensors according to first and second embodiments of the invention;

Figure 2 shows the sensor according to Figure 1b with fibres of the sensing element aligned in a single direction;

Figures 3a to 3c show a schematic side view and a top view of the sensor according to Figure 1b subjected to a number of loading cycles;

Figures 4a and 4b schematically illustrate a loading force applied during a loading cycle to a structure and a sensor according to an embodiment of the invention; and

Figures 5a to 5c show sensors according to embodiments of the invention wherein the sensor comprises a plurality of separate sensing elements, and wherein the fibres in each sensing element are aligned in a distinct direction.

Detailed description

Figure 1a shows a sensor 1 according to an embodiment of the present invention. The sensor 1 is arranged to indicate the number of loading cycles that a structure 18 has been subjected to. The structure 18 can be made from any material such as steel, aluminium, reinforced concrete or fibre reinforced polymer composite. The structure 18 could be made of other materials such as thermoplastic polymers or metals.

The sensor 1 comprises a transparent layer 12 and a sensing element 14.

The transparent layer 12 can be constructed from glass reinforced composite, or other translucent fibre, typically but not exclusively with an epoxy resin matrix. The transparent layer 12 can be translucent. The sensing element 14 can be partially visible through the transparent layer 12.

The sensing element 14 is formed from a material which is relatively opaque compared to the transparent layer. The sensing element 14 can for example be constructed from fibre reinforced polymer composite or any other layered material. Carbon fibre grades are available in a very wide range and are particularly suitable for use in the sensing element due to them having a variety of well-defined material properties.

The sensing element 14 has a thickness T1, which can for example be 0.5 mm or between 0.1mm and 1mm. The transparent layer has a thickness T2, which can for example be 0.2 mm or between 0.1mm and 0.5mm. The thicknesses T1, T2 can each be uniform throughout non-chamfered portions of the sensing element and the transparent layer.

The sensing element 14 and has a first, upper surface 14a and a second, lower surface 14b. The lower surface 14b of the sensing element 14 is connected to the upper surface 14a by the first side 14c so as to define a first edge E1. The first edge E1 is arranged to serve as a delamination instigation line between the sensing element 14 and the transparent layer 12, as described in more detail below. A first internal angle α between the first surface 14a and the first side 14c is between 75° and 105° and preferably approximately 90° because the inventors have found that approximately 90° results a minimal or negligible delay between the application of loading cycles to the structure 18 and the instigation of delamination. It is preferred that the first internal angle α is between 85 ° to 95°.

The lower surface 14b of the sensing element 14 is also connected to the upper surface 14a by a second side 14c so as to define a second edge E2. In theory, both of the first and second edges E1, E2 may, over time, decouple from the transparent layer 12 to form decoupled zones. However, the second edge E2 is chamfered in a way to delay such decoupling initiation to after the end of structure's fatigue lifetime. Therefore, the sensor is designed in a way that decoupling propagates only from the first edge E1. The edge which is closer to 90° will decouple first. It is therefore preferred that a second internal angle θ between the first surface 12a and the second side 14d is relatively remote from 90°, such that the second side 14d is relatively chamfered in comparison to the first side 14c, so as to completely delay instigation of delamination from the second edge E2. This configuration builds a delay into the instigation of delamination at the second edge, so as to allow the first decoupled zone to propagate through a desired amount of a measurement zone (described in relation to Figures 3a to 3b) without interference from delamination propagating from the second edge. It is preferred that the second angle θ is between 150° and 179° and preferably approximately 170°. Higher angles towards 180° are more preferred. Such shallow angles may be achieved by ply-drops over a long overlap using thin layered materials. This will produce a few steps in thickness change from full sensing layer thickness to the end.

The top surface 14a of the sensing element 14 is coupled to the bottom surface 12b of the transparent layer 12; for example, by the resin in composite sensing element 14 and transparent layers 12 or by way of adhesive bonding. The same technique can be applied to attach the sensor 10 to the structure 18 at surface 14b. As illustrated, the top surface 14a of the sensing element 14 is bonded to a lower surface 12b of the transparent layer 12 (gaps are shown for clarity purposes only).

The sensor 10 is attached to the structure 18 such that a force applied to the structure 18 is experienced by the sensor 10 similarly and deformation of the structure 18 causes corresponding deformation of the sensing element 14 of the sensor 10. Thus the sensing element 14 is subject to substantially the same strain as the region of the structure 18 to which it is attached. When the structure 18 is subjected to loading cycles, the sensing element 14 experiences a corresponding number of loading cycles.

In the illustrated embodiment, the sensor 10 defines an attachment surface via which it is arranged to be coupled to the structure 18. The transparent layer 12 has a larger footprint than the sensing element 14 so as to define a border region B around the sensing element 14. The attachment surface is defined by the lower surface 12c of the border region B and the lower surface 14b of the sensing element 14. The surfaces 12c and 14b can be bonded or otherwise attached to the structure 18. The border region B helps to secure the sensing element 14 to the structure 18. The edge 12a of the transparent layer 12 can be chamfered to reduce the risk of premature de-bonding of the whole sensor due to peeling and shear-stress concentration.

The sensor 10 can include a bottom layer (not shown) arranged between sensing element 14 and the structure 18. As such, the sensing element 14 can be encapsulated between the transparent layer 12 and the bottom layer. The bottom layer can be identical to the transparent layer 12.

In another embodiment there is no direct coupling between the sensing element 14 and the structure at surface 14b, so that the sensor is secured to the structure only at surface 12c around the sensing layer. The sensing element in this case is deformed through force applied by the transparent layer.

In other embodiments, the sensor 10 can be incorporated into a structure at the point of manufacture.

When the sensor 10 is attached to a structure 18, the sensing element 14 lies between the transparent layer 12 and the structure 18.

Referring additionally to Figure 1b, the sensor 10 can alternatively include first and second sensing elements 14, 15 arranged in a side by side, parallel manner. The second sensing element 15 can be of similar or identical construction to the first sensing element 14. The first and second sensing elements 14, 15 can be orientated with the first edge E1 of the first sensing element E2 being parallel and adjacent with respect to a third edge E3 of the second sending element, such that their sensing directions are aligned. Alternatively, the first and third edges E1, E3 can be non-parallel so that the sensor has a plurality of sensing elements with distinct sensing directions. Like the first edge E1, the third edge E3 is arranged to serve as a delamination instigation line between the second sensing element 15 and the transparent layer 12.

In embodiments where the first and third edges E1, E3 are parallel, the first and second sensing elements 14, 15 can be formed by a cut C made through the thickness T1 of a unitary sensing element to form the two sensing elements 14, 15. The cut C can be made for example using a ply cutter arrangement or by placing two separate sensing elements adjacent one another.

The following description will refer to the sensor 10 in which first and second sensing elements 14, 15 have been formed by way of the cut C. It will however be appreciated that the disclosure also applies to embodiments in which a single sensing element is provided or where a plurality of distinct sensing elements are arranged relative to one another to form a sensor.

Referring additionally to Figure 2, the sensing element comprises fibres 24. The fibres 24 of the sensing elements 14, 15 are collimated in a single direction D1 which defines the sensing direction of the sensor 10 and also defined the measurement axis along with delamination zones will propagate, as described in more detail below. The fibres 24 are collimated in a direction parallel to the length of the sensing element 14, but the fibres 24 can be collimated in any direction relative to the length of the sensing element 14. The cut C is schematically represented in a central position of the sensing element 14. The cut C is perpendicular to the intrinsic direction D1 of the fibres 24.

Referring additionally to Figures 3a to 3c, schematic representations of the operation of the sensor 10, attached on a structure 18 is illustrated. Figure 3a to 3c show three side views SV and top views TV of the sensor 10 under three different loading conditions.

A number of visual markers V are provided that indicate the number of loading cycles the structure has been subjected to. The visual markers V are visible from the top surface of the sensor 10. The arrangement of the visual markers V defines a measurement region MR which includes the cut C. Each visual marker indicates a distance from the cut C along the length of the first sensing element 14. The visual markers V define a scale that can be used to relate the propagation length of a decoupled zone to a number of load cycles. In the illustrated embodiment, the visual markers V are a regularly spaced array of lines extending in a perpendicular manner with respect to the length of the first sensing element 14. The lines of the visual markers V can be printed on the top surface of the transparent layer 12. However, in other embodiments the visual markers can take any suitable form.

In Figure 3a, the structure 18 and the sensor 10 have not been subjected to any loading. Therefore, a decoupled zone Z is not present, while any light directed to the sensor 10 is completely absorbed by the sensing element of the sensor 10. A schematic representation of the cut C is illustrated. The cut is positioned at the 0k mark of the visual marker V.

In Figure 3b the structure 18 and sensor 10 have been subjected to a number of loading cycles. The edges E1 and E3 have been decoupled from the transparent layer 12 to define a decoupled zone Z. The waved lines W represent the extent of the delamination of the first sensing element 14 from the transparent layer 12. Due to the presence of the decoupled zone Z, light directed to the sensor surface is reflected. Therefore, the decoupled zone Z is visible as a light grey area in the TV of the sensor 10. The decoupled zone Z can appear as a light grey or white strip with a length L. The decoupled zone Z provides a visible indication of the number of loading cycles, since the length L of the decoupled zone Z corresponds to the number of loading cycles that the structure 18 has been subjected to. The length L of the decoupled zone is linearly proportional to the number of loading cycles that the structure 18 has been subjected to. The specific number of loading cycles can be measured by relating the decoupled zone propagation to the visual markers. According to the visual marker V on the TV of the sensor 10, the number of loading cycles that the structure in Figure 4b has been subjected to is about 50K.

In Figure 3c, the decoupled zone Z is further propagated. The waved lines W indicate the further propagation of the decoupling between the sensing element 14 and the transparent layer 12. The length L in this case corresponds to 150K loading cycles.

Referring additionally to Figures 4a and 4b, mechanical loading of a structure 18 is schematically illustrated. The loading may comprise loading cycles, which are repeatedly applied to the structure 18. Such loading may be oscillatory with constant maximum loading per loading cycle. Alternatively, such oscillatory loading may comprise a non-constant maximum loading per loading cycle. Figure 4a shows the structure 18 with no loading applied. In Figure 4b, a bending force F is applied during a loading cycle, resulting in tensile stress T being applied to the fibres 24 of the sensing element 14 in a direction which is parallel to the direction D1 of the fibres 24. Loading cycles applied to the sensor 10 cause the two edges E1 and E3 of the cut C to delaminate from transparent element creating the decoupled zone Z. If a loading force is applied to the structure in a way that the tensile strain is perpendicular to the direction D1 or parallel to the cut C, the two edges E1 and E3 of the sensing element 14 will not experience delamination along the length of the sensor and therefore no visible change will appear.

Therefore when the sensing element comprises fibre reinforced composite material the direction of collimation of the fibres of the sensing element defines the sensing direction of the sensing element.

Thus, one can determine the direction in which the structure has been subjected to loading.

Figure 5a shows a sensor 40a with a transparent layer 42, a first sensing element 44 and a second sensing element 46. Both of the sensors comprise fibres collimated in a single direction. The fibres of the first sensing element are aligned in a first direction D1, and the fibres of the second sensing element are aligned in a second direction D2, as indicated by the arrows. The first direction D1 is perpendicular to the second direction D2.

Thus the two sensing element 44 and 46 can determine in which direction loading cycles have been applied to a structure, as well as the number of loading cycles in each direction, by identifying the extent of the visual change of the sensing element in the sensor 40a of Figure 5a.

Figure 5b shows the sensor of Figure 5a after a number of loading cycles has been applied in one direction. The two parallel lines, represent the decoupled zone Z between the two edges E1 and E2 of the sensing element 46, which indicates the visible change of the second sensing element 46. If one knows the sensing direction (i.e. the direction of collimation of fibres) in the second direction, then they can determine the direction of the loading the structure has experienced. Similarly, if one knows the direction of collimation of the fibres in the first sensing element, they can determine that the structure has not been subject to loading in a specific direction.

If a decoupled zone Z appears both in the first and second sensing elements, then the structure has been subjected to loading in both directions.

A single sensor could indicate loading in more than two directions through including multiple sensing element, with each sensing element having a single sensing direction (e.g. fibres collimated in a single direction), wherein all directions are distinct. Such a sensor 40b is shown in Figure 5c, with sensing element 44 to 49 each with a different sensing direction. The sensor 40b therefore can indicate whether the structure has been subjected to loading in any of four directions.

The skilled person will appreciate that other arrangements of sensing element could be used to provide a multi-directional sensor. More than four, or fewer than four, sensing elements could be used. For example, if ten sensing element were used, the sensor could indicate whether the structure has been subject to loading in any one of ten directions.

Alternatively, more than one sensor each with a single sensing element could be attached to a structure to determine the direction of loading. Each sensing element has a sensing direction, and the sensors can be attached to the structure at different angles such that the sensing direction of each sensing element is at a different angle. This has the advantage that the user can customise the direction of detection of loading. The user may attach sensors to indicate a loading along the principal axes, or along the directions which are most vulnerable for the material to experiencing fatigue.

To design a sensor for non-variable oscillatory loading cycles, e.g. those in pressure vessels, a pre-set length L for the decoupling zone Z for a given sensor at the end of a structure's lifetime is determined. Non-variable oscillatory loading cycles means that the maximum working pressure or loading per cycle is constant.

The pre-set length of the decoupled zoned due to delamination is represented as 'a' in the following equations. The number of fatigue cycles 'N' that the structure will be subjected to until the end of its lifetime can be determined from experimental data, the design phase of the product or it may be directly defined by the number of loading cycles the sensor is aimed to be used for. Based on a given 'a' and 'N', the maximum load for the oscillatory fatigue cycles '$G_{II\max}$' can be determined according to equation (1). '$G_{II\max}$' is the maximum mode-II energy release rate for the maximum applied load '$F_{\max}$' or strain '$\varepsilon_{\max}$' and is the driving force of the delamination propagation for the sensor.

$$\frac{da}{dN} = C\left(\frac{G_{II\max}}{G_{IIC}}\right)^{\frac{b}{(1-R)^2}} \qquad (1)$$

Where 'G_{IIC} ' is the mode II fracture toughness, 'C' and 'b' are empirically derived constants depending on the mechanical properties of the delaminating interface.

$R = \frac{F_{min}}{F_{max}} = \frac{\varepsilon_{min}}{\varepsilon_{max}}$, also called ‘R-ratio’, is the ratio of the minimum to maximum loads or strains in one loading cycle. 'G_{IImax}', 'C' and 'b' are material properties, empirically derived. 'G_{IImax}' depends on the stiffness of the cut and continuous portions of the sensing element and applied maximum load.

Finding 'G_{IImax}' enables 'β' to be calculated, according to equation 2, which is the thickness ratio between sensing element and transparent layer.

Equation 2 defines the relationship for remote applied maximum strain, 'ε_{max}', for the maximum energy release rate:

$$G_{IImax} = \frac{E_C(1 + \alpha\beta)\alpha\beta t_C}{4} \varepsilon_{max}^{2} \tag{2}$$

The material properties of a material combination set, selected based on availability or previous experience, can be the inputs for the equation (2). Whereas, 'E_c' and 'E_D' are the stiffness of the transparent layer and the stiffness of the sensing element respectively, $\alpha = \frac{E_D}{E_C}$ is the modulus ratio and $\beta = \frac{t_D}{t_C}$ is the thickness ratio of the sensing element 't_c' to the transparent layer 't_c'. The thickness of the the transparent 't_c' is usually around 0.1mm.

The last step is to check if the stiffness of the sensing element 'K_P' is less than 10% of the stiffness of the structure 'K_S'.

'Kp' is calculated according to the following equation:

$$K_P = E_D t_D + E_C t_C \tag{3}$$

If this condition is not satisfied, then a new set of material combination can be assumed and the previous steps can be repeated until this final condition is fully fulfilled.

For an unknown load spectrum or non-constant oscillatory loading cycles, the following equations (4) and (5) are utilised.

The relationship between the length of the decoupled zone 'a' to the number of fatigue cycles 'ΔN' is given according to the following equation:

$$a = BP_{max}^{\frac{2b}{(1-R)^2}} \Delta N \Rightarrow \Delta N = \frac{a}{B} P_{max}^{\frac{-2b}{(1-R)^2}} \tag{4}$$

'R' is the load ratio, 'P_{max}' is the maximum working pressure or load in a cycle of loading. The constant 'B' depends on the mechanical properties, moduli and geometry of the sensing element and the transparent layer and critical fracture toughness.

For an unknown load spectrum the maximum working pressure or load in a cyclic loading 'P_{max}' is not known, in order to design a sensor the user would require to start with a number of sensors 'm' which have known but different parameters to each other.

Therefore, to design a sensor where loading is variable, 'ΔN' and 'P_{max}' can be found from different lengths $(a_1, a_2, \ldots, a_m)$.

In this case 'n' cyclic loads with the maximum of '$P_{\max\_i}$' and R ratios of 'R_i' where $i = 1,2,\ldots to\ n.$ are assumed. These initial load spectrum history can be estimated through previous experience and their highest probability of occurring. The following equations indicate what will be the delamination length in hybrid patches 1 to 'm', $(a_1, a_2, \ldots, a_m)$.

$$\begin{aligned}
a_1 &= B_1 P_{\max\_1}^{\frac{2b}{(1-R\_1)^2}} \Delta N_1 + B_1 P_{\max\_2}^{\frac{2b}{(1-R\_2)^2}} \Delta N_2 + \cdots + B_1 P_{\max\_n}^{\frac{2b}{(1-R\_n)^2}} \Delta N_n \\
a_2 &= B_2 P_{\substack{\max \\ 1}}^{\frac{2b}{(1-R1)^2}} \Delta N_1 + B_2 P_{\substack{\max \\ 2}}^{\frac{2b}{(1-R_2)^2}} \Delta N_2 + \cdots + B_2 P_{\substack{\max \\ n}}^{\frac{2b}{(1-R_n)^2}} \Delta N_n \\
&\vdots \\
a_m &= B_m P_{\max\_1}^{\frac{2b}{(1-R1)^2}} \Delta N_1 + B_m P_{\max\_2}^{\frac{2b}{(1-R\_2)^2}} \Delta N_2 + \cdots + B_m P_{\max\_n}^{\frac{2b}{(1-R\_n)^2}} \Delta N_n
\end{aligned} \tag{5}$$

To find all 'ΔN_i', i =1 to n, 'm' should be greater equal 'n'. In this way, the number of unknowns will be equal or more than input variables.

The set of equations (5) allows all 'ΔN' values to be determined. From this point, the previous method for non-variable oscillatory loading cycles along with equations (1) and (2) can be used for to calculate 'β' which is the thickness ratio between cut and continuous portions.

It should be noted that the above-mentioned embodiments illustrate rather than limit the invention, and that those skilled in the art will be capable of designing many alternative embodiments without departing from the scope of the invention as defined by the appended claims. In the claims, any reference signs placed in parenthesis shall not be construed as limiting the claims. The word "comprising" does not exclude the presence of elements or steps other than those listed in any claim or the specification as a whole. The singular reference of an element does not exclude the plural reference of such elements and vice-versa. Parts of the invention may be implemented by means of hardware comprising several distinct elements. In a device claim enumerating several parts, several of these parts may be embodied by one and the same item of hardware. The mere fact that certain measures are recited in mutually different dependent claims does not indicate that a combination of these measures cannot be used to advantage.

Claims

1. A sensor for indicating the number of loading cycles that a structure has been subjected to, the sensor comprising:

a transparent layer;

a first sensing element comprising a first surface and a second surface connected to the first surface by a first side to define a first edge of the first surface where the first surface meets the first side, the first surface being coupled to and being relatively opaque with respect to the transparent layer, the second surface being arranged to be secured to the structure via a coupling interface such that loading of the structure causes corresponding deformation of the first sensing element; and

a measurement region including one or more first visual markers, the measurement region being positioned to include or be aligned with the first edge, each first visual marker indicating a distance from the first edge along a measurement axis which extends in a generally perpendicular manner with respect to the first edge,

wherein loading of the structure causes the first edge to decouple from the transparent layer causing a first decoupled zone resulting in a visible change in the external appearance of the sensor, and further loading causes the first decoupled zone to propagate along the measurement axis in accordance with the number of the loading cycles to which the structure has been subjected to.

2. A sensor according to claim 1, wherein the first surface and the second surface are connected by a second side to define a second edge of the first surface where the first surface meets the second side, wherein a first internal angle between the first surface and the first side is closer to 90° than a second internal angle between the first surface and the second side, such that the second edge is relatively chamfered in comparison to the first edge.

3. A sensor according to claim 1 or claim 2, further comprising a second sensing element having a third surface and a fourth surface connected by a third side to

define a third edge of the third surface where the third surface meets the third side, the third surface being bonded to the transparent layer, the fourth surface being arranged to be secured to the structure via a coupling interface such that loading of the structure causes corresponding deformation of the second sensing element, wherein the measurement region includes one or more second visual markers, the measurement region being positioned to include or be aligned with the third edge, each second visual marker indicating a distance from the third edge along the measurement axis,

wherein loading of the structure causes the third edge to decouple from the transparent layer causing a second decoupled zone resulting in a visible change in the external appearance of the sensor, and further loading causes the second decoupled zone to propagate along the measurement axis in accordance with the number of the loading cycles to which the structure has been subjected to.

4. A sensor according to claim 3, wherein the third surface and the fourth surface are connected by a fourth side to define a fourth edge of the third surface where the third surface meets the fourth side, wherein a third internal angle between the third surface and the third side is closer to 90° than a fourth internal angle between the third surface and the fourth side, such that the fourth edge is relatively chamfered in comparison to the third edge.

5. A sensor according to any of claims 3 and 4, wherein the first and second sensing element are arranged in a side-by-side parallel manner with the first edge adjacent to the third edge.

6. A sensor according to any preceding claim, wherein the first and/or third sidewalls and/or edges extend across the respective sensing element(s) in a linear manner.

7. A sensor according to any preceding claim, wherein the second and/or fourth surfaces are secured directly or indirectly to the structure.

8. A sensor according to any preceding claim, wherein at least one of the visual markers is positioned closer to the first edge of the first sensing element than the second edge of the first sensing element.

9. A sensor according to any preceding claim, comprising a plurality of visual markers arranged in a regular spacing along the measurement axis of the, or each, sensing element.

10. A sensor according to any preceding claim, wherein one or more of the visual markers each comprises a line arranged generally perpendicular to the measurement axis of the, or each, sensing element.

11. A sensor according to any preceding claim, wherein one or more or each sensing element comprises unidirectional fibres.

12. A sensor according to any preceding claim, wherein one or more or each sensing element comprises fibre reinforced composite material.

13. A sensor according to any preceding claim, wherein one or more or each sensing element can and the transparent layer each comprises a fibre reinforced thermosetting polymer composite material.

14. A sensor according to any preceding claim comprising a second layer on the opposite side of the first sensing element with respect to the transparent layer so as to encapsulate one or more or each sensing element.

15. A sensor according to any preceding claim when dependent on claim 2, wherein each sensing element has a sensing direction defined by the intrinsic orientation of the fibres of the sensing element and each sensing element has a distinct sensing direction.

16. An assembly comprising one or more sensors according to any preceding claim secured to a structure.

17. An assembly according to claim 16 wherein one or more of the sensors are integrally formed with the structure.

18. An assembly according to any one of claims 16 and 17 comprising a single sensor that covers the majority of the surface area of the structure.

19. A method of forming an assembly comprising:
securing one or more sensors according to any preceding claim to a structure; or forming a structure with one or more integrally formed sensors according to any preceding claim.