(12) UK Patent (19) GB (11) 2544792 (13) B

(45) Date of B Publication **19.02.2020**

(54) Title of the Invention: Strain Overload Sensor

(51) INT CL: ***G01L 23/06*** (2006.01) ***G01L 7/02*** (2006.01) ***G01L 7/08*** (2006.01) ***G01L 7/10*** (2006.01) ***G01L 19/06*** (2006.01)

(21) Application No: **1520988.5**

(22) Date of Filing: **27.11.2015**

(43) Date of A Publication **31.05.2017**

(56) Documents Cited:
WO 2005/034666 A1
CN 100491944 C
DD 000157221 A1
US 5789680 A

(58) Field of Search:
As for published application 2544792 A viz:
INT CL **G01L**
Other: **WPI, EPODOC**
updated as appropriate

Additional Fields
INT CL **A42B, G01B, G01M, G01N**
Other: **EPODOC, WPI**

(72) Inventor(s):
Michael Wisnom
Kevin Potter
Gergely Czel
Meisam Jalavand

(73) Proprietor(s):
The University of Bristol
(Incorporated in the United Kingdom)
Senate House, Tyndall Avenue, BRISTOL, BS8 1TH, United Kingdom

(74) Agent and/or Address for Service:
Withers & Rogers LLP
4 More London Riverside, LONDON, SE1 2AU, United Kingdom

GB 2544792 B

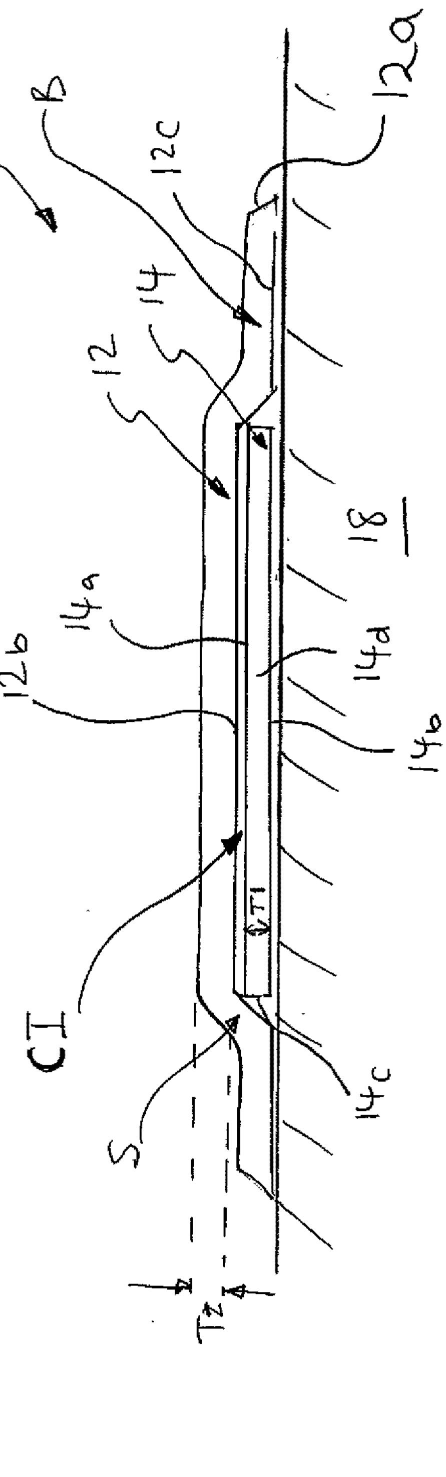

Figure 1

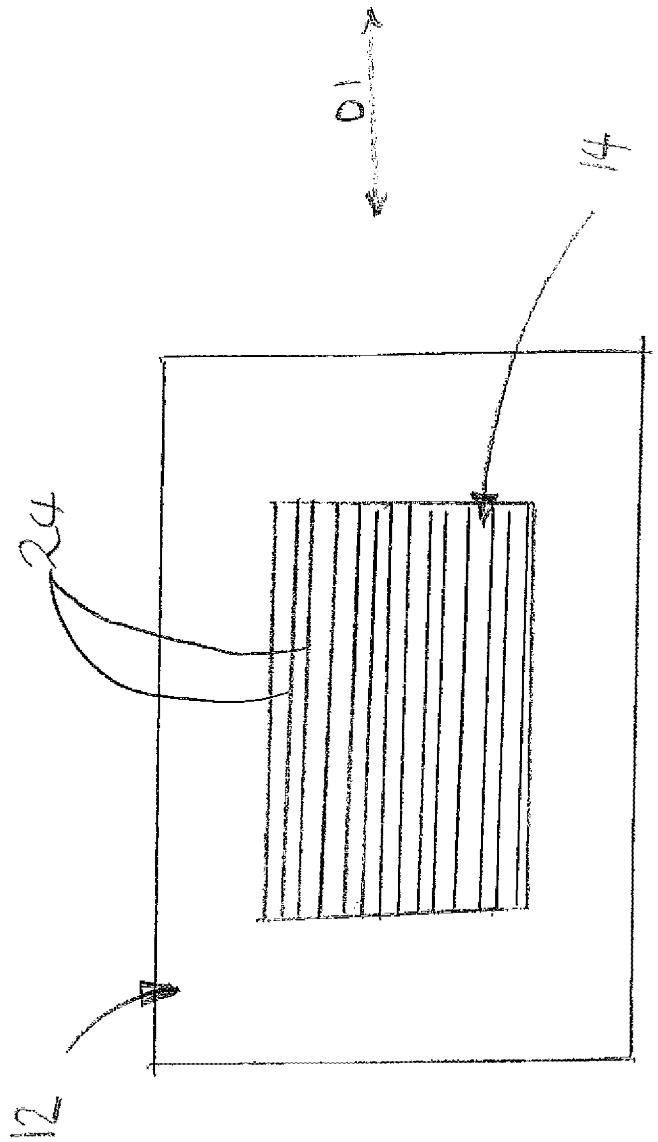

Figure 2

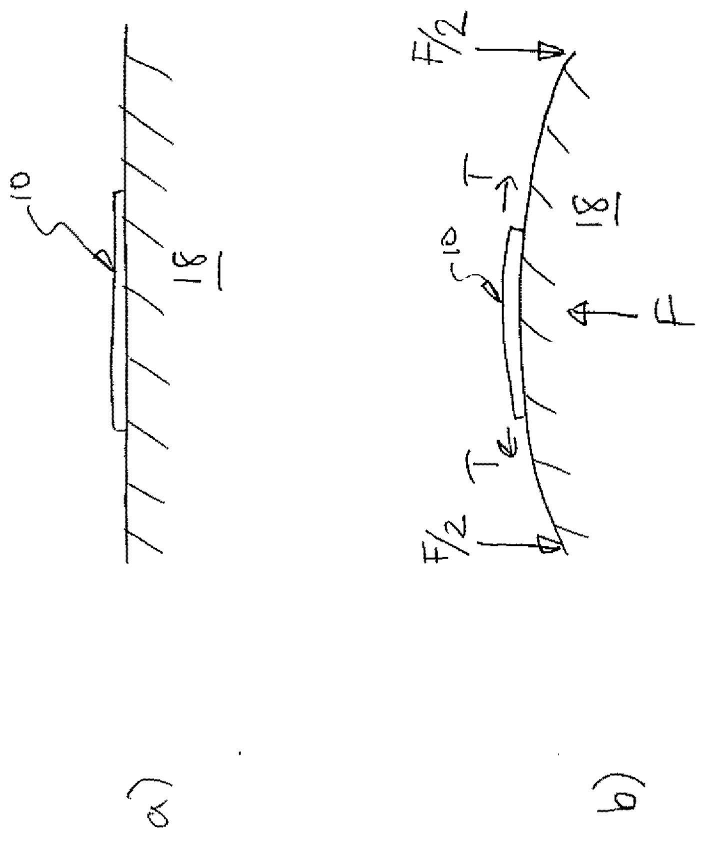

Figure 3

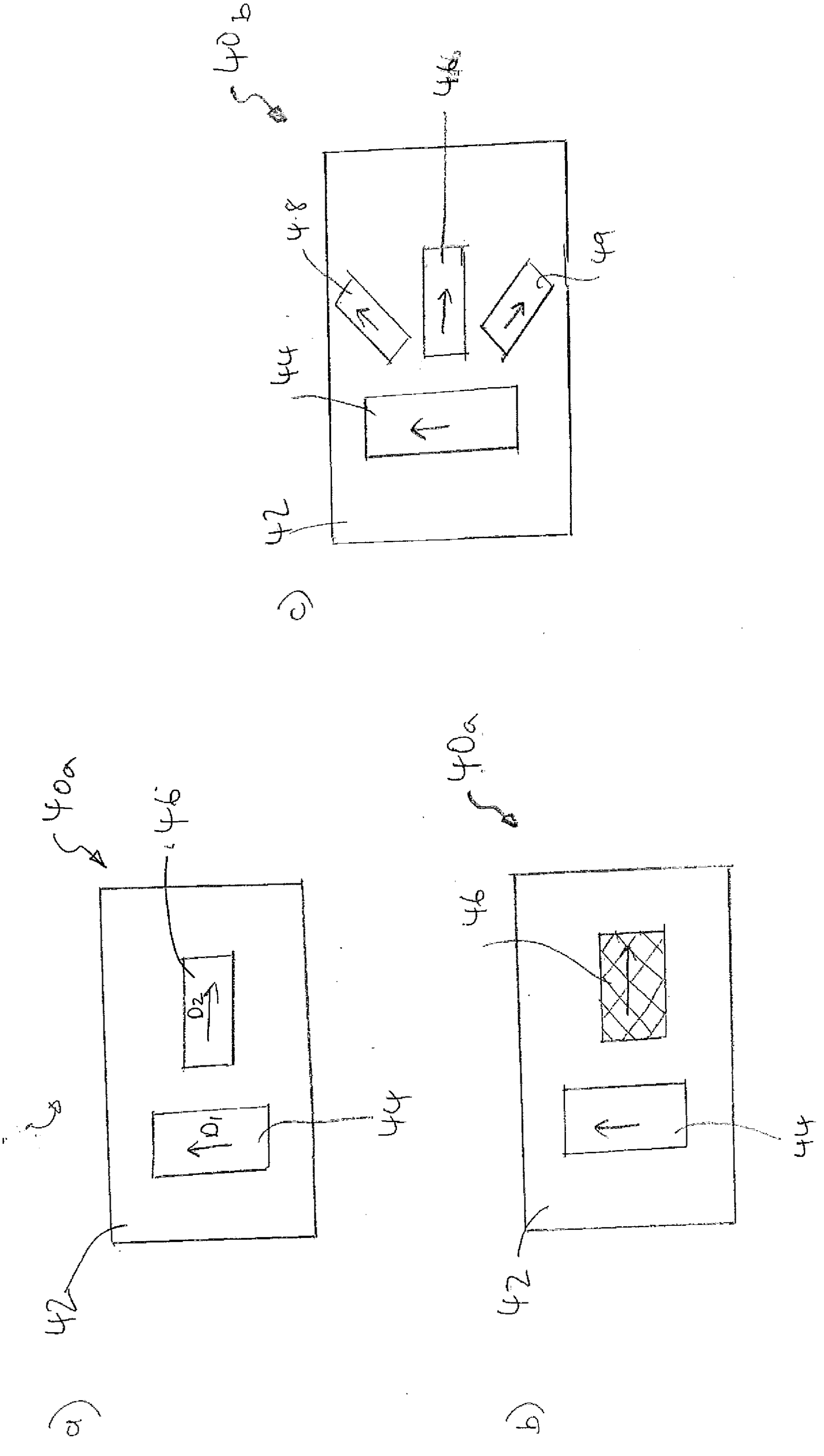

Figure 4

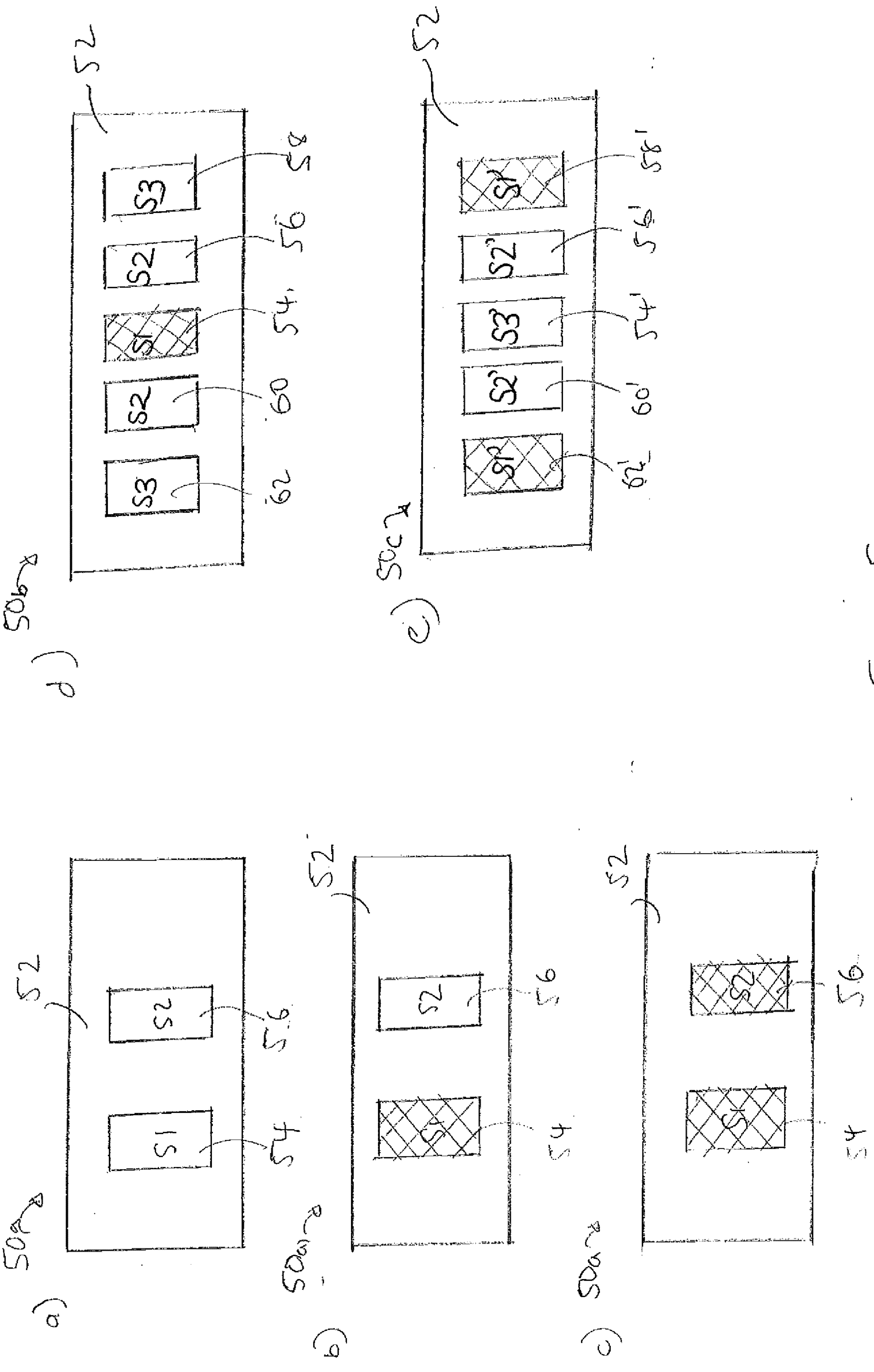
a)
50a
52
S1
S2
54
56
b)
50a
52'
S1
S2
54
56
c)
50a
52
S1
S2
54
56
d)
50b
52
S3
S2
S1
S2
S3
62
60
54
56
58
e)
50c
52
S1'
S2'
S3'
S2'
S1'
62'
60'
54'
56'
58'

Figure 5

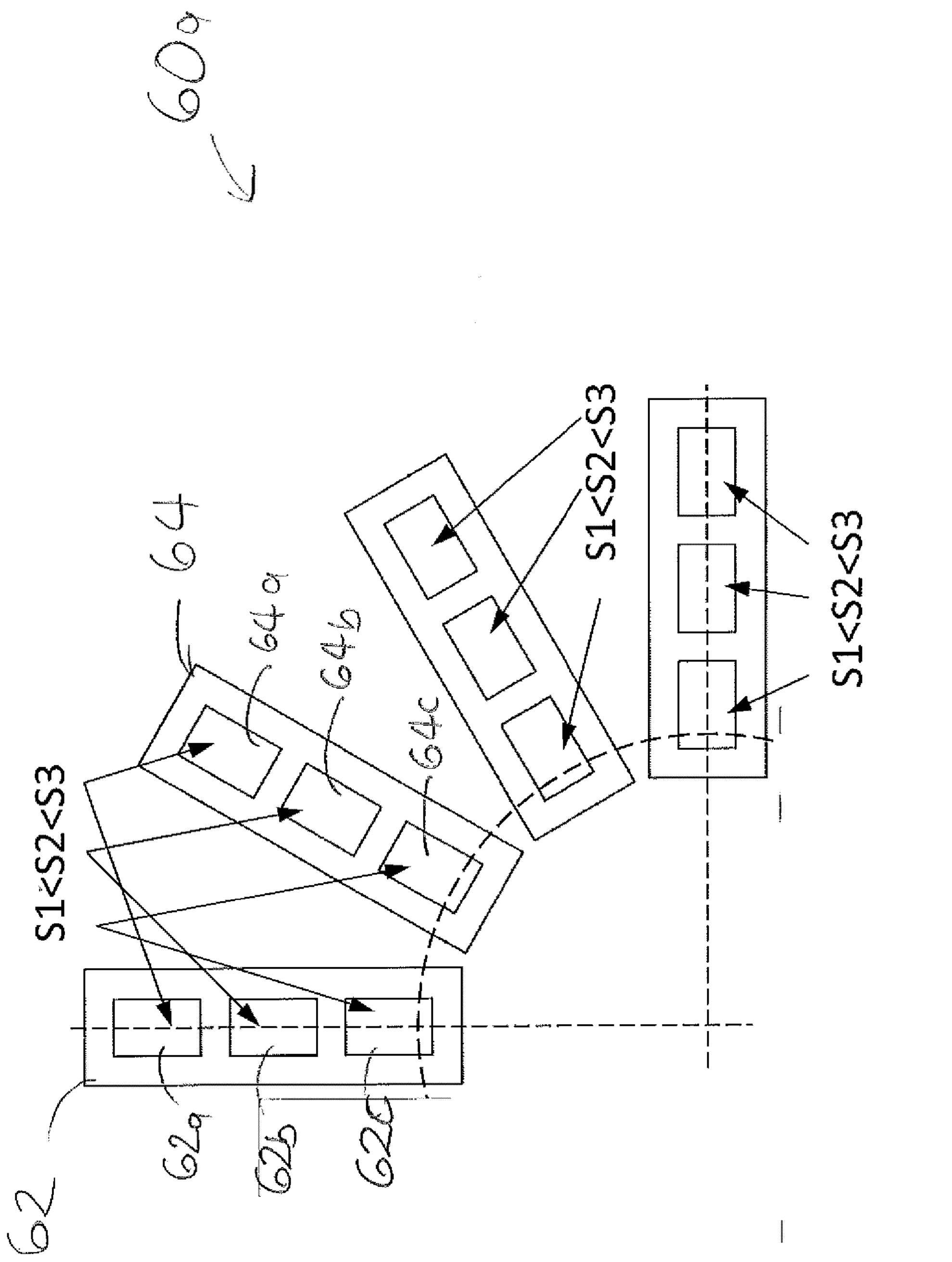

Figure 6a

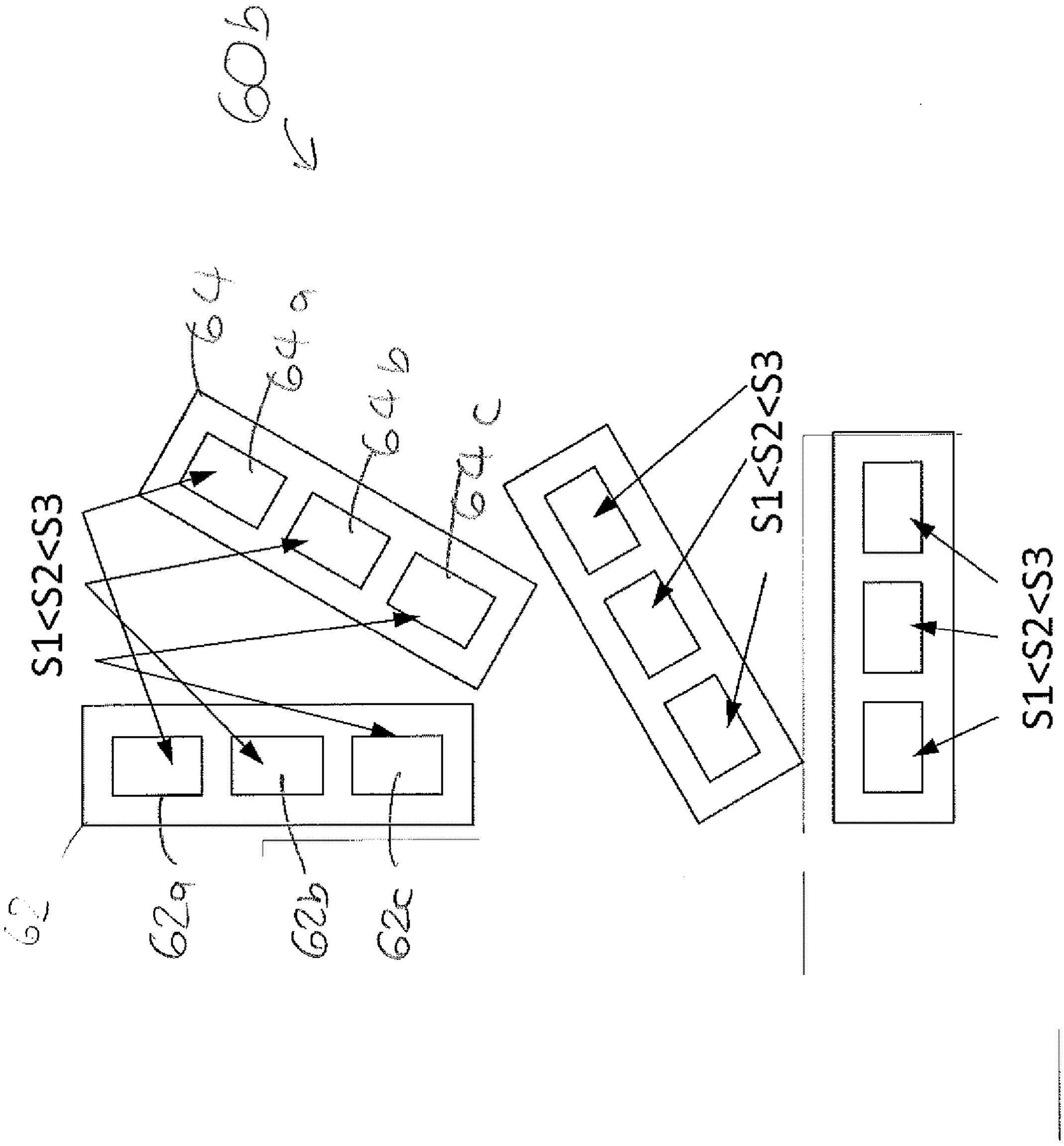

Figure 6b

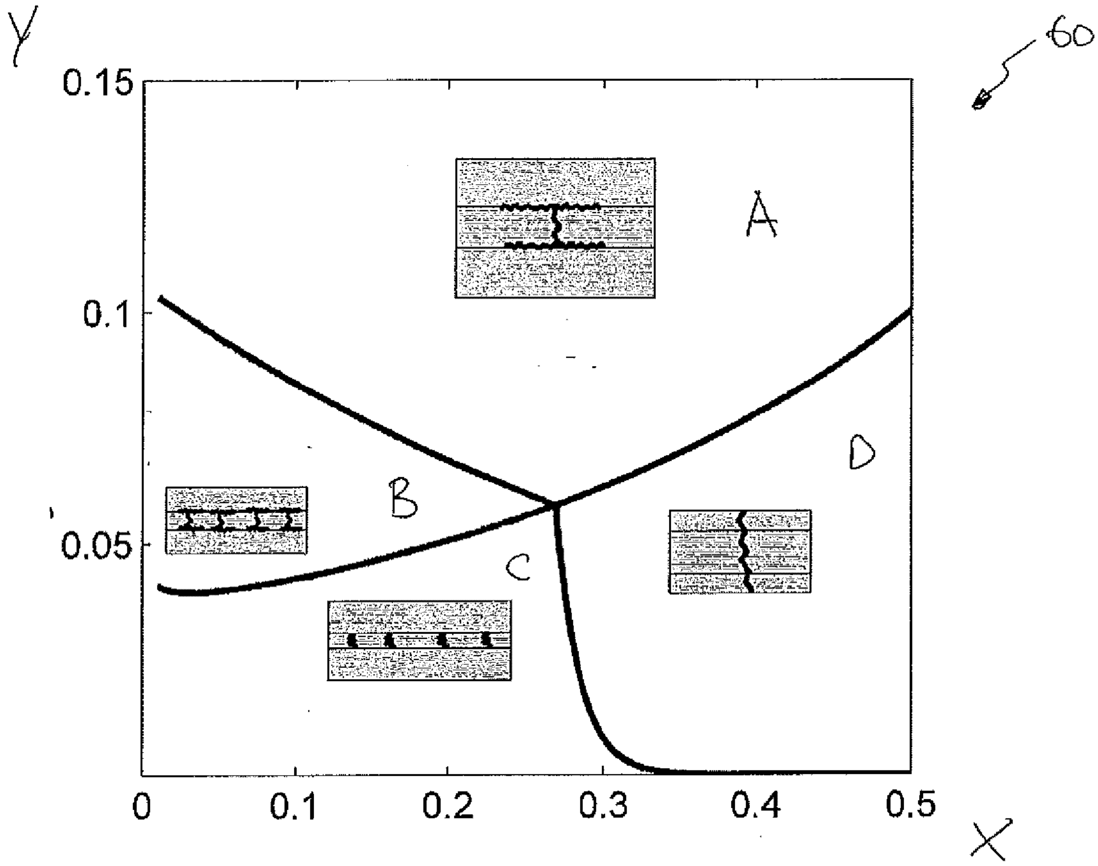

Figure 7

Strain Overload Sensor

Background

Composite materials are increasingly relied upon in many industries because of their strength, stiffness, corrosion resistance and low density. However, due to their sudden and complicated failure process, designs including composite structures are often complicated to cover uncertainties and fulfil safety requirements. There is a trade-off between current composite structures' lightness and safety. The same is true of structures formed from other materials.

A problem with such structures, in particular composite structures, is that it can be difficult to spot any damage until final failure. Final failure often presents itself as a fracture that can cause serious casualties if the structure is a bicycle frame or the like.

Summary of invention

According to a first aspect of the present invention, there is provided a sensor according to claim 1 that a structure has been subjected to a strain overload condition.

Thus, the sensor according to the first aspect utilises fracture of the first sensing element to provide a visual indication, visible through the transparent layer, that the first sensing element and the corresponding structure has been exposed to an overload strain. The sensor therefore results in a simple, robust overload gauge that can be cheap to manufacture. The sensor according to embodiments of the invention can be used to determine that a structure has been subject to load/strain sufficiently high that the material may be damaged and/or should be replaced.

The first sensing element and 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 could be done through other means, for example using adhesive.

The second surface of the sensing element can be secured directly or indirectly to the structure. The transparent layer can have a larger footprint than the sensing element so as to define a border region which can be used to secure the sensor to the structure. Thus, the transparent layer can have a major surface which is larger than that of the sensing element, the transparent layer being arranged to be attached directly to the structure so that the sensor element is held between the two. If the transparent layer has a larger footprint than the sensing element, and thus is capable of being coupled directly to the structure (bonded or integrally formed with) then the transparent layer can secure the sensing element in place so that it is mechanically coupled to the structure. Alternatively, or in addition, the sensing element can be coupled directly to the structure.

If the transparent layer is not capable of being directly coupled to the structure, then the sensing element should be bonded or otherwise directly coupled to the structure.

The visible change in the external appearance of the sensor can be caused by the fracture and decoupling of the first sensing element from the transparent layer.

The sensor can comprise a second layer on the opposite side of the first sensing element with respect to the transparent layer such that the first sensing element is indirectly coupled to the structure.

The sensing element can have a distinct sensing direction defined by the intrinsic orientation of the sensing element material and/or structure. The first sensing element can comprise fibre reinforced composite material, such as carbon fibre reinforced composite material, with fibres collimated in a single direction. The inventors have found this to result in a sensor with a precise strain to failure value. When the sensing element comprises fibre reinforced composite material, the direction of the collimation of the fibres defines the sensing direction of the sensing element.

The sensing element can comprise highly orientated thermoplastic polymer films, where the sensing direction can be defined by the direction of the macromolecules.

The sensing direction can be defined by other means depending on the material of the sensing element; for example, a suitable isotropic sensing element, where the overload condition in any direction can be indicated, but the exact direction of the overload may not be detected.

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.

The thickness of the first sensing element and the ratio of the thickness of the first sensing element to the thickness of the transparent layer can be such that the energy release rate upon failure is sufficient to cause one single crack in the sensing element followed by catastrophic delamination. Catastrophic delamination is visible as only one clear fracture in the sensing layer.

In embodiments of the present invention, the thickness of each of a plurality of sensing elements and the ratio of the thickness of each sensing element to the thickness of the transparent layer above said sensing element is such that the energy release rate upon failure is sufficient to cause catastrophic delamination, and wherein each sensing element has a distinct strain to failure value.

Catastrophic delamination can present as a single delamination or an initial catastrophic delamination followed by a stable delamination between the sensing element and the transparent layer when the structure is stretched at strains higher than the strain to failure of the sensing layer. The sensing element fractures only once in catastrophic delamination.

Another type of sensing element failure is visible as multiple fractures indicated by several stripes in the sensing layer.

The sensor can comprise one or more further sensing elements each bonded to the transparent layer and arranged to be coupled to the structure. In such embodiments, the transparent layer can be formed from a single piece of material, or a plurality of contiguous pieces of material.

The sensor can comprise a plurality of sensing elements, wherein each sensing element has a sensing direction and wherein two or more of the sensing directions are distinct from each other, such as perpendicular to each other.

The sensor can comprise a second sensing element, which can have the same sensing direction as the first sensing element. The first sensing element can have a first strain to failure value and the second sensing element can have a second, different strain to failure value, such that a first applied strain will cause only one of the first and second sensing elements to fracture and a second applied strain of greater magnitude than the first strain will cause the second sensing element to fracture.

The sensor can comprise one or more further sensing elements which can have the same sensing direction, each further sensing element having a respective strain to failure value, wherein each strain to failure value is distinct.

The sensing elements of distinct strain to failure values can be positioned under the transparent layer according to a pre-defined pattern and coupled to the structure to form a sensor assembly. The sensing elements can be positioned on the structure side by side, in a line, with all sensing elements aligned in the same direction. The sensing elements can be positioned in a self-explanatory or user identifiable pattern e.g. by putting the lowest strain element in the middle of a row and the further higher strain elements symmetrically towards the end of the row. The sensing elements can also be positioned with the highest strain to failure values at the centre of the line and the lowest strain to failure values at the ends of the line. Such a self-explanatory arrangement can be checked quickly in any orientation and human error is minimised.

Portions of the transparent layer can be colour coded above the sensing element(s) such that fracture and de-bonding of a sensing element from the transparent layer will display a given colour, and the visible colours can be used to determine the maximum strain applied to the material.

Thus a sensor can comprise one or more sensing elements of the same or different strain to failure values and sensing directions. A sensor can comprise a single transparent layer and one or more sensing elements. Sensors can comprise several arrays of sensing elements of different strain to failure values and different sensing directions, with a common transparent layer or individual transparent layers.

In accordance with a second aspect of the invention, there is provided an assembly according to claim 20.

The sensor can be bonded or otherwise secured to the structure.

One or more parts of a sensor can be formed integrally with a structure formed of a fibre composite material or non-composite (e.g. thermoplastic polymer or metallic) material.

The strain to failure value of the sensing elements can be lower than the strain to failure value of the structure.

The sensor can cover the majority, or the whole, of the surface area of the structure. It can contribute to the stiffness and the load bearing capacity of the structure until the sensing layer is fractured. Such a sensor is multifunctional by contributing to the mechanical performance and the safety of the structure at the same time.

The assembly can comprise a first sensor comprising one or more first sensing elements, each first sensing element having the same or a different sensing direction and/or a distinct strain to failure value with respect to the other first sensing elements; and a second sensor comprising one or more second sensing elements, each second sensing element having the same or a different sensing direction and/or a distinct strain to failure value with respect to the other second sensing elements; wherein optionally when each one of the first sensing elements is in the same sensing direction, and each one of the second sensing elements in the same sensing direction, the sensing direction of the first sensing elements and the sensing direction of the second sensing elements are distinct.

The sensing elements are arranged to indicate the magnitude and the direction of the applied overload strain at the same time. The direction of overload can be indicated by arranging sensing elements along specific lines which are self-explanatory or user identifiable. The indication of magnitude can be done by colour coding the sensing elements or by arranging them into a self-explanatory or user identifiable pattern such as a concentric array with lower strains towards the centre of the array and higher strains towards the perimeter. Portions of the transparent layer can be colour coded above the sensing element(s) such that fracture and de-bonding of a sensing element from the transparent layer will display a given colour, and the visible colours can be used to determine the maximum strain applied to the material.

Optional features of a first aspect of the invention can be applied to the assembly in an analogous fashion. Sensors with any one of the above features can thus be applied to the same structure, forming an assembly of a structure with one or more sensors, each sensor possessing a feature of the above described sensors. Each sensor can have a separate transparent layer, such that not every one of the multiple sensing elements secured to the structure is bonded to the same transparent layer.

In accordance with a third aspect of the invention, there is provided a method according to claim 25.

When a sensor is integrally formed with the structure, at least the transparent layer can be integrally formed with the structure.

Brief description of the drawings

For a better understanding of the present invention, and to show more clearly how it may be carried into effect, reference will now be made, by way of example, to the following drawings, in which:

Figure 1 shows a sensor according to an embodiment of the invention;

Figure 2 shows a sensor according to an embodiment of the invention with fibres of the sensing element aligned in a single direction;

Figures 3a and 3b schematically illustrate a bending force applied to a structure inducing tensile strain in a sensor according to an embodiment of the invention;

Figures 4a to 4c show sensors according to embodiments of the invention wherein the sensor comprises multiple sensing elements, and wherein the fibres in each sensing element are aligned in a distinct direction;

Figures 5a to 5e show sensors according to embodiments of the invention wherein the sensor comprises multiple sensing elements, each sensing element having a distinct strain to failure value;

Figures 6a and 6b show sensors according to embodiments of the invention wherein the sensor comprises multiple arrays of sensing elements, each array comprising multiple sensing elements aligned in the same direction with distinct strain to failure values, wherein the elements in each array are aligned at a distinct direction compared to the elements in a different array; and

Figure 7 shows a damage mode map for a SkyFlex™ USN020A inter-laminar carbon/glass hybrid composite.

Detailed description

Those skilled in the art will appreciate that various amendments and alterations can be made to the embodiments described above without departing from the scope of the invention as defined in the claims appended hereto.

Figure 1 shows a sensor 10 according to the present invention. The sensor 10 is arranged to identify when a structure 18 has been exposed to strains beyond its design limits. The structure 18 can be made from any material such as steel, aluminium, reinforced concrete or fibre reinforced polymer composite.

The sensor 10 comprises a transparent layer 12 and a sensing element 14. The transparent layer 12 and sensing element 14 are selected so as to each have a strain to failure value that falls within a pre-defined range. The strain to failure value represents the degree of strain that the material can be subjected to before the material fails. The material failing may include the material fracturing or fragmenting. The strain to failure value of the sensing element 14 is lower than the strain to failure value of the transparent layer 12, such that the sensing element 14 will fail before the transparent layer 12.

The relatively high strain to failure transparent layer 12 can be constructed from glass reinforced composite, or other translucent fibre, typically but not exclusively with an epoxy resin matrix. The relatively low strain to failure sensing element 14 can be constructed from fibre reinforced polymer composite. Carbon fibre grades are available in a very wide range of failure strains and are particularly suitable for use due to them having a variety of well-defined failure ranges.

The sensing element 14 is coupled to the transparent layer 12 at surface 12b and 14a; for example, by the resin in the composite sensing and transparent layers or by way of adhesive bonding. The same technique can be applied to attach the sensor to the structure 18 at surface 14b. As illustrated, the upper face 14a of the sensing element 14 is bonded to a lower surface 12b of the transparent layer 12 to define a coupling interface CI. The sensing element 14 is visible through the transparent layer 12, which can be translucent.

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 of the sensing element 14b. 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. It is possible to design a sensor, where there is no direct coupling between the sensing element 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 the transparent layer.

In other embodiments, the sensor 10 can be incorporated into a structure at the point of manufacture. The structure could be made of fibre reinforced composite materials, or of other materials such as thermoplastic polymers or metals.

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

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 sensor 10. Thus the sensor 10 is subject to substantially the same strain as the region of the structure 18 to which it is attached.

If the sensing element 14 is stressed by a force applied to the structure 18 which creates a strain equal to or greater than the strain to failure value of the sensing element 14, but less than the strain to failure value of the transparent layer 12, then the sensing element 14 will fail but the transparent layer 12 will not fail. Such a failure can cause fracturing and/or fragmentation of the sensing element 14, causing de-bonding and delamination of the sensing element 14 from the transparent layer 12 at the bonded surface CI. Such cracking, de-bonding or delamination is visible through the transparent layer 12 and provides a visible indication of the level of strain the sensor 10 has been subjected to.

The behaviour of the sensing element 14 and the transparent layer 12 upon failure of the sensing element 14 can depend on the material(s) from which each is formed and the thickness T1 of the sensing element 14 and the ratio of the thickness of the sensing T1 element 14 to that T2 of the transparent layer 12, which is described below in more detail with reference to Figure 7.

The strain to failure value of the structure 18 is greater than the strain to failure value of the sensing element 14, such that the sensing element will fail before the structure 18 fails. Therefore the sensor 10 can provide a visible indication that the structure 18 has been subjected to a strain which has not resulted in final failure of the structure 18 but is nevertheless constitutes an overload i.e. because it is above the structure's design limit strain.

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. In addition the edge 14c of the sensing layer 14 can be chamfered as well to make the shoulder portion S of the transparent layer 12 smooth, reduce shear stress concentration and avoid premature de-bonding of the sensing layer 14 from the transparent layer 12 resulting in false indication of an overload condition.

Referring additionally to Figure 2, the sensing element 14 of the illustrated embodiment is made of a fibre reinforced composite material, such as a carbon fibre reinforced composite material. The fibres 24 are collimated in a single direction D1.

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.

Referring additionally to Figures 3a and 3b, mechanical loading of a structure 18 is schematically illustrated. Figure 3a shows the structure 18 with no bending force applied. In Figure 3b, a bending force F is applied, 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. The fibres 24 fracture when a force is applied to the structure 18 that places the fibres 24 in tensile stress inducing strain in the sensing element 14 in D1 direction that exceeds the element's strain to failure value. If a bending force is applied to the structure in a way that the tensile strain is perpendicular to direction D1, the individual fibres will not experience deformation along their length and therefore will not fail.

Therefore when the sensing element comprises fibre reinforced composite material the direction of collimation the fibres of the sensing element define a "sensing direction" in which the element can detect that the structure has been subjected to an overload strain.

Thus if the direction of the fibres in a failed sensing element is known, one can determine the direction in which the structure has been subjected to an overload.

Figures 4a to 4c shows sensors 40a, 40b according to further embodiments, which include multiple sensing elements, wherein each sensing element has a distinct sensing direction. If the sensing elements comprise fibre reinforced composite material, then the sensing direction will be determined by the direction of collimation of the fibres.

A highly oriented polymer film (such as PP stripes) is anisotropic, and can have lower strain in the principal direction, which can define the sensing direction. In this case the direction of the orientation of macromolecules determined the sensing direction.

Alternatively, the sensing direction can be defined by other means depending on the material of the sensing element.

The sensors 40a, 40b can be of the same or similar construction to those described above and therefore, for brevity, the following description will focus on the differences.

Sensors 40a and 40b are shown with multiple sensing elements and a common transparent layer. Where the transparent layer is made from glass/epoxy, or other fibrous materials, it is preferable to use an individual transparent layer for each sensing element such that the fibre direction of the transparent later is aligned with the fibre direction of the sensing element.

Figure 4a 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 one can determine in which direction an overload strain has been applied to a structure by identifying which sensing elements in the sensor 40a of Figure 4 have failed.

Figure 4b shows the sensor of Figure 4a after an overload condition has been applied in one direction. Crosshatching indicates the visible failure 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 overload condition the structure has experienced. Similarly if the user knows the direction of collimation of the fibres in the first sensing element, they can determine that the structure has not been subject to an overload condition in a specific direction.

If both the first and second sensing elements have failed, then the structure has been subject to an overload condition in both directions.

A single sensor could indicate an overload condition in more than two directions through including multiple sensing elements, 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 4c, with sensing elements 44 to 49 each with a different sensing direction. The sensor 40b therefore can indicate whether the structure has been subjected to an overload condition in any of four directions.

The skilled person will appreciate that other arrangements of sensing elements 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 elements were used, the sensor could indicate whether the structure has been subject to an overload condition 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 overload. 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 an overload condition. The user may attach sensors to indicate an overload condition along the principal axes, or along the directions which are most vulnerable to experiencing an overload force.

Figures 5a to 5d show sensors 50a, 50b according to further embodiments with multiple sensing elements having the same sensing direction and a range of strain to failure values. The sensors 50a, 50b can be of the same or similar construction to those described above and therefore, for brevity, the following description will focus on the differences.

Figure 5a shows a sensor 50a with a transparent layer 52, a first sensing element 54 and a second sensing element 56. The first sensing element 54 has a first strain to failure value S1, and the second sensing element 56 has a second strain to failure value S2. In this embodiment the first strain to failure value is less than the second strain to failure value (i.e $S1 < S2$).

If the sensor 50a is subject to a force which induces a strain in the sensor which is equal to or greater than the first strain to failure value S1, but less than the second strain to failure value (i.e. $S1 \leq$ applied strain $< S2$), then the first sensing element 54 will fail but the second sensing element 56 will not. This is shown in Figure 5b, with failure of the sensing element indicated by crosshatching. The user can determine by visually checking the sensor that the strain experienced by the sensor is greater than the first strain but less than the second strain. Therefore the sensor can provide an indication of the magnitude of the strain experienced by the sensor (and, by association, the structure it is attached to).

If the sensor 50a is subject to a force which induces a strain in the sensor which is within or greater than the first strain to failure value and the second strain to failure value (i.e $S2 \leq$ applied strain), then both of the sensing element 54, 56 will fail. This is shown in Figure 5c, with failure of the sensing elements indicated by crosshatching. The user can determine that the sensor, and therefore the structure to which it is attached, has been subject to a strain equal to or greater than the highest strain to failure value of the sensing elements.

Sensing elements having different strain to failure values can be included in a single sensor to visually display the value of the overload strain which the sensor has been subjected to. A number of sensing elements with the same sensing direction could be included, each sensing element labelled with its strain to failure value. If the element has failed, then the skilled person can identify that the sensor has been subject to a strain of at least that value. Any combination of sensing elements could be used. A number of sensing elements with distinct strain to failure values but all within a small range will provide an accurate determination of the strain to which the sensor has been subjected to. Alternatively, sensing elements with strain to failure values which cover a large overall range could be used. Such a sensor would provide a less accurate determination of the strain which the sensor has been subjected to, but over a wider range.

It may be beneficial to provide a sensor which the user can use to determine the magnitude of strain the sensor has been subjected to which doesn't include reference numeral or signs on the indicator i.e. the pattern is self-explanatory or user identifiable. This will make it easier for quick visual identification, and removes the possibility of the signs being misread, numbers rubbing off, or any translational difficulties etc. For example, the sensing elements are positioned in a user identifiable pattern. Such a pattern can be read to determine the strain which the sensor has been subjected to without having to read numerals or signs. Such patterns can be read univocally in any orientation and the possibility of human error in general is reduced.

One example of a user identifiable or self-explanatory pattern is shown in Figure 5d) where sensor (50b) includes five sensing elements 54 to 62 positioned side by side, in a line, wherein the fibres of each sensing element are aligned in the same direction. Each sensing element has a specific strain to failure value, indicated on the figure. Sensing element 54 has a strain to failure value S1, sensing elements 56 and 60 have an equal strain to failure S2, and sensing elements 58 and 62 has an equal strain to failure value S3, where S1 < S2<S3. Therefore the central sensing element 54 has the lowest strain to failure value and the sensing elements 58, 62 with the highest strain to failure value are positioned symmetrically at the end of the line. If the sensor is subjected to increasing amounts of strain, the central sensing element 54 will fail first, followed by the two intermediate sensing elements 56, 60, followed by the two outer sensing elements 58, 62. The pattern of failed sensing elements will indicate the magnitude of strain which the sensor has been subjected to regardless of the orientation of the sensor during reading, which minimises human error.

In Figure 5d the central sensing element 54 has failed (indicated by crosshatching) and no other sensing elements have failed. Therefore the sensor has been subjected to a strain equal to or greater than the strain to failure value of the central sensing element 54 but less than the strain to failure value of the intermediate sensing elements 56, 60.

Figure 5e shows a different pattern of sensing elements. Again, a single sensor 50c includes five sensing elements 54' to 62' positioned side by side, in a line, wherein the fibres of each sensing element are aligned in the same direction. The sensing elements are labelled with their respective strain to failure values, where again S1' < S2'<S3'. Thus, in this embodiment, the central sensing element 54' has the highest strain to failure value and the sensing elements at the end of the line 58', 62' have the lowest strain to failure value. If the sensor is subjected to increasing amounts of strain, the end sensing elements 58', 62' will fail first, followed by the two intermediate sensing elements 56', 60', followed by the central sensing element 54'.

Any other user identifiable or self-explanatory pattern of sensing elements could be used in a similar manner to provide an indication of the magnitude of the strain which the sensor has been subjected to.

Figures 6a and 6b show sensors 60a, 60b according to further embodiments with multiple arrays of sensing elements, wherein the sensing elements within each array have the same sensing direction and a range of strain to failure values, and wherein each array is aligned in a distinct direction. The sensors 60a, 60b can be of the same or similar construction to those described above and therefore, for brevity, the following description will focus on the differences.

Figure 6a shows a sensor 60a with a first array 62 of sensing elements 62a, 62b, 62c and a second array 64 of sensing elements 64a, 64b and 64c. Each of the sensing elements in the first array (62a, 62b, 62c) are aligned in the same sensing direction. Each of the sensing elements of the second array (64a, 64b and 64c) are aligned in a common sensing direction. The sensing direction of the sensing elements in the first array is distinct from the sensing direction of the sensing elements in the second array. Thus each of the first and the second array indicate an overload condition applied to an object in different directions.

Each array has an individual transparent layer, such that an array is a plurality of sensing elements beneath a common transparent layer. Alternatively, all arrays may share a common transparent layer. In another embodiment, each sensing element may have an individual transparent layer, with each sensing element positioned into the pattern shown in Figures 6a and 6b.

The sensing elements within each array have distinct stain to failures grades. Sensing elements 62a, 62b and 62c have stain to failure grades S1, S2 and S3 respectively, wherein $S1 < S2 < S3$. Thus each array provides an indication of the magnitude of the tensile strain experienced in a given direction by having e.g. the low strain sensing elements towards the centre and the high strain sensing elements towards the perimeter of a radial arrangement as shown on Fig. 6a. Such self-explanatory or user identifiable pattern makes it possible to read a sensor without any notations regardless of the orientation of the sensor. The combination of multiple such arrays, each array aligned at a different angle, provides a sensor which can give a two-parameter indication (the direction and the magnitude) of the tensile strain experienced by the material to which it is attached.

In the embodiment in Figure 6, the sensing elements are arranged to indicate the magnitude and the direction of the applied overload strain at the same time. The direction of overload can be indicated by arranging the sensing elements along specific lines which are self-explanatory or user identifiable. The indication of magnitude can be done by colour coding the sensing elements or by arranging them into a self-explanatory or user identifiable pattern such as a concentric array with lower strains towards the centre of the array and higher strains towards the perimeter.

Figure 6b shows a similar sensor 60b with multiple array of sensing elements, wherein like reference numerals are used. The arrangement of arrays in Figure 60b is more compact than sensor 60a.

The sensing elements can be colour coded according to their strain. This technique is a good alternative to the user-identifiable positioning of sensing elements in order to indicate the magnitude of the overload in a sensing element array. For example when a specific sensing element fails it can display a specific colour to the user. Any configuration of sensing elements within a sensor could be used, with failure of each sensing element appearing as a different colour to the user. For example, a sensing element which appears blue upon failure may have a low strain to failure value and a sensing element which appears red upon failure may have a high strain to failure ratio. Information can be encoded in the colour a sensing elements displays upon failure.

Colour coding can be achieved by colouring the transparent layer. Each sensing element is bonded to a specific section of the transparent layer. This specific section is coloured depending on the strain to failure of the sensing element which it will be bonded to.

Colour coding can be used in sensors with multiple sensing elements, where different sections of the same transparent layer are coloured differently depending on the strain to failure value of the sensing element which is bonded to that section. Colour coding can also be used on sensors with single sensing elements. The transparent layer of the sensor could be colour coded depending on the strain to failure value of the sensing element in the sensor. In this way, a user could attach individual sensors to a structure to create a customised sensor with sensing elements of chosen strain to failure values. A user identifiable colour scheme would allow a user to create and read a customised pattern of sensing elements.

Both the key to a pre-defined user identifiable sensing element arrangement or to a colour code can be used to restrict access to the information indicated by a sensor having no numerals or other marks. For example the key can only be shared with authorised personnel. This feature could be particularly valuable in some sensitive applications.

As set out above, sensors according to embodiments of the invention are arranged such that under overload conditions the low strain to failure sensor element will fail. The sequence of events after the initial failure of the low strain to failure layer will depend on the thickness of the low strain to failure layer. For a relatively thick layer of sensing element, a single fracture followed by sudden delamination will form at the interface between the low and high strain to failure layers, which changes the colour of the whole sensor from black to a light colour depending on the resin in the high strain to failure layer. For a relatively thin layer, the initial failure of the sensing element will not lead to complete catastrophic delamination and as the level of overload increases the number of fractures will increase up to a saturation value. At each crack in the low strain to failure layer, a local delamination occurs between the low strain to failure and transparent outer layers, which appears as a bright stripe in the sensor element.

The strain at which overload will be sensed can be controlled in some embodiments by the selection of specific suitable grades of fibres to form the sensing layer. Alternative methods of controlling the strain at failure or localising such failures to aid in detection are available. These include the use of a low strain to failure layer, which in itself consists of a number of thinner layers, one or more of which has been weakened or pre-cut to control and localise the failure. Additionally, known techniques are available for modifying failure by hybridising aligned discontinuous fibre preforms and for fibre steering to match strain fields.

Figure 7 shows a damage mode map for a SkyFlex™ USN020A high strength carbon/S-glass hybrid. The 'carbon layer thickness' Y axis refers to the thickness of the sensing element, and the 'carbon/glass proportion' X axis is the ratio of the thickness of the sensing element to that of the transparent layer. These material properties of a sensor define how the sensing element will fail.

Delamination of the sensing element from the transparent layer provides an easy to recognise visual indication of failure of the sensing element. Therefore it is preferred that sensors according to embodiments of the present invention are designed with properties within three quadrants of the damage mode map of Figure 6: quadrant A which results in catastrophic delamination, quadrant B which results in fragmentation and delamination and quadrant C which results in delamination without fragmentation. Quadrant D results in premature failure of the sensor.

To achieve a sudden change of appearance in the sensor following an overload strain, the low strain material failure should lead to an unstable delamination between the layers without breaking the high strain material. This means that the stress required to develop a delamination between the layers should be lower than the stress required to fail the high strain material and to produce the second failure in the low strain material. Such a failure process can be achieved satisfying either of the following conditions:

$\sigma_{@del} < \sigma_{@LF} < \sigma_{@HF}$ or $\sigma_{@del} < \sigma_{@HF} < \sigma_{@LF}$

Where σ is the overall stress in the laminate and the subscripts *del*, *LF* and *HF* are for different failure modes of delamination, Low strain material Failure, and High strain material Failure. The required stress value for each of these damage modes can be found using the equations in Table 1, where the modulus and thickness ratios $\alpha = \frac{E_L}{E_H}$ and $\beta = \frac{t_L}{t_H}$ are constant for each specific hybrid combination, S_L and S_H are the strengths of the low and high strain materials and G_{IIC} is the mode II interlaminar fracture toughness.

Table 1- Overall stress at laminate level for each damage mode

Damage mode	Criterion
Fragmentation in the low strain material	$\sigma_{@LF} = S_L \frac{\alpha\beta + 1}{\alpha(\beta + 1)}$
Delamination	$\sigma_{@del} = \frac{1}{1+\beta}\sqrt{\left(\frac{1+\alpha\beta}{\alpha\beta}\right)\left(\frac{2G_{IIC}E_H}{t_H}\right)}$
Failure of the high strain material	$\sigma_{@HF} = \frac{S_H}{(1+\beta)}$

The damage mode map illustrated in Figure 7 provides a simple visual method for designing a sensor according to embodiments of the invention. The damage mode maps divide the whole design domain into four groups with different failure processes so the desired number of plies of the constituent materials can be selected very easily based on the available ply thicknesses provided that the basic mechanical properties (inc. E and S) of the cured composite plies are available.

Catastrophic delamination (quadrant A) presents in a de-bonding of the majority of the sensing element from the transparent layer upon failure of the sensing element. Catastrophic delamination is easily visible as a broadband colour change across the sensing element. The length of catastrophic delamination depends on how far is the design from the border between areas A and B in the damage mode map in Figure 7. If the design is far away from the border, the catastrophic delamination length is long. If the design point is very close to the border, we will get a small catastrophic delamination length. It is therefore beneficial for any sensor described above to have a thickness of the sensing element, and a ratio of the sensing element to the transparent layer, such that failure of the sensing element causes broadband delamination of the sensing element from the transparent layer.

Fragmentation and delamination (quadrant B) results in a stripy pattern after overload. The low strain material fragments first followed by local delaminations initiating from the tips of the fragments. So the following condition should be satisfied:

$$\sigma_{@LF} < \sigma_{@del} < \sigma_{@HF}$$

Thus, embodiments of the invention provide a sensor for indicating that a structure has been subject to an overload strain condition. Such a sensor is particularly suitable for application to structures such as pressure vessels, aerospace components, pipes, buildings or in consumer goods that may be subject to high loads, or where sudden failure would present a safety risk, such as bicycle frames.

Claims

1. A sensor for indicating that a structure has been subjected to a strain overload condition, the sensor comprising:

a transparent layer; and

a first sensing element with a first surface bonded to the transparent layer via a first coupling interface, and a second surface arranged to be secured to the structure via a second coupling interface such that deformation of the structure causes corresponding deformation of the first sensing element,

wherein the first sensing element has a lower strain to failure value than the transparent layer, such that upon the structure being subjected to a first strain, the sensing element will fail but the transparent layer will not fail, causing a visible change in the external appearance of the sensor through fracture of the first sensing element,

wherein the failure of the sensing element causes fracture and/or fragmentation of the sensing element, causing de-bonding and delamination of the sensing element from the transparent layer at the first coupling interface, the delamination causing the visible change in the external appearance of the sensor to provide a visual indication of the level of strain the sensor has been subjected to.

2. A sensor according to claim 1 wherein sensor is arranged such that the visible change in the external appearance of the sensor is caused by the fracture and de-coupling of the first sensing element from the transparent layer.

3. A sensor according to any of the above claims wherein the first surface of the first sensing element faces the transparent layer and a second, opposite surface of the first sensing element is arranged to be secured to the structure.

4. A sensor according to any of the above claims, wherein the first sensing element comprises fibre reinforced composite material.

5. A sensor according to any of the above claims, wherein the transparent layer has a larger footprint than the sensing element so as to define a border region which forms at least part of the second coupling interface and can be used to secure the sensor to the structure.

6. A sensor according to any of the above claims wherein the sensor further comprises a second layer on the opposite side of the first sensing element with respect to the transparent layer and wherein the second layer defines at least part of the second coupling interface.

7. A sensor according to any of the above claims wherein the first sensing element has a sensing direction defined by an intrinsic orientation of the material of the first sensing element.

8. A sensor according to any of the above claims, comprising one or more further sensing elements.

9. A sensor according to claim 8, wherein each sensing element has an individual sensing direction, and wherein two or more of the sensing directions are distinct from each other.

10. A sensor according to claim 9 wherein two or more of the sensing directions are perpendicular to each other.

11. A sensor according to claims 8, 9 or 10, wherein one of the further sensing elements is a second sensing element and is coupled to the transparent layer with the same sensing direction as the first one and wherein the strain to failure value of the first sensing element is different to a second strain to failure value of the second sensing element, such that: a first applied strain will cause only one of the first and second sensing elements to fail; and a second applied strain of greater magnitude will cause both the first sensing element and the second sensing element to fail.

12. A sensor according to claim 11 wherein one or more of the further sensing elements is a third sensing element with the same sensing direction, each third sensing element having a respective strain to failure value, wherein each strain to failure value is distinct from that of at least one other sensor element.

13. A sensor according to claim 12 wherein the sensing elements are positioned side by side, in a line, with all sensing elements having the same sensing direction.

14. A sensor according to claim 13 wherein the sensing elements are positioned with the lowest strain to failure grades at the centre of the line and the highest strain to failure grades at the ends of the line symmetrically.

15. A sensor according to claim 13 wherein the sensing elements are positioned with the highest strain to failure grades at the centre of the line and the lowest strain to failure grades at the ends of the line symmetrically.

16. A sensor according to any of the above claims, wherein portions of the transparent layer are colour coded above the sensing element(s) such that failure of a sensing element from the transparent layer will display a given colour, and the visible colours can be used to determine the maximum strain applied to the material.

17. A sensor according to any of the preceding claims wherein the transparent layer is chamfered at its edges to minimise stress concentration at the edges of the sensor.

18. An assembly comprising one or more sensors according to any of the above claims secured to a structure.

19. An assembly according to claim 18 wherein the strain to failure value of at least one of the sensing elements is lower than the strain to failure of the structure.

20. An assembly according to claim 18 or claim 19 wherein one or more of the sensors are integrally formed with the structure.

21. An assembly according to any one of claims 18 to 20 comprising a single sensor that covers the majority of the surface area of the structure.

22. An assembly according to any one of claims 18 to 21,

wherein at least one of the sensors is a first sensor comprising a plurality of first sensing elements, and each first sensing element of the first sensor has the same or a different sensing direction and/or a distinct strain to failure value with respect to the other first sensing elements; and

wherein at least one of the sensors is a second sensor comprising a plurality of first sensing elements, and each first sensing element of the second sensor has the same or a different sensing direction and/or a distinct strain to failure value with respect to the other first sensing elements of the second sensor.

23. An assembly according to claim 22, wherein when each one of the first sensing elements of the first sensor is in the same sensing direction, and each one of the first sensing elements of the second sensor is in the same sensing direction, the sensing direction of the first sensing elements of the first sensor and the sensing direction of the first sensing elements of the second sensor are distinct.

24. 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.