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(54) **SMART BLAST SENSING**

(71) Applicant: **UNIVERSITY OF ULSTER**, County Londonderry, Northern Ireland (GB)

(72) Inventor: **Faris Abed Al-Hafidh ALI**, Carrickfergus, Antrim (GB)

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E04C 2/06 (2006.01)
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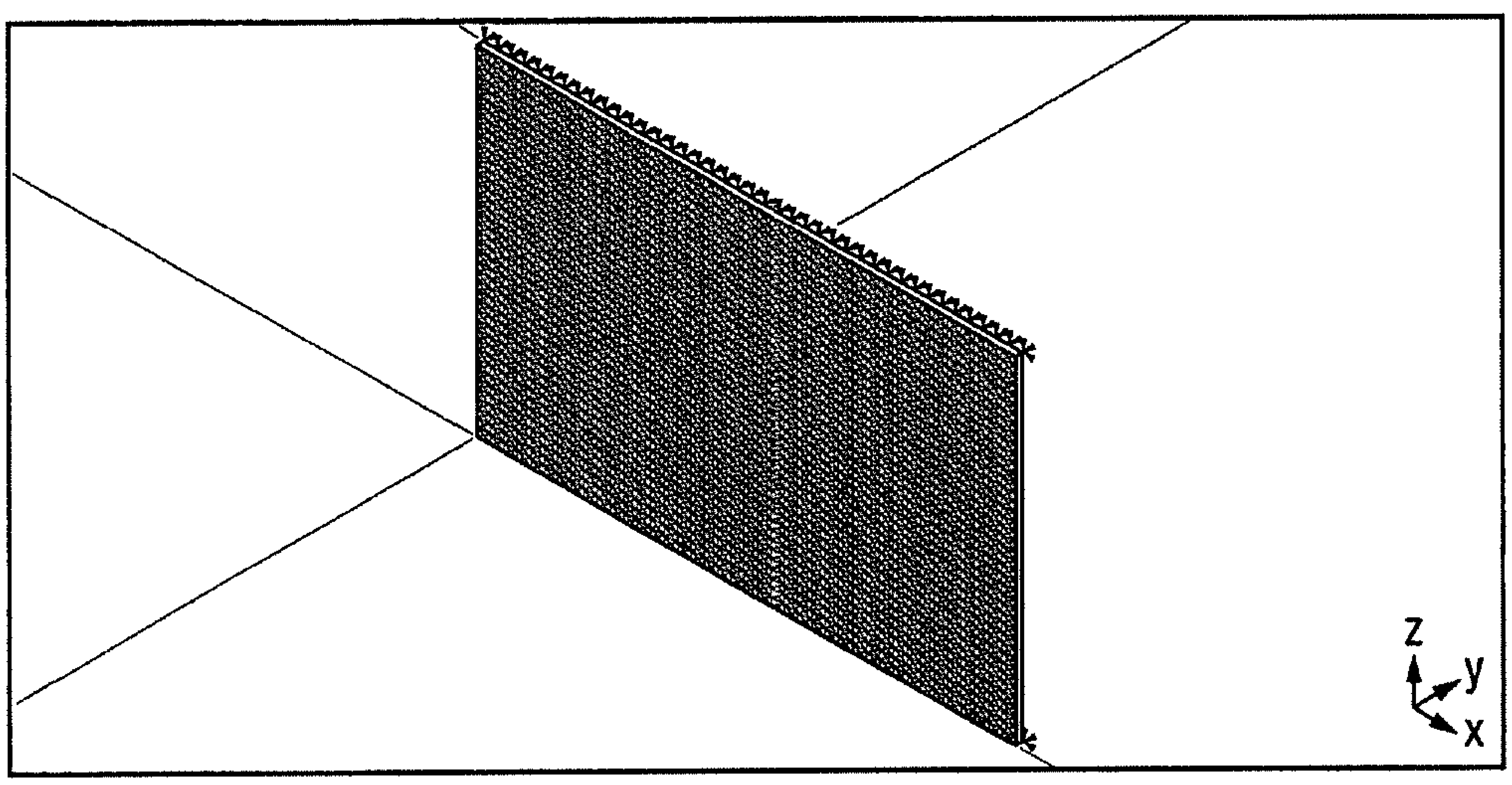
(52) **U.S. Cl.**

CPC .. ***F41H 5/24*** (2013.01); ***E04C 2/06*** (2013.01); ***E04C 2/46*** (2013.01); ***E04C 2/528*** (2013.01); ***E04C 5/012*** (2013.01); ***E04F 13/072*** (2013.01)

(57) **ABSTRACT**

An automated smart system for forming a blast resistant structure comprises one or more remote blast sensors connected to at least one actuator arranged to actively deform a panel of the structure from an initial configuration to a curved configuration in response to sensing a blast.



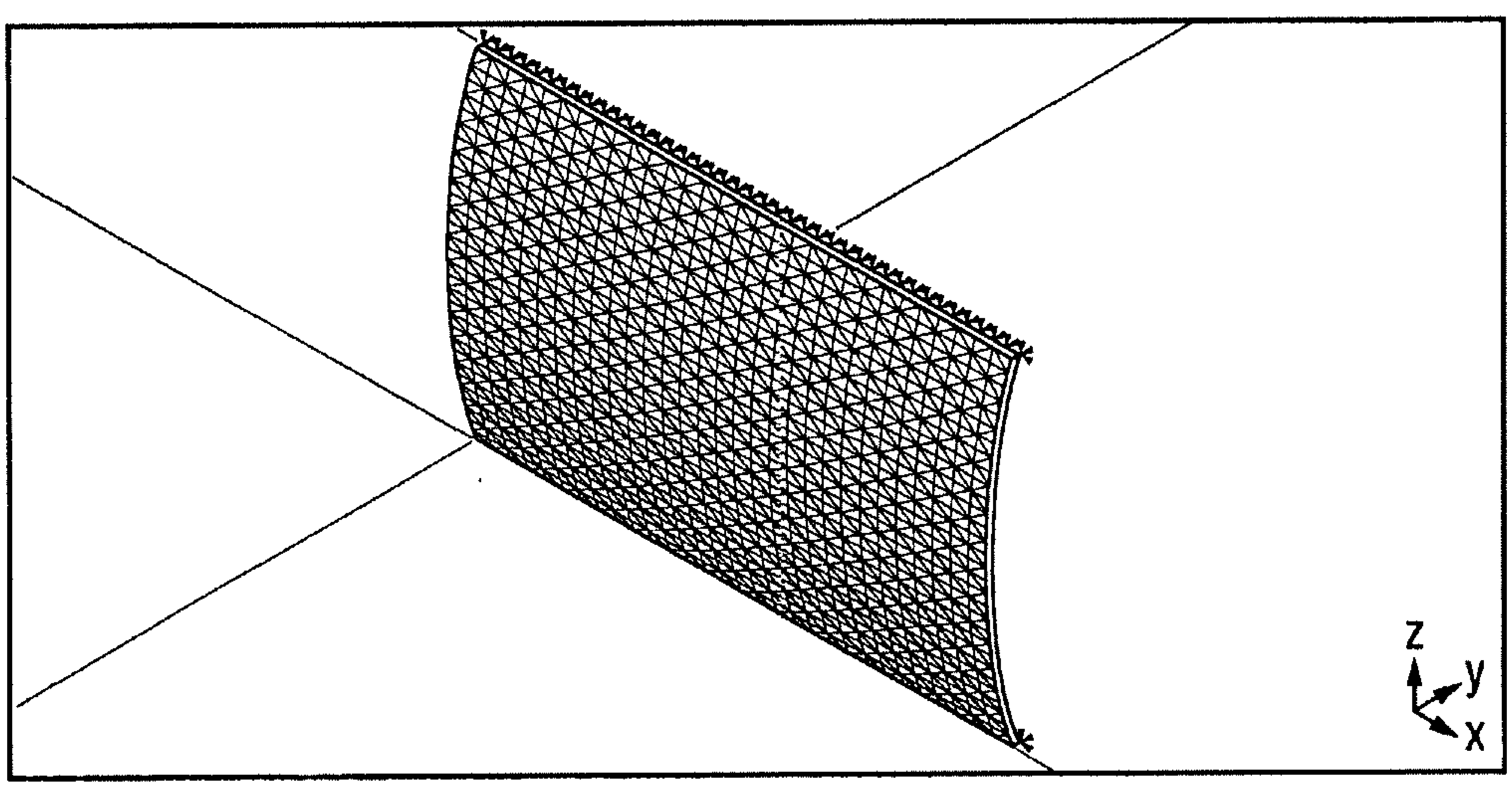
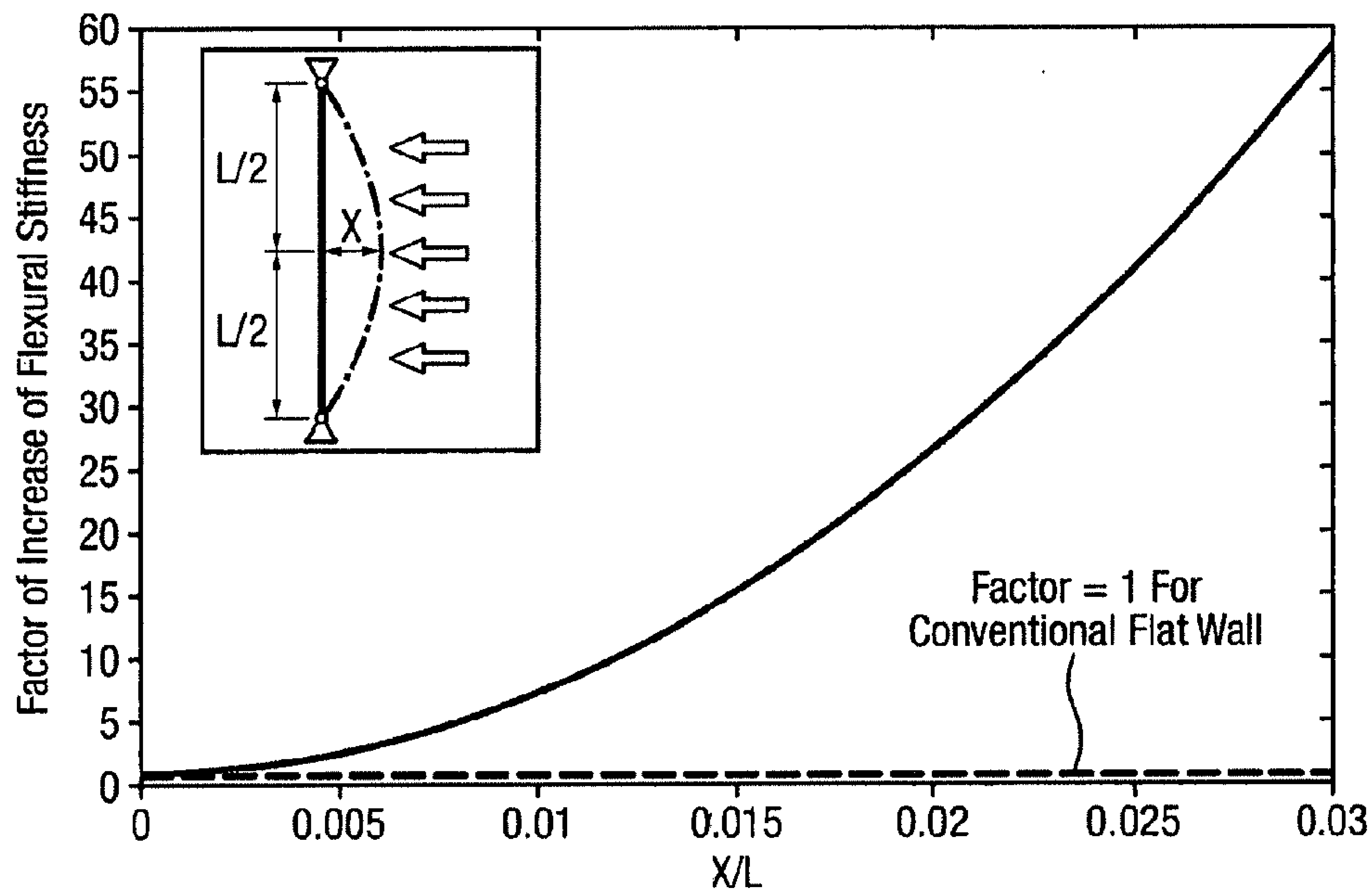


Fig. 1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50
45
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20
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5
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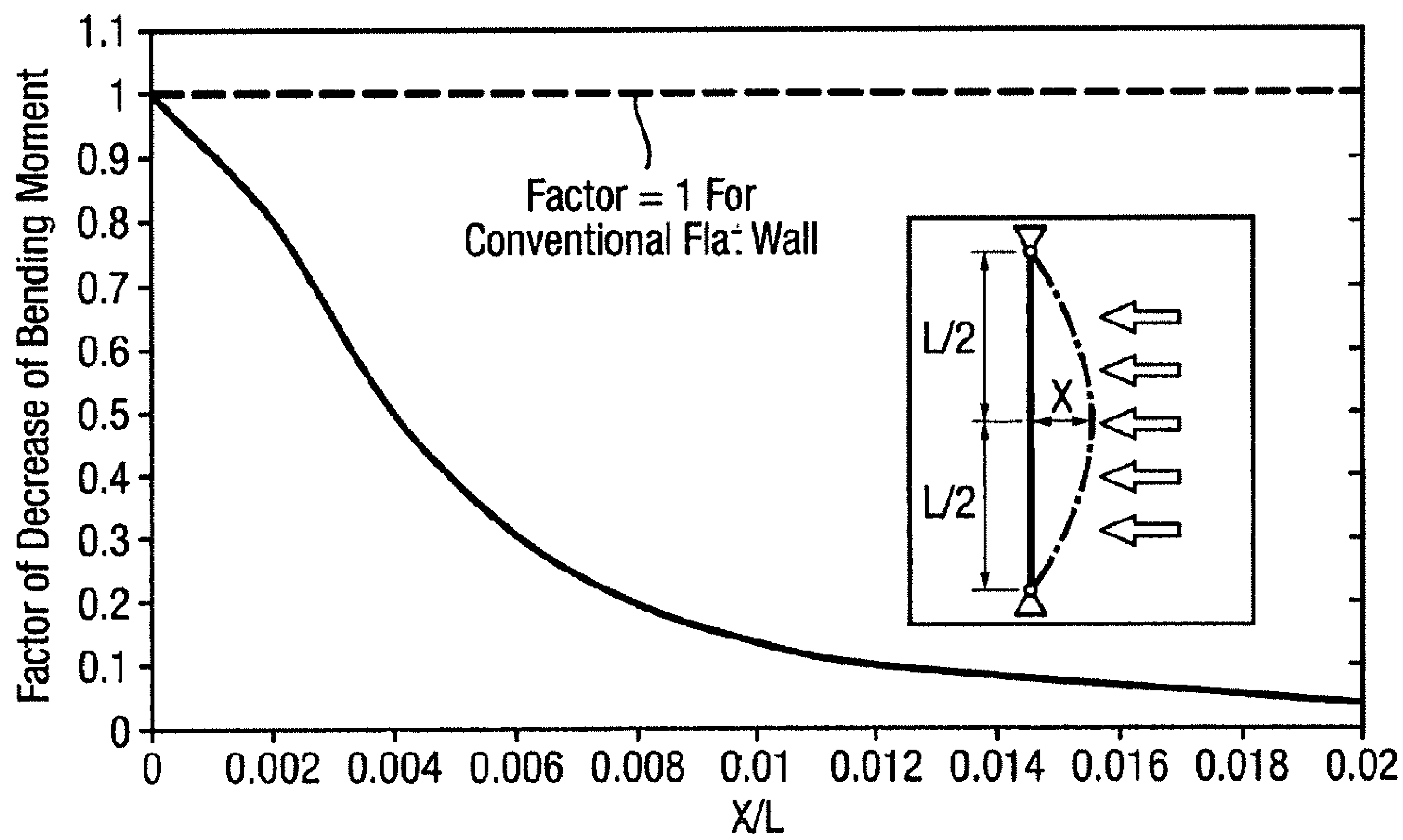
L/2
X
L/2
Factor = 1 For
Conventional Flat Wall
0
0.005
0.01
0.015
0.02
0.025
0.03
X/L

Fig. 2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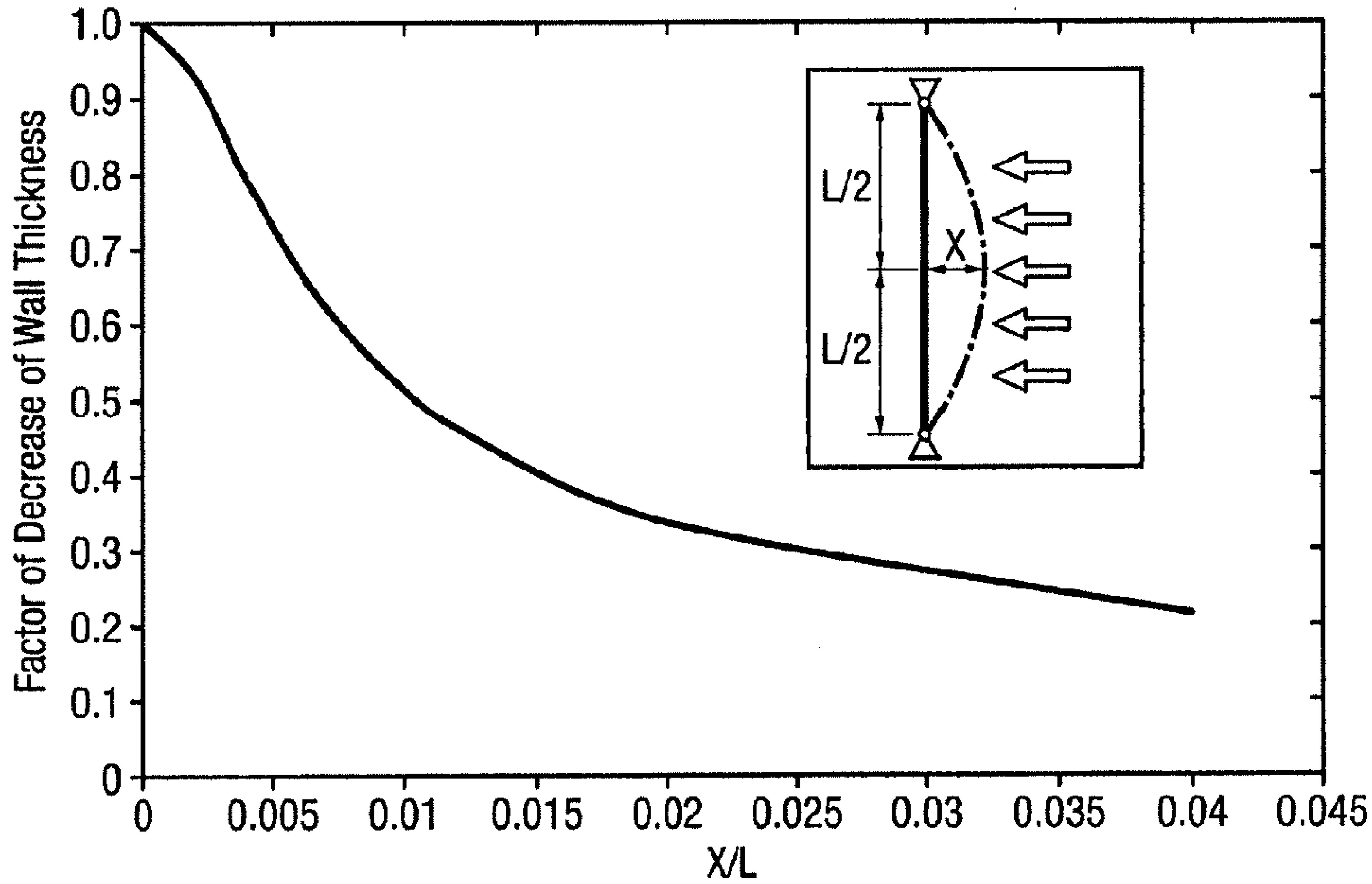
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Factor = 1 For
Conventional Flat Wall
L/2
X
L/2
0
0.002
0.004
0.006
0.008
0.01
0.012
0.014
0.016
0.018
0.02
X/L

Fig. 3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0.9
0.8
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0.6
0.5
0.4
0.3
0.2
0.1
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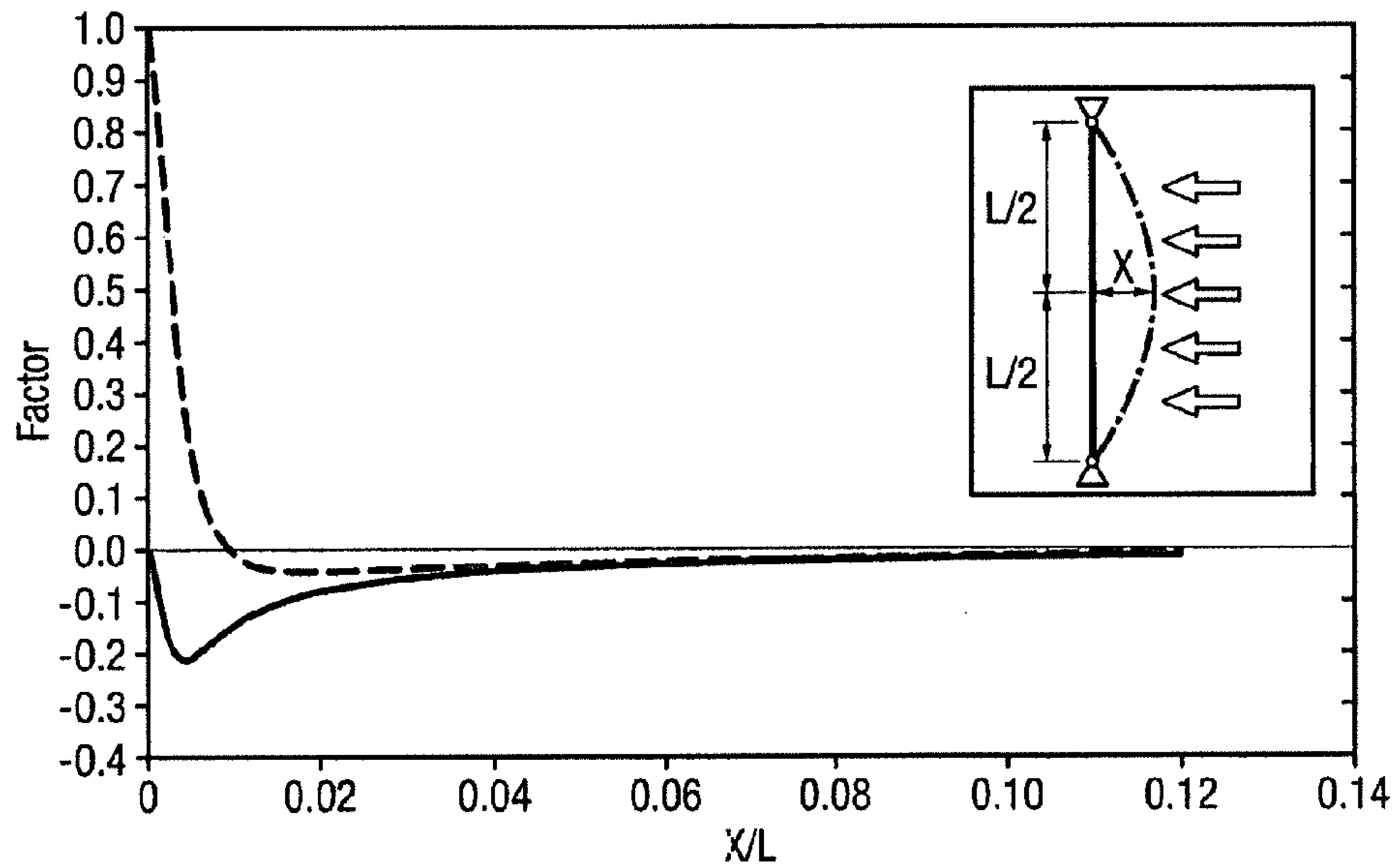
Factor of Decrease of Wall Thickness
0
0.005
0.01
0.015
0.02
0.025
0.03
0.035
0.04
0.045
X/L
L/2
L/2
X

Fig. 4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0.5
0.4
0.3
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0.1
0.0
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-0.2
-0.3
-0.4
Factor
0
0.02
0.04
0.06
0.08
0.10
0.12
0.14
X/L
L/2
L/2
X

Fig. 5

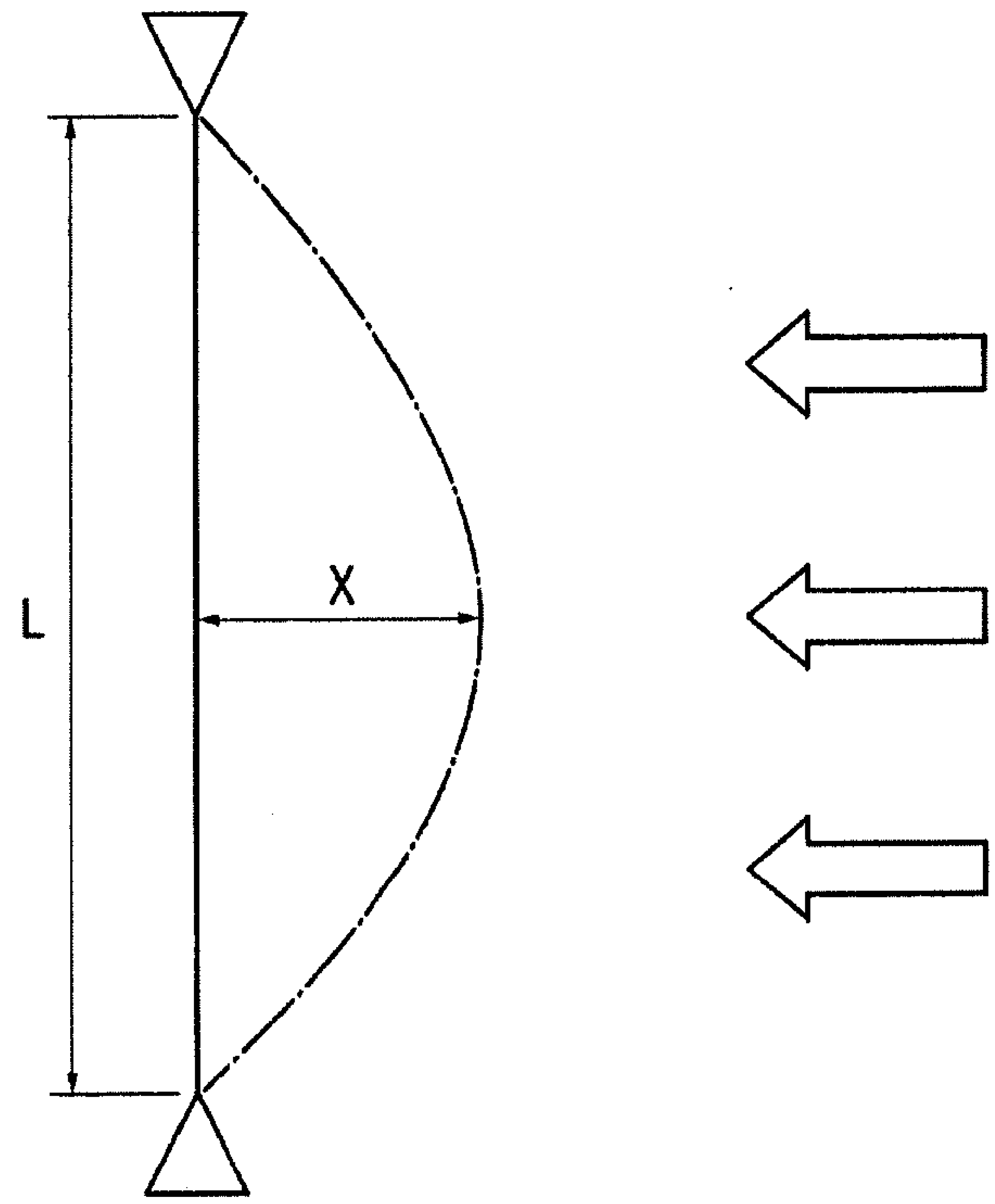


Fig. 8

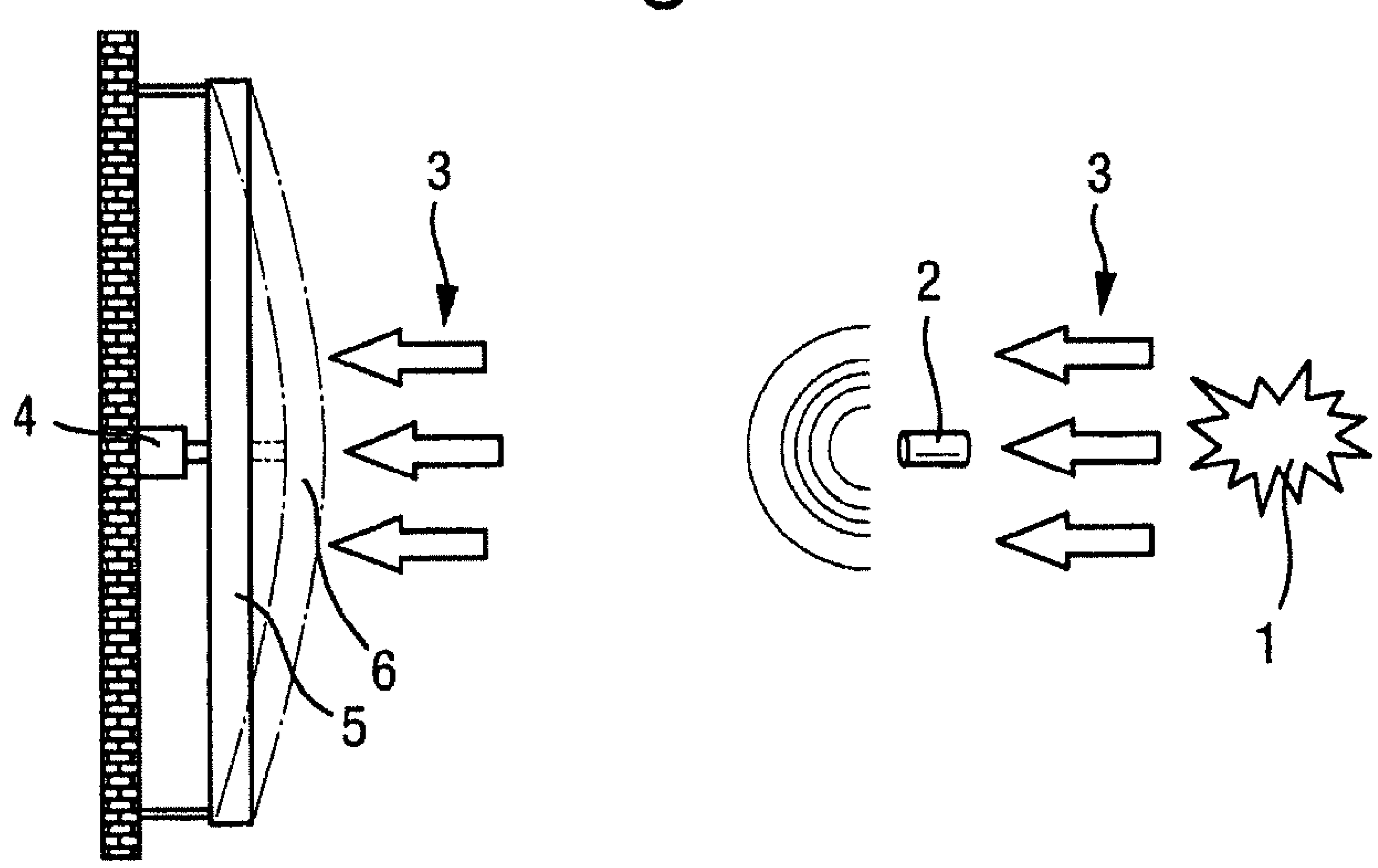


Fig. 6a

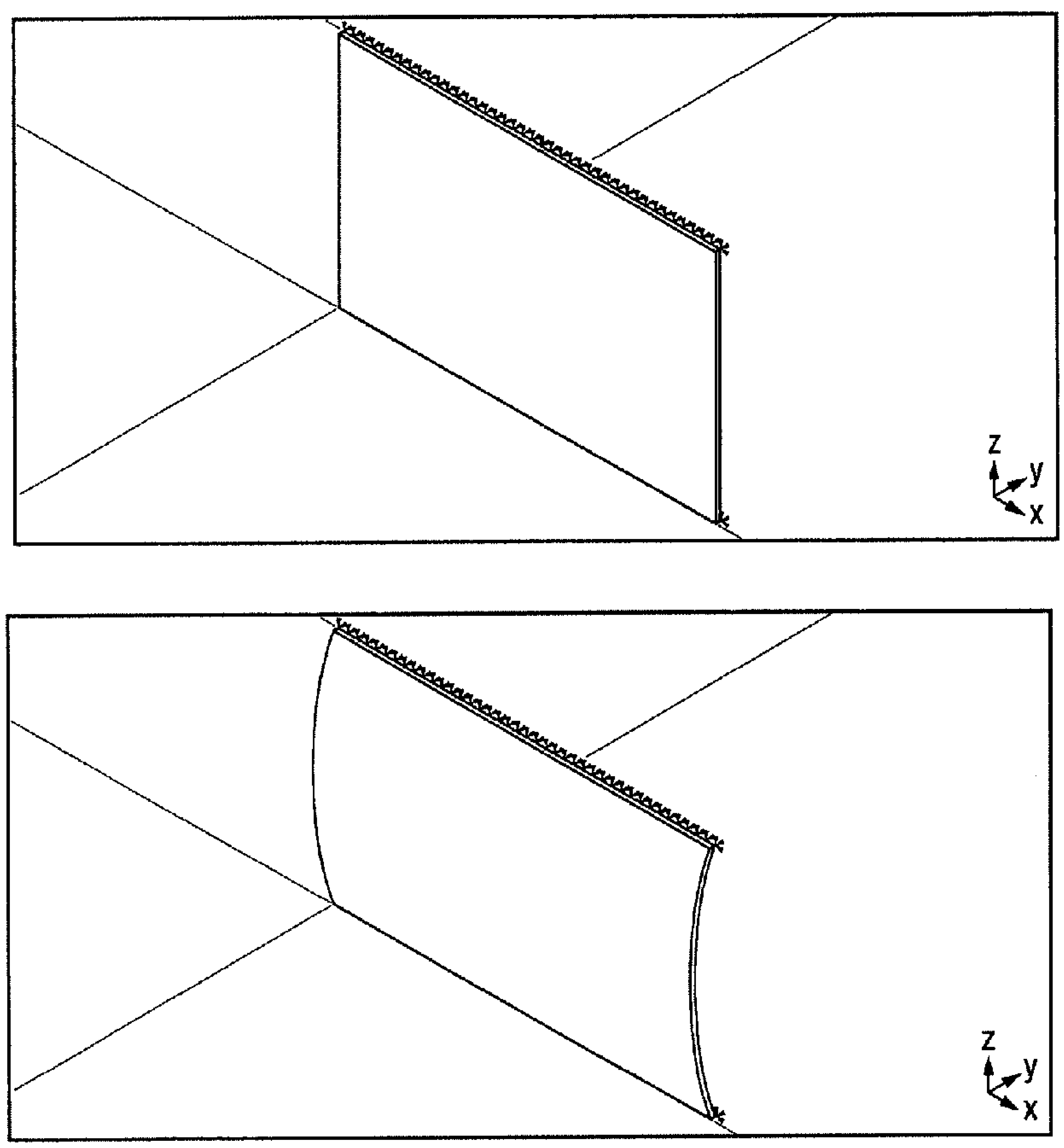


Fig. 6b

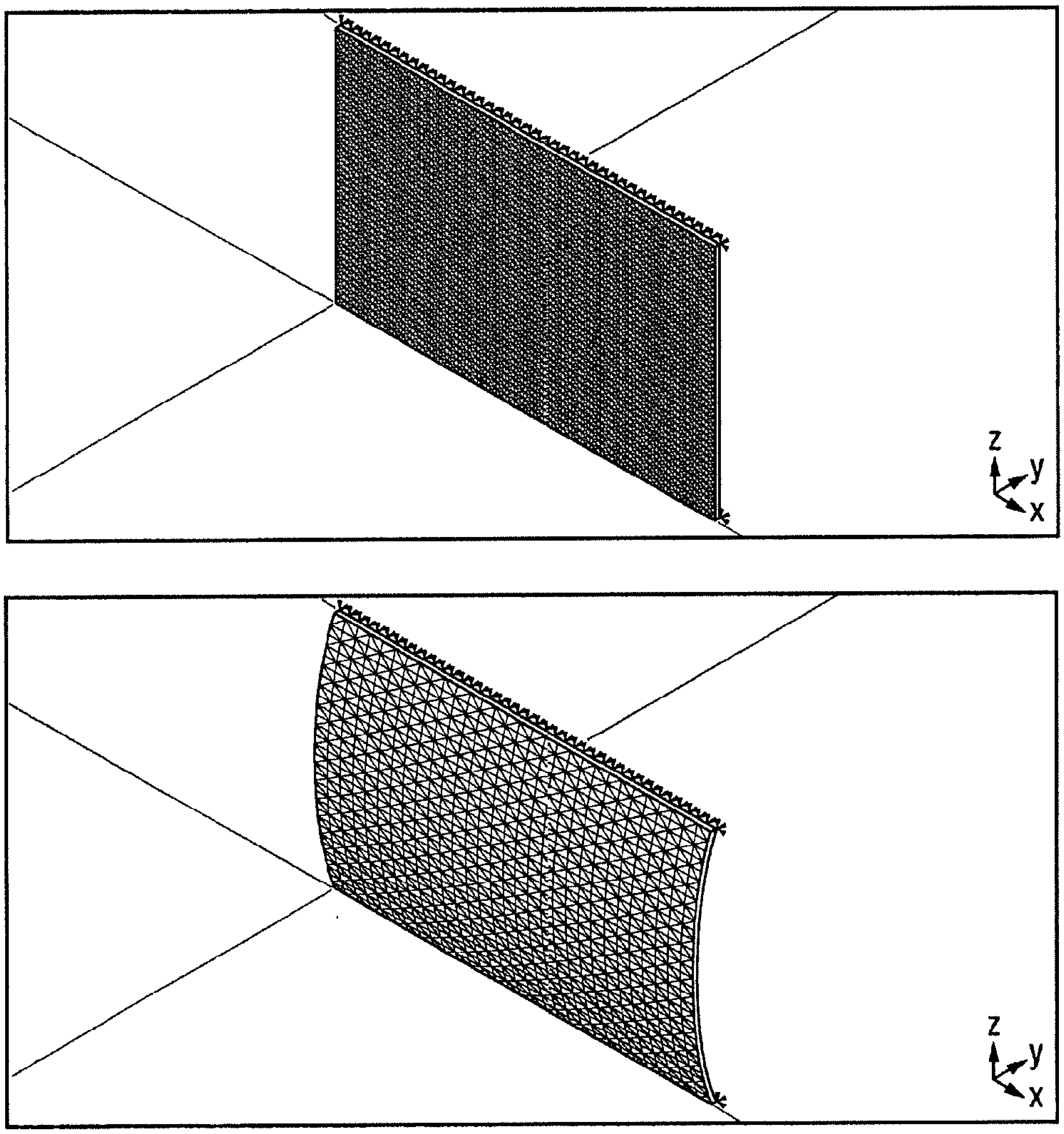
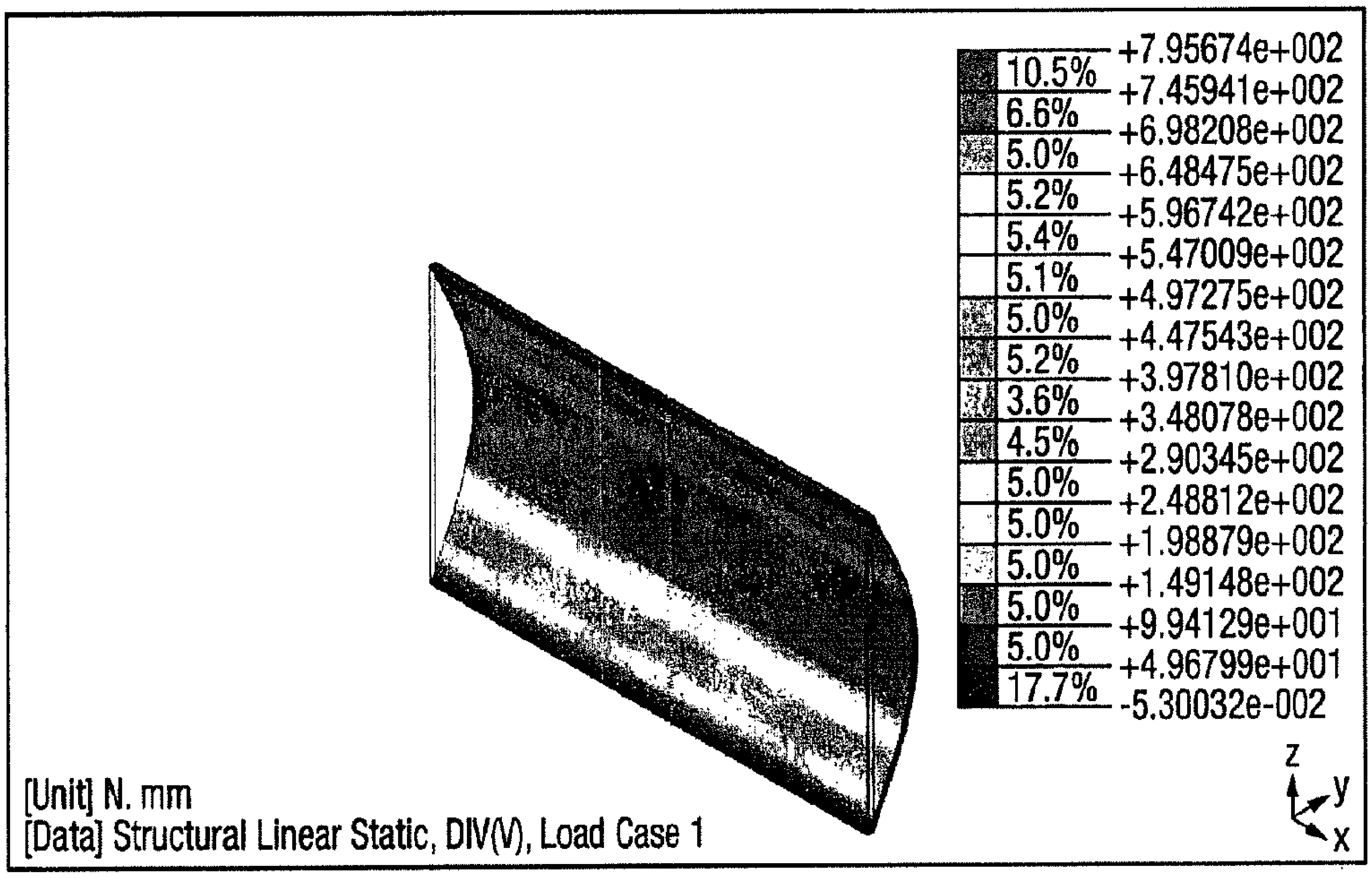


Fig. 6c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5.0%
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5.0%
5.0%
17.7%
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+1.49148e+002
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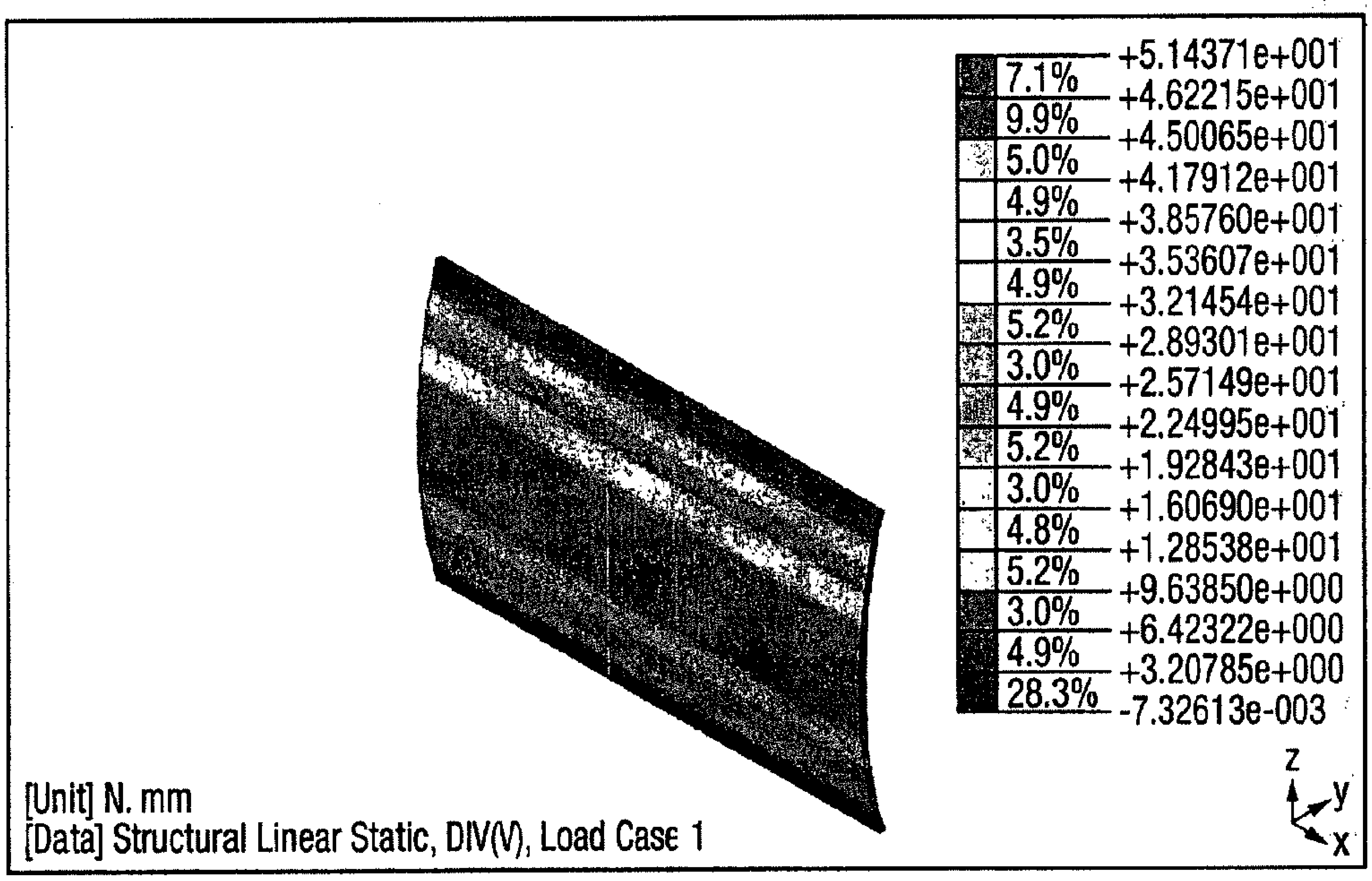
[Unit] N. mm
[Data] Structural Linear Static, DIV(V), Load Case 1
z
y
x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3.0%
4.8%
5.2%
3.0%
4.9%
28.3%
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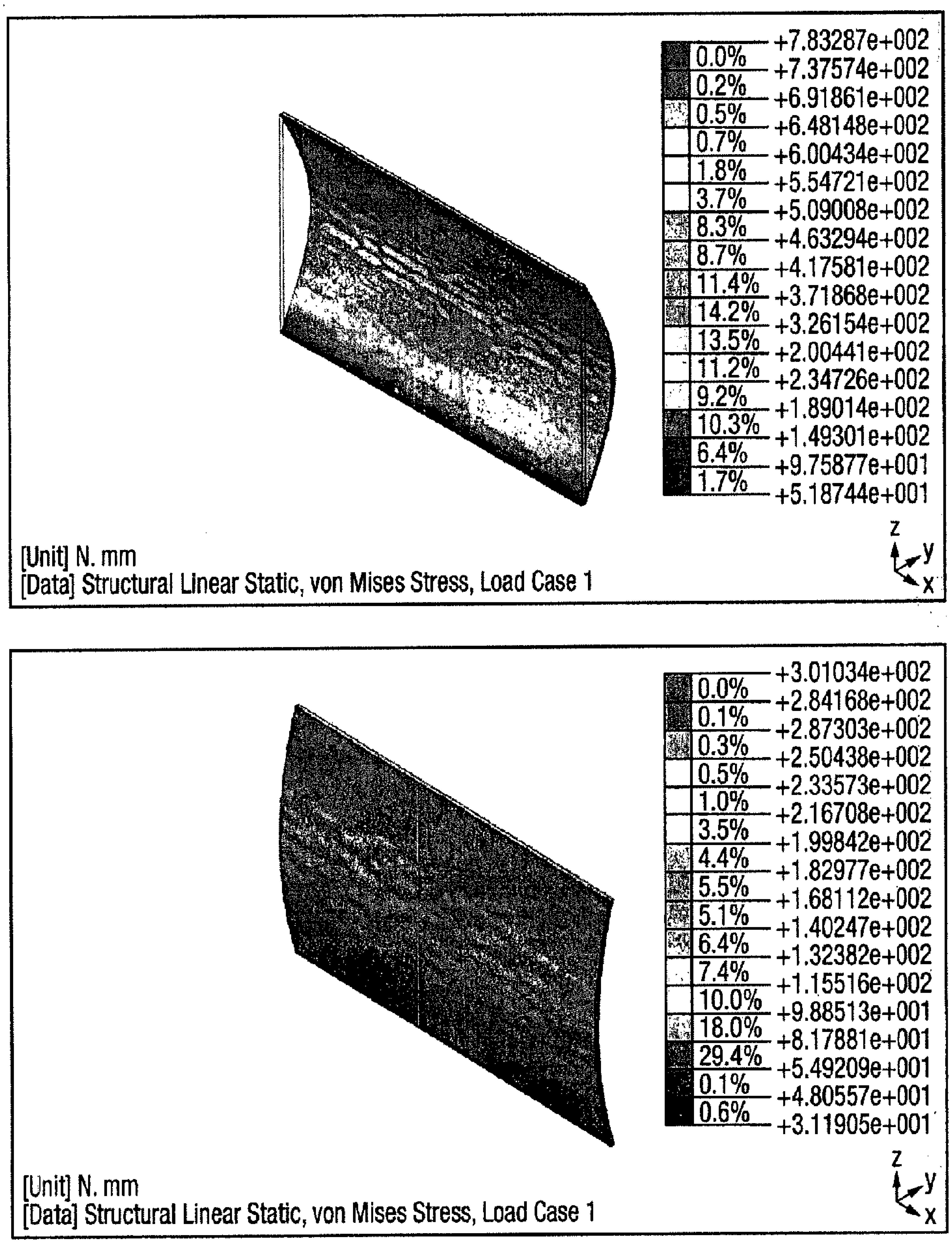
[Unit] N. mm
[Data] Structural Linear Static, DIV(V), Load Case 1
z
y
x

Fig. 6d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0.7%
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[Unit] N. mm
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y
x
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4.4%
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6.4%
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18.0%
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+3.01034e+002
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+5.49209e+001
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[Data] Structural Linear Static, von Mises Stress, Load Case 1
z
y
x

Fig. 7a

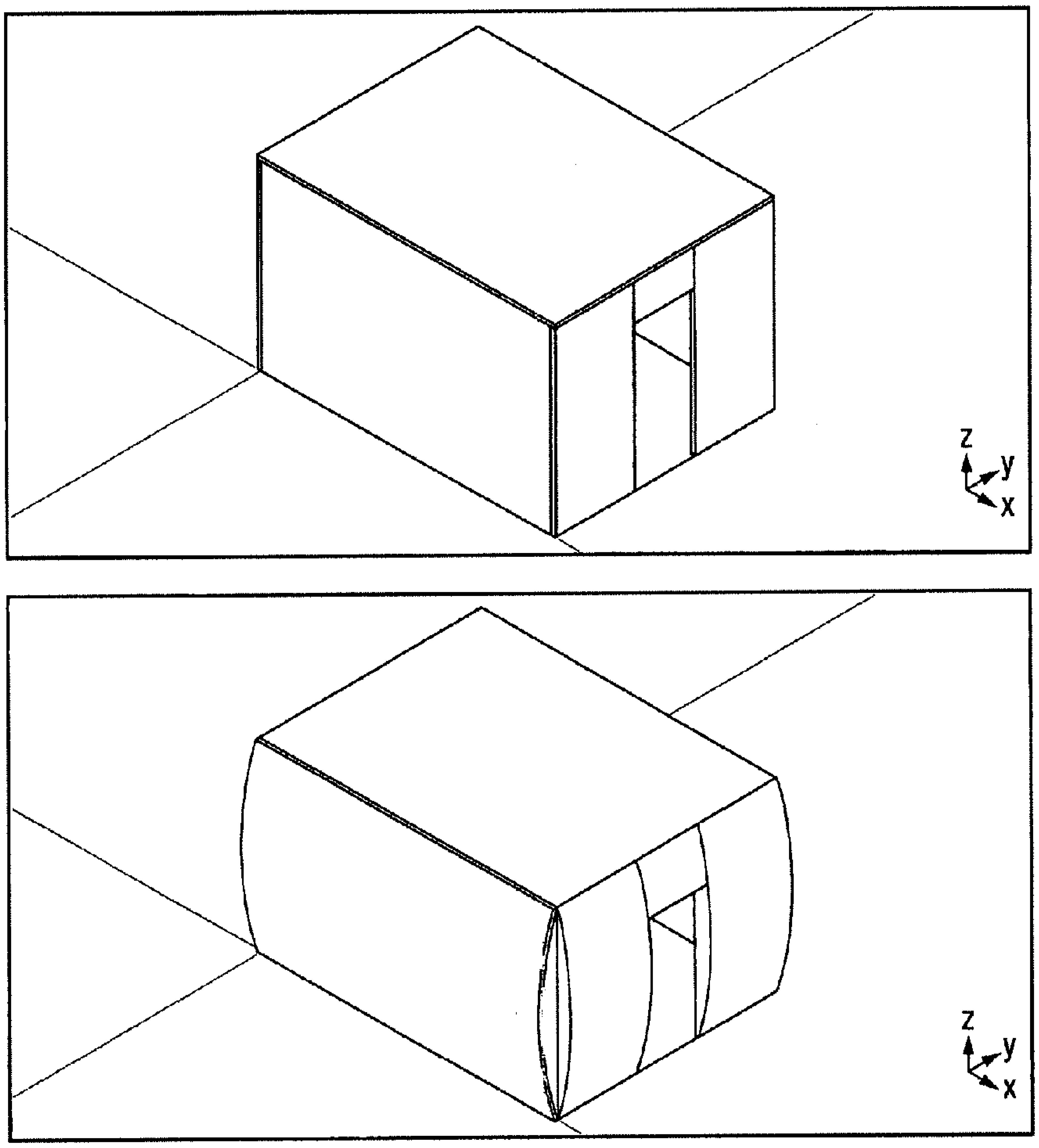


Fig. 7b

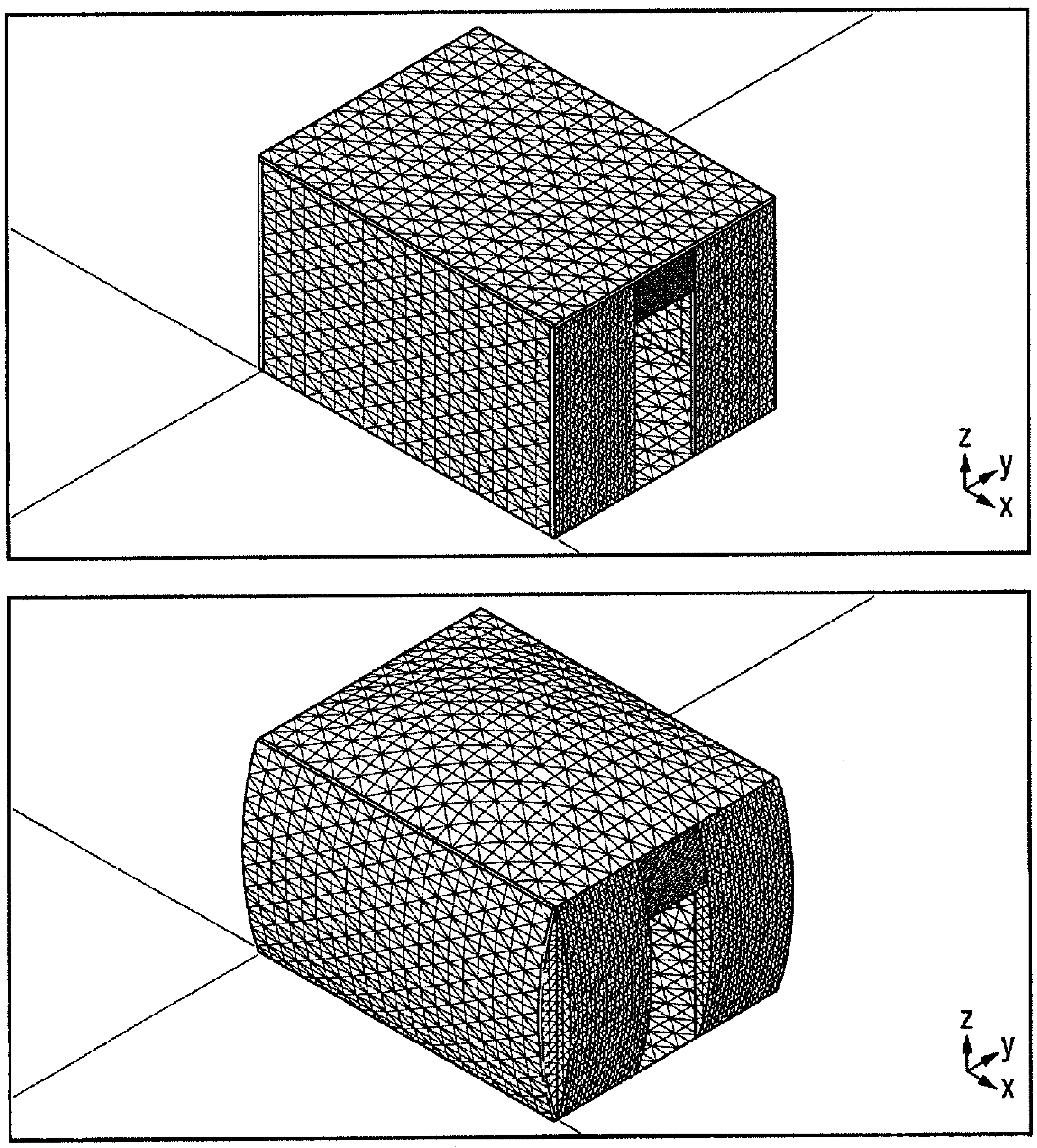
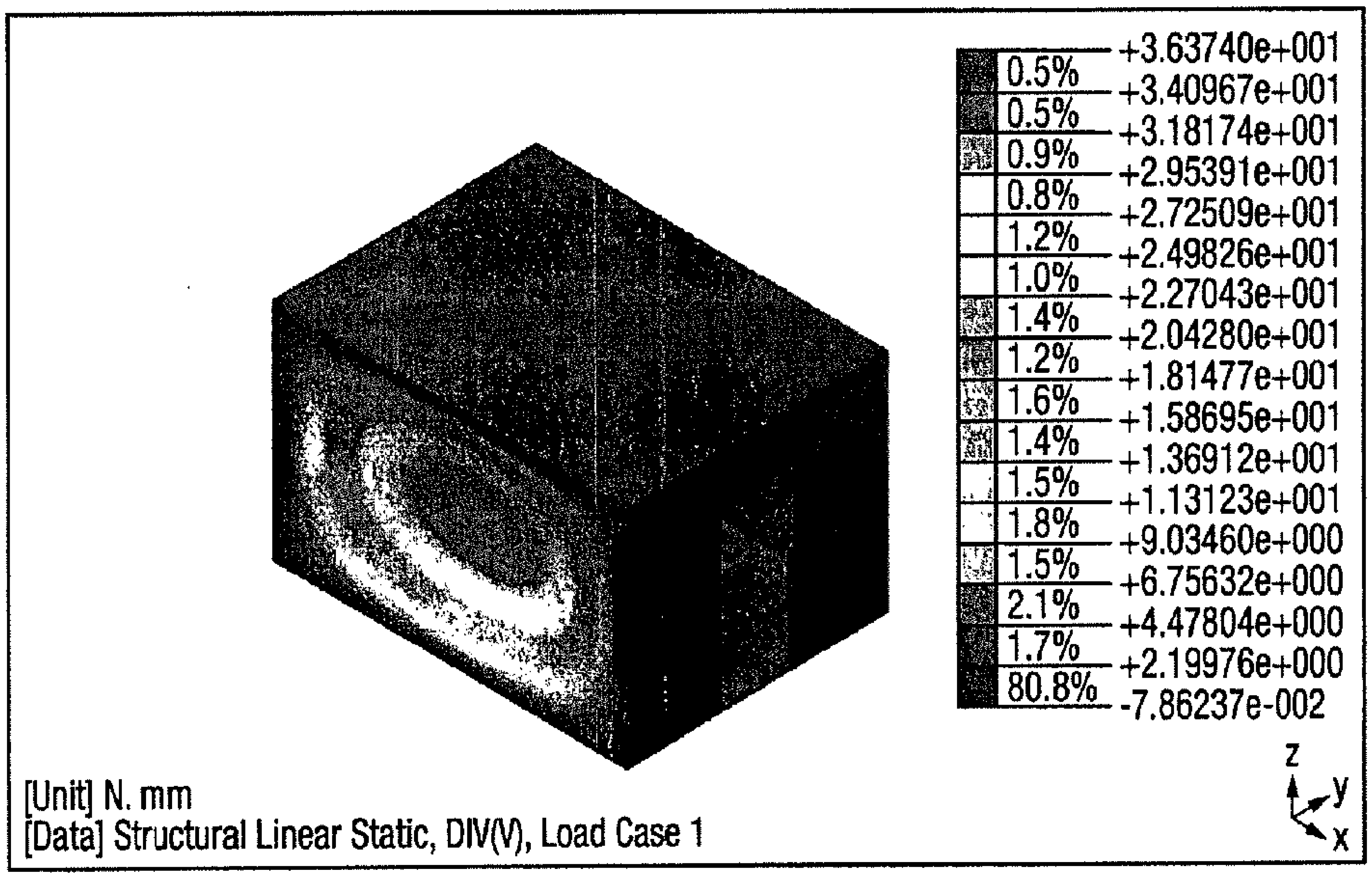


Fig. 7c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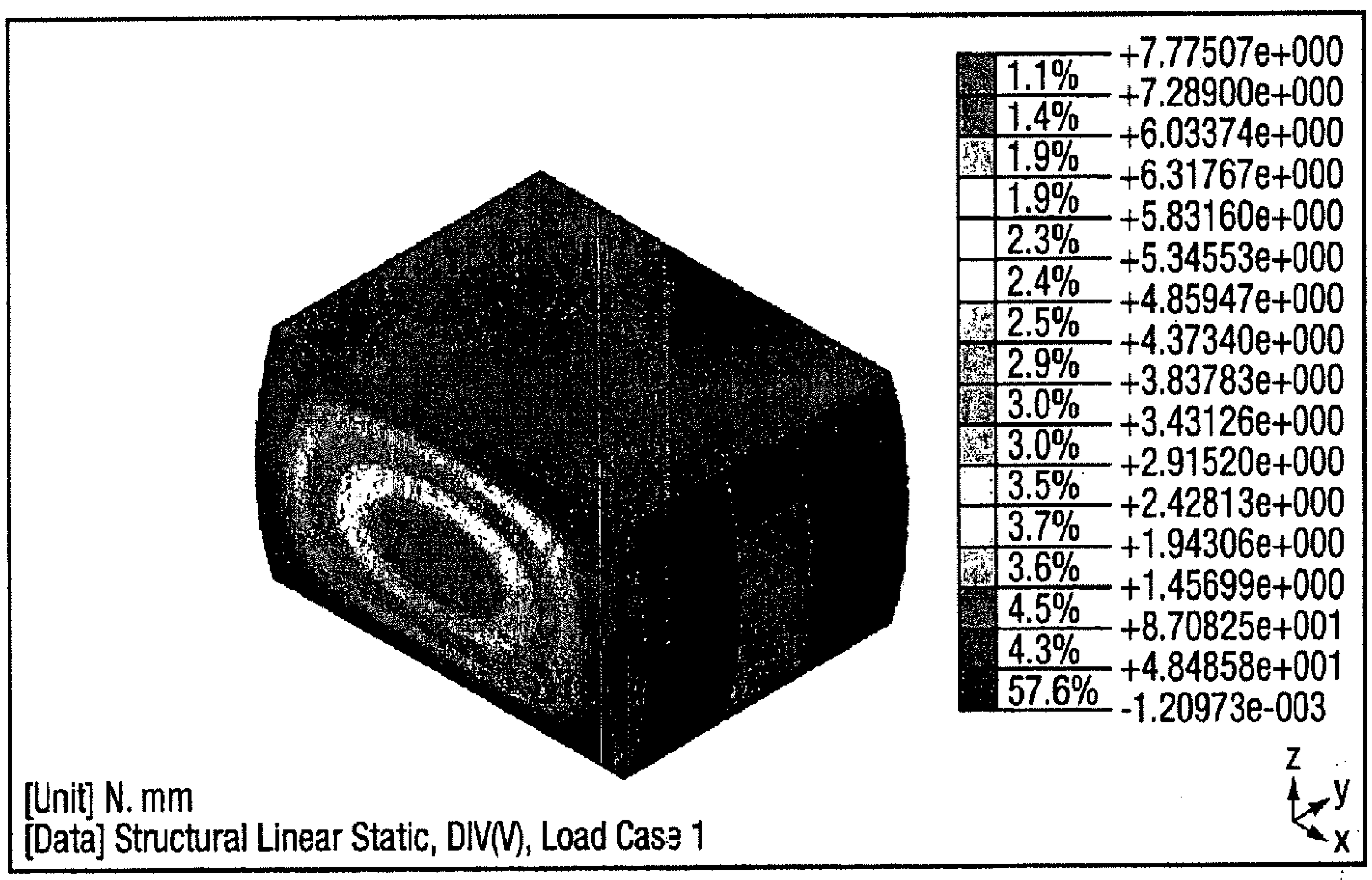
z
y
x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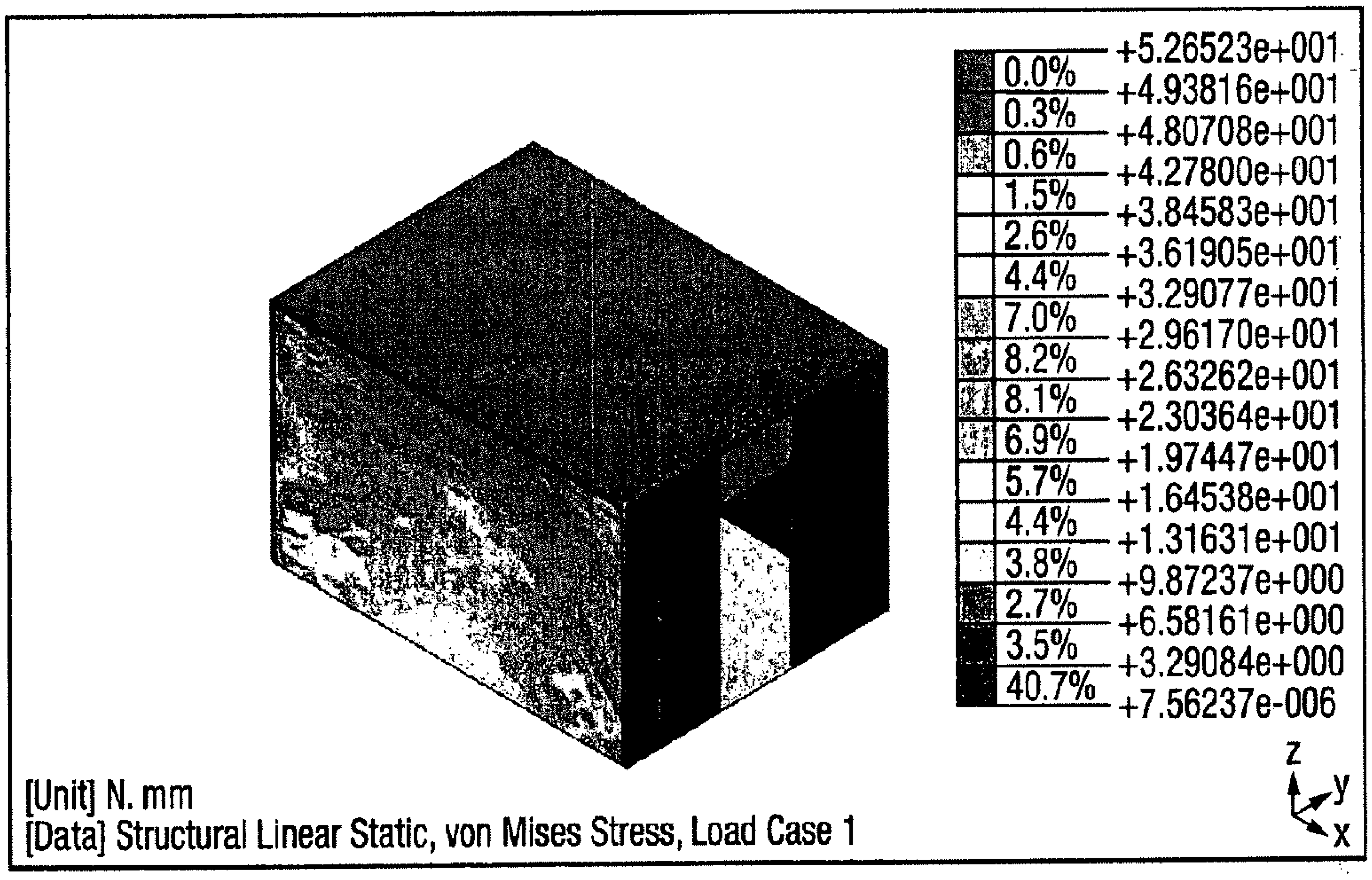
z
y
x

Fig. 7d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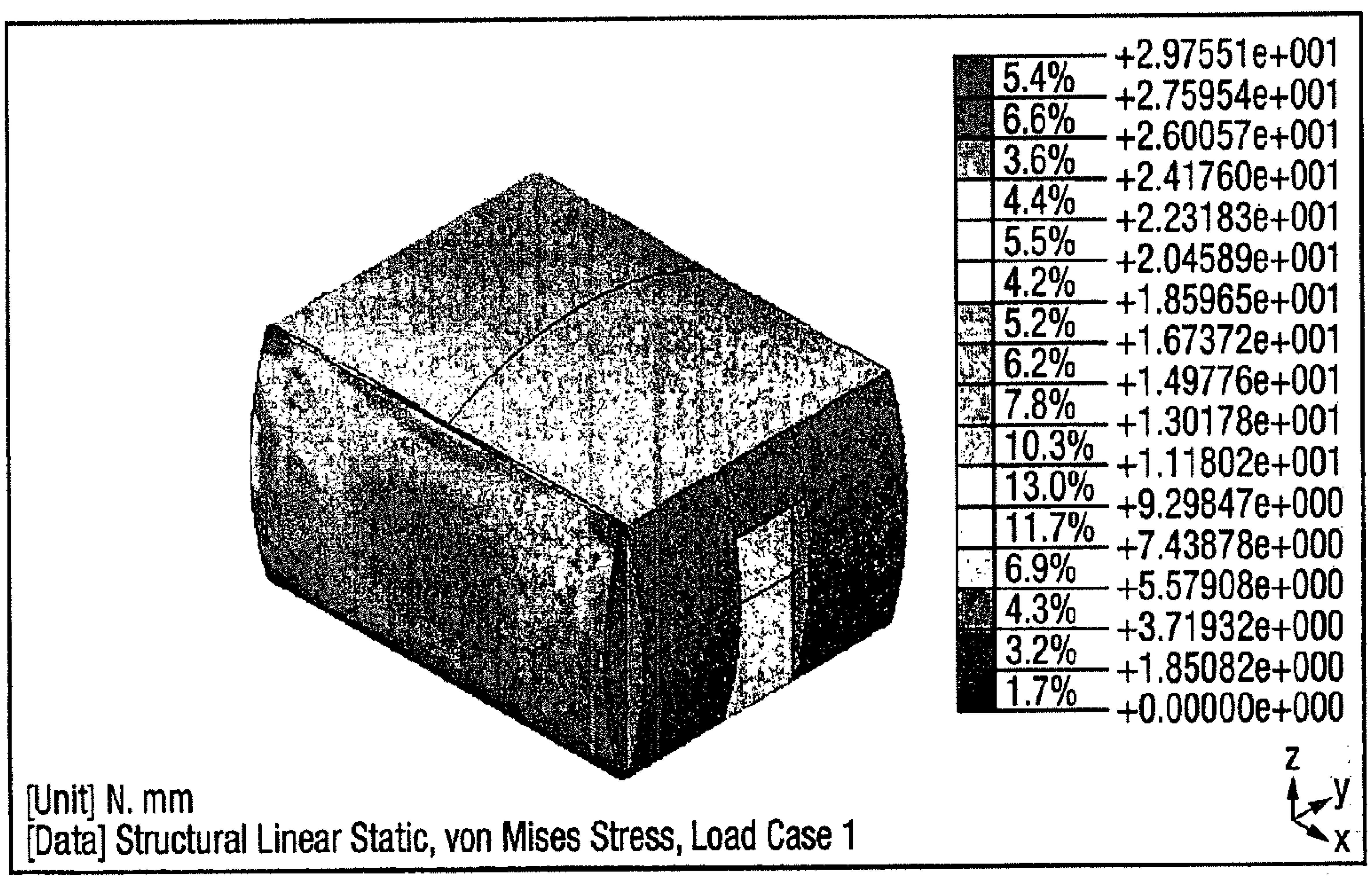
[Data] Structural Linear Static, von Mises Stress, Load Case 1
z
y
x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+2.60057e+001
+2.41760e+001
+2.23183e+001
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[Unit] N. mm
[Data] Structural Linear Static, von Mises Stress, Load Case 1
z
y
x

Fig. 9

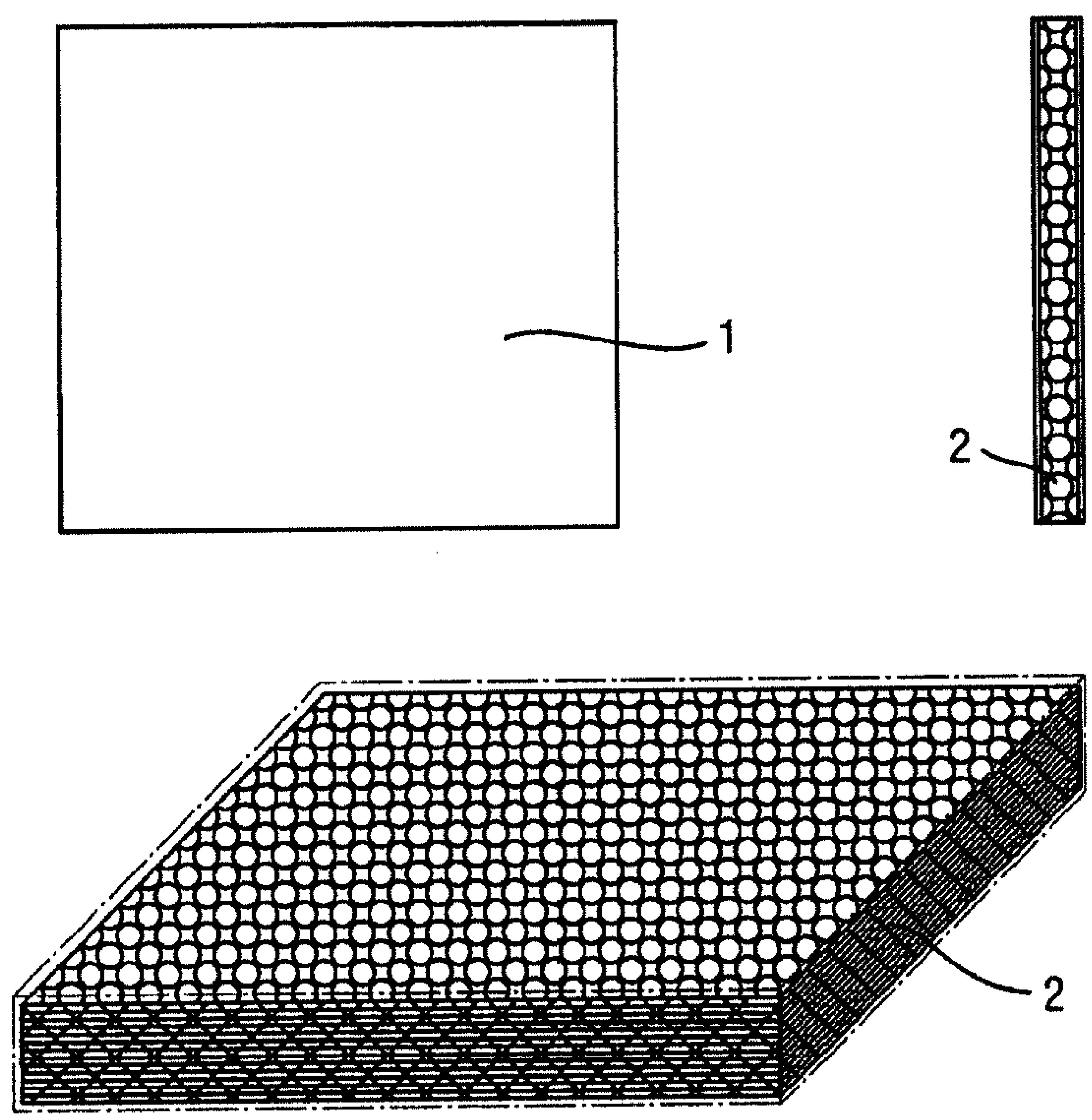


Fig. 10

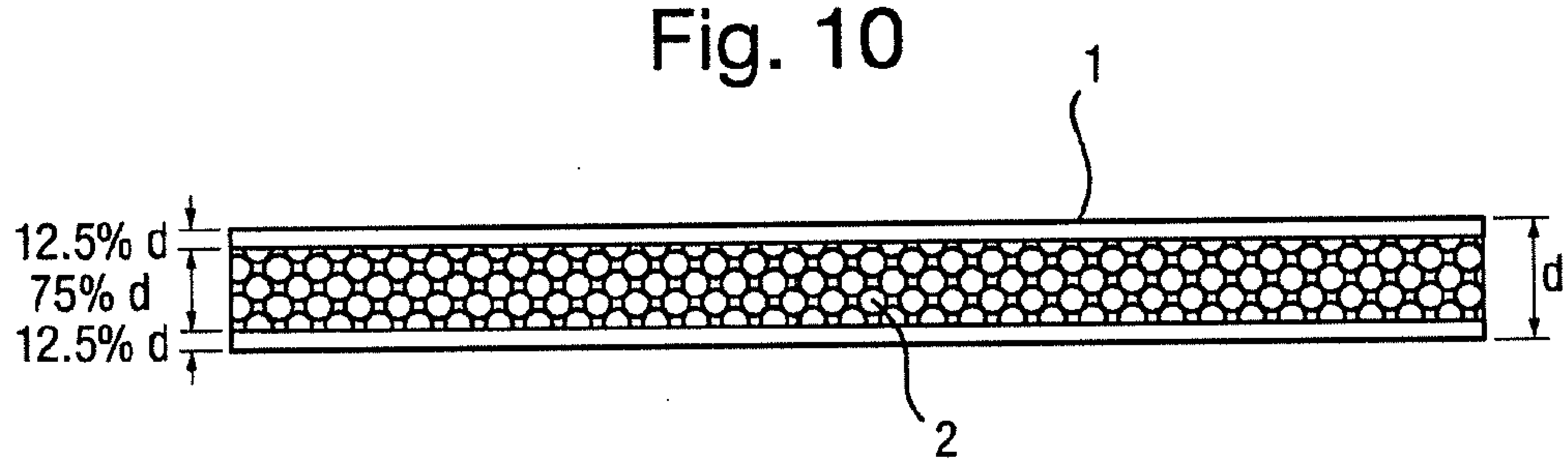
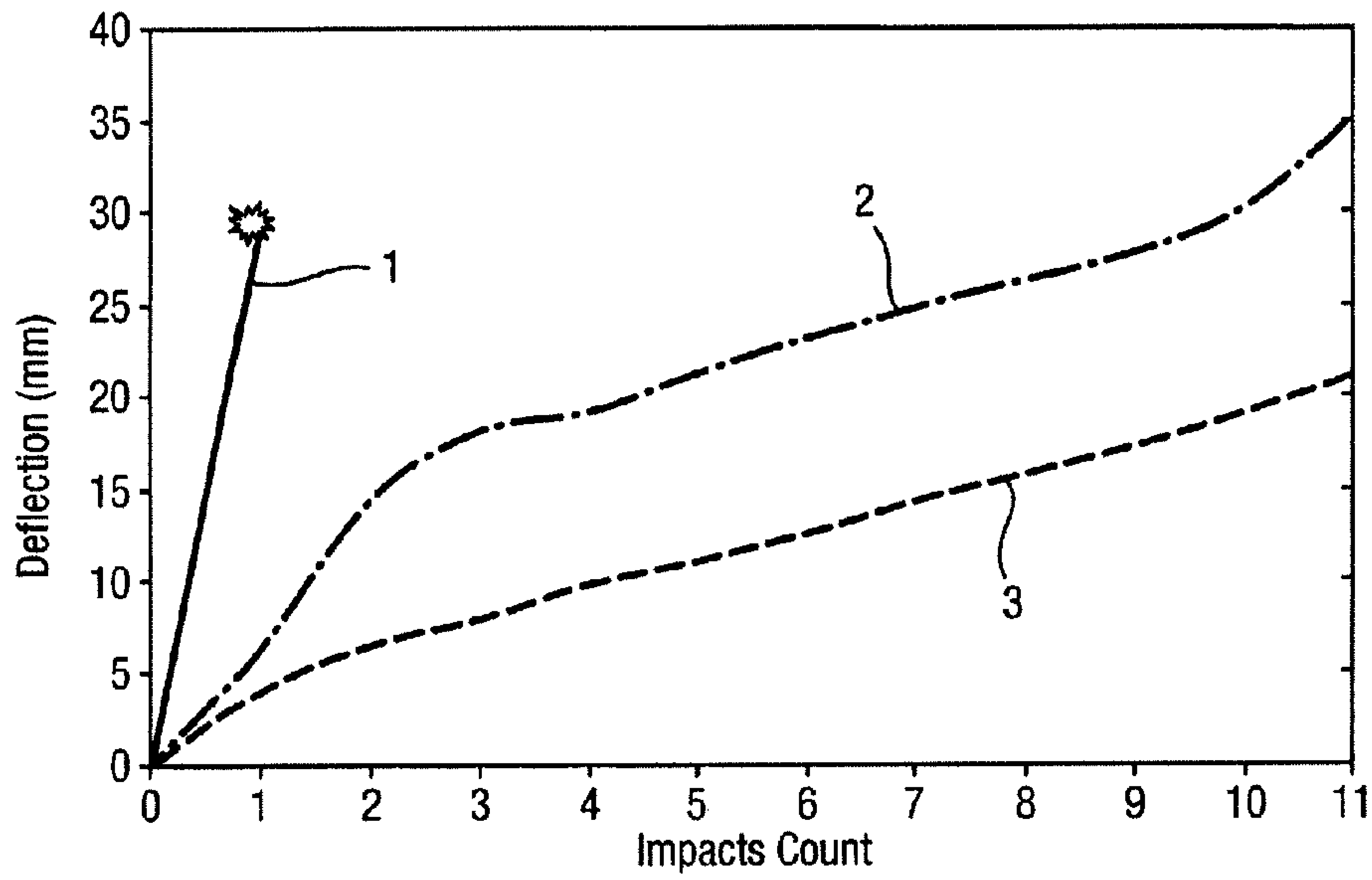


Fig. 11



40
35
30
25
20
15
10
5
0
Deflection (mm)
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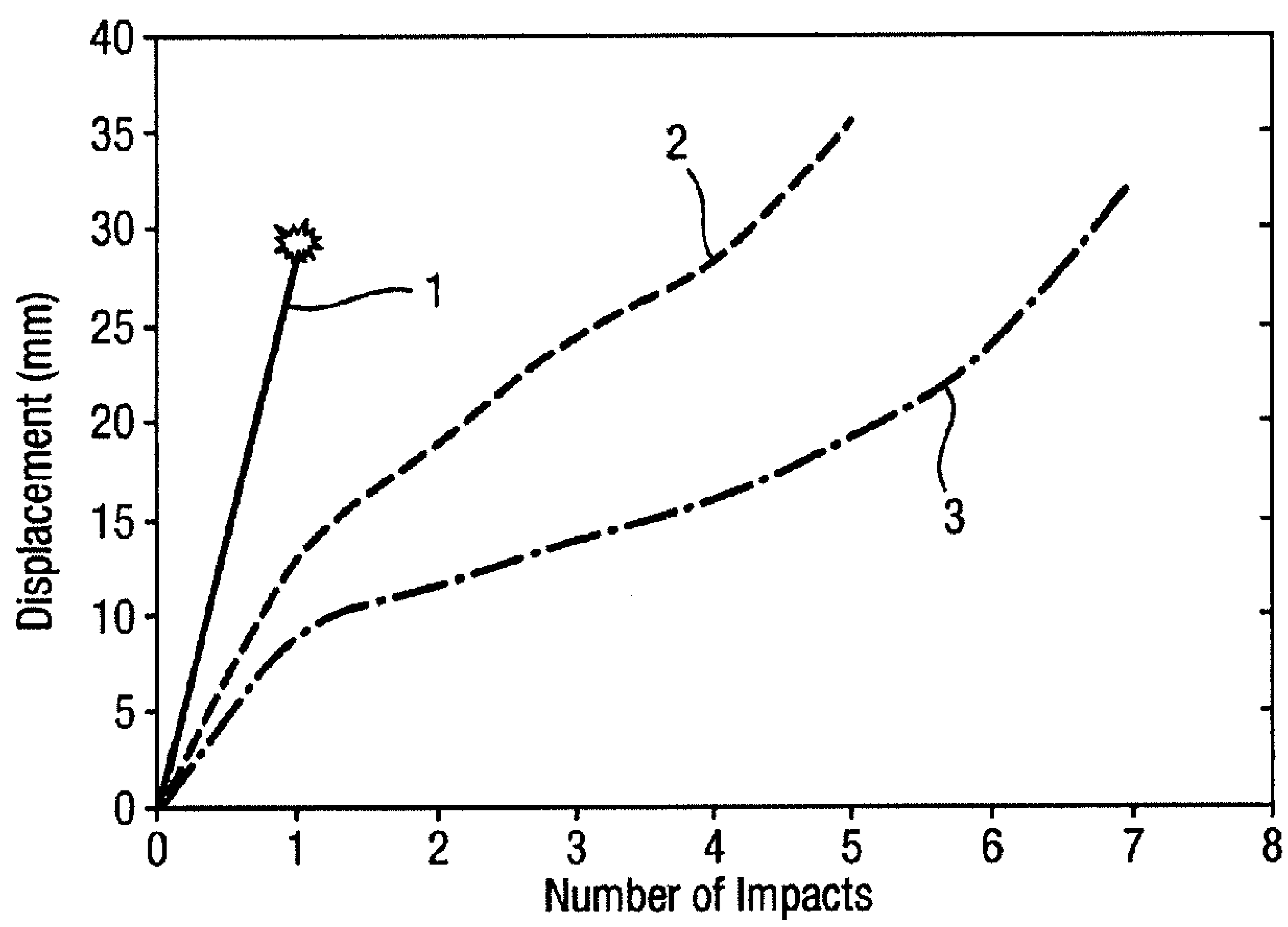
2
3
0
1
2
3
4
5
6
7
8
9
10
11
Impacts Count

Fig. 12



40
35
30
25
20
15
10
5
0
Displacement (mm)
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2
3
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1
2
3
4
5
6
7
8
Number of Impacts

Fig. 13

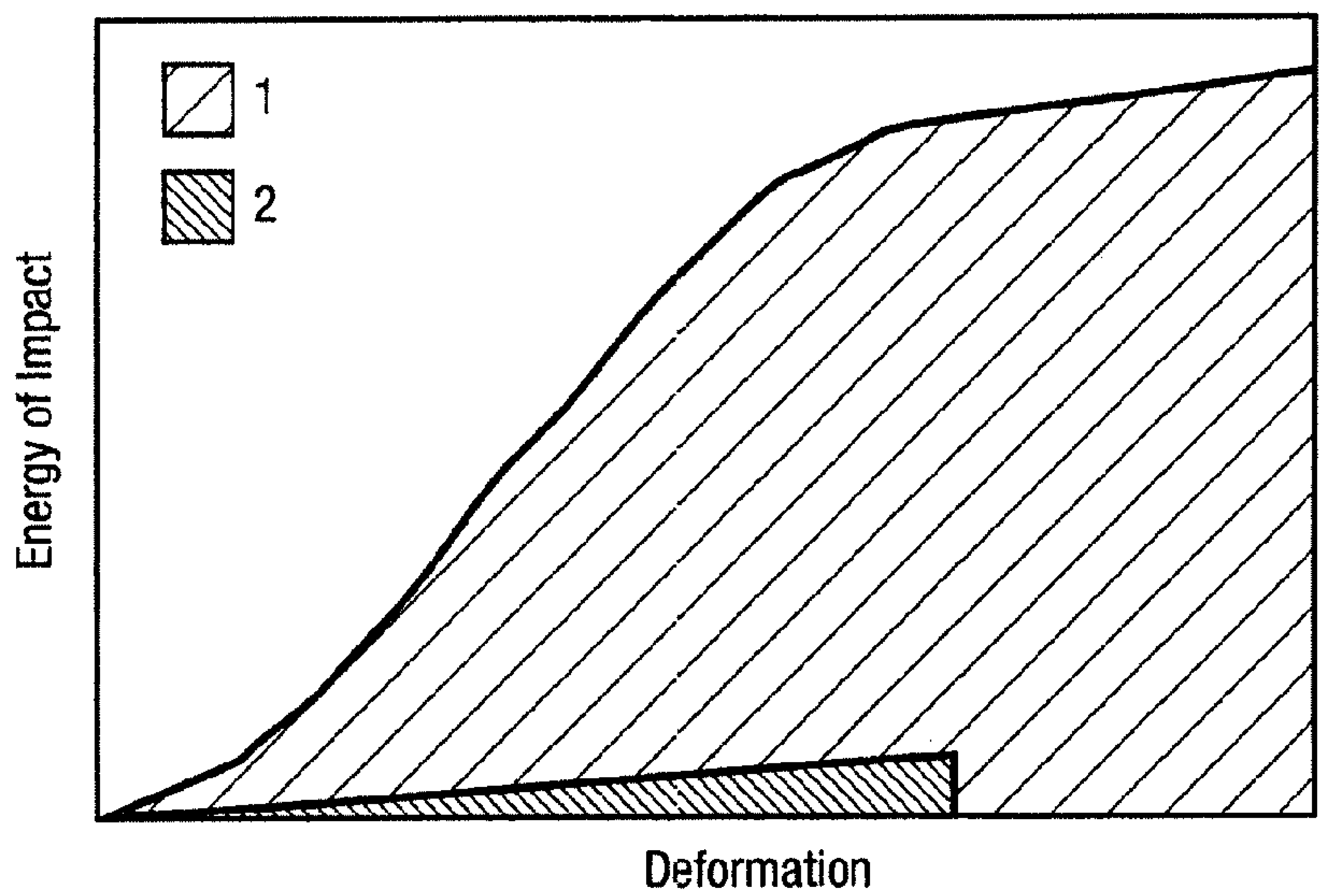
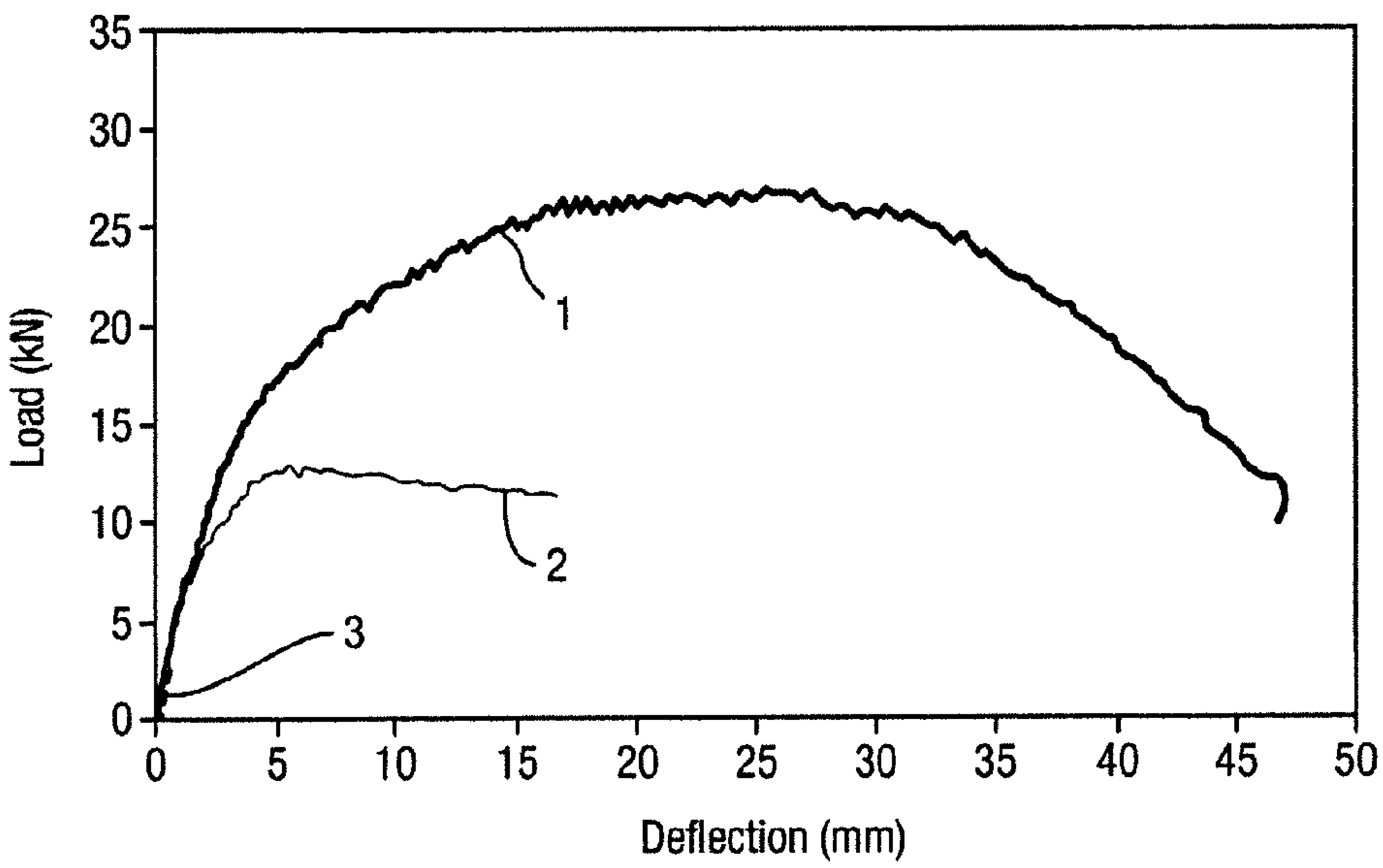

1
2
Energy of Impact
Deformation

Fig. 14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30
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10
5
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Load (kN)
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20
25
30
35
40
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Deflection (mm)
1
2
3

Fig.15

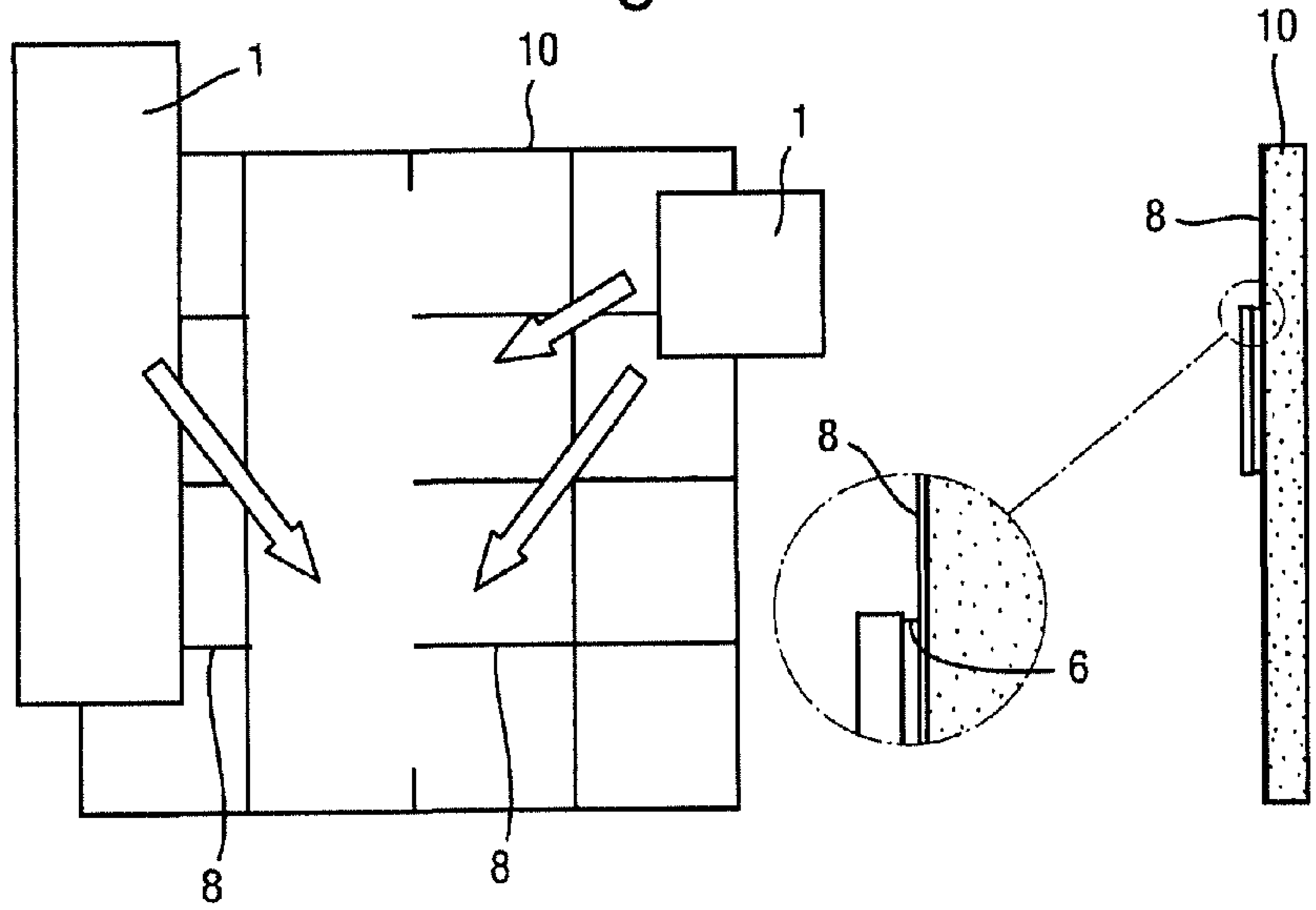
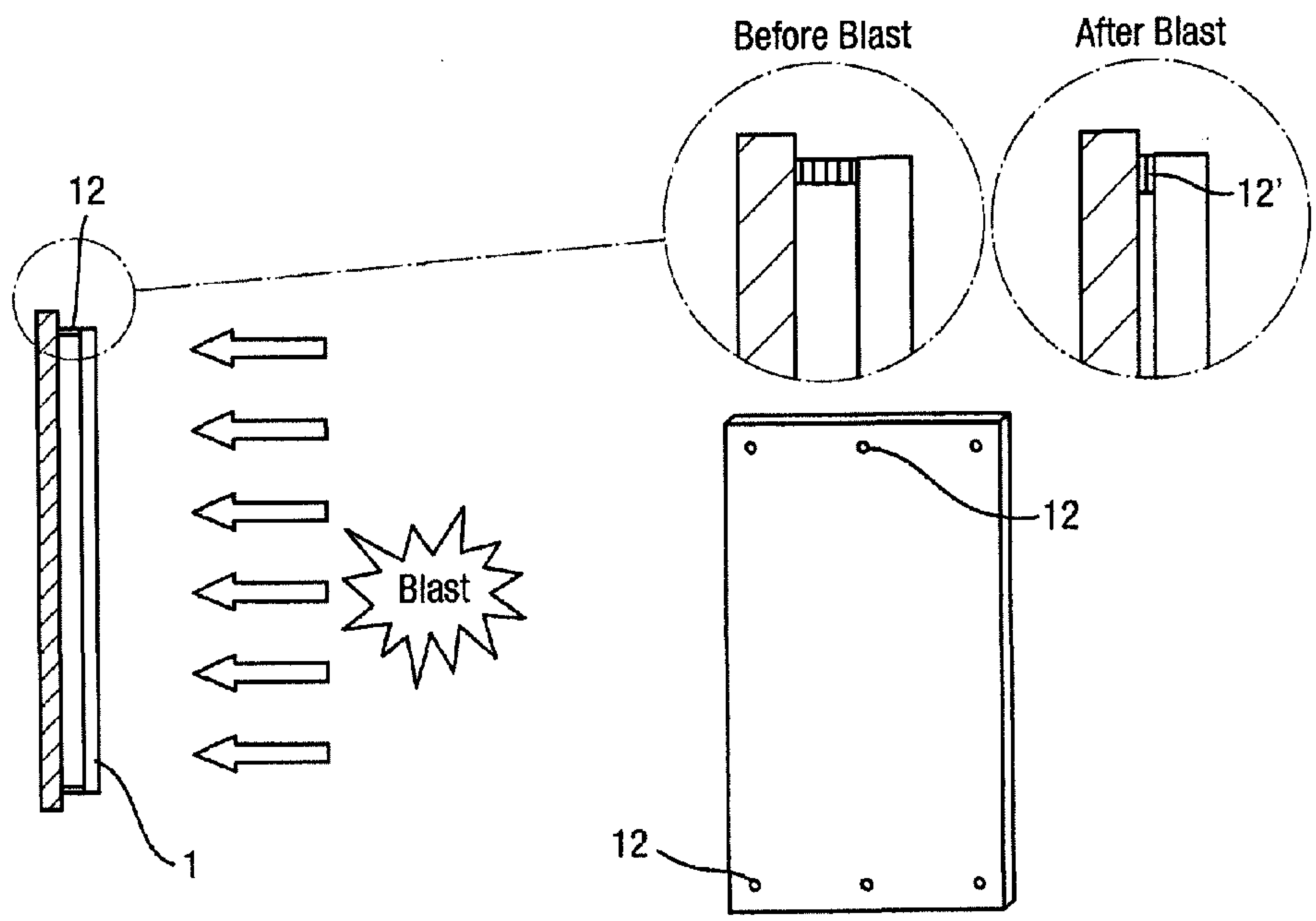


Fig.16



SMART BLAST SENSING

[0001] The need to enhance the protection and performance of construction materials and building structures under extreme situations is rapidly increasing. Incidents such as accidental explosions or terrorist attacks are becoming more frequent in the modern world. The 1995 Oklahoma bombing is an example of the devastating effect of blast forces. The blast shock wave was triggered by the detonation of 1,814 kg of TNT at a 4.5 m standoff distance, and caused devastating destruction to the surrounding buildings. A blast can take place in a domestic or industrial environment. Moreover, it is more likely that a blast will trigger a fire than a fire triggering a blast. If the initial blast does not destroy a building then the subsequent fire can cause damage resulting in structural collapse. While the fire resistance of various structural materials has been studied in the last few decades, relatively little research has investigated the blast resistance (or blast-fire resistance) of typical construction materials such as concrete and steel.

[0002] In recent years, there have been attempts to develop blast mitigation methods that can also provide some resistance to fire. Some of the methods available use steel (or a core material covered with steel) as the main material of blast walls. Although steel has a high resistance to blast forces, its very heavy weight (7.8 ton per m^3) can cause difficulties with handling and installation. Steel also is prone to corrosion, and has very poor thermal insulation properties (thermal conductivity of steel is approximately 45 times that of concrete), which means that it can assist the spreading of a fire by thermal conductivity.

[0003] Traditional concrete has also been used in blast-resistant walls. Although it is approximately three times lighter than steel, it has two major drawbacks. Firstly, it is very brittle and, therefore, prone to fragmentation during blasts. Secondly, it is susceptible to explosive spalling when subjected to fire. Structural damage caused by the explosive spalling of concrete can result in buildings being left unsafe for use following a fire.

[0004] A third approach uses purposely developed materials, or sandwich panels, that contain multiple layers of various materials. For example, US 2011/212320 discloses multilayer composite materials including three or more gradient-contributing layers of microscale particles comprising e.g. silica, aluminium hydroxide, polymeric materials, metal spheres, and ceramics. In general, the costs associated with this group tend to be very high. Some solutions involve the use of resin or polyethylene-based ingredients to assist in the absorption of a blast's shock wave, however such components can be compromised by fire, as they melt at approximately 160° C. This makes them functionless under fire, particularly if the fire takes place before the blast.

[0005] The cost of any blast protection system can be an important parameter when being widely used to provide safer environments. The challenge is to produce a system that is cost effective, capable of resisting blasts (and preferably also fire), and that is logistically viable.

[0006] According to a first aspect of the present invention there is provided a panel that can use its curvature to resist blast forces, wherein the panel has a two-dimensional footprint defined by a width or height L and a curvature defined by a maximum lateral displacement x in a direction perpendicular to its footprint and towards a source of a blast, wherein $0.001 \le x/L \le 0.5$.

[0007] It has been found that such a curvature provides the panel with an inherent ability to resist blast forces. Sophisticated calculations using the theory of structures and the Finite Element Method have shown that providing a degree of curvature defined by x/L within such a range can significantly increase the panel strength, stiffness and reduce the bending moments. Such a curvature can also eliminate tensile stresses and make the panel subject to compression stresses only, which is very important for materials that behave asymmetrically under compressive and tensile stresses e.g. concrete widely used in structural panels. The concept of curved panels to form blast-resistant structures represents a new approach that can be independent of material choice.

[0008] A panel may be provided alone, for example as a shielding wall for an object that may be subjected to blast forces. In a set of embodiments a plurality of such panels are arranged to form a curved wall. However it will be appreciated that a wall may not need to be formed from a plurality of panels and all that is important is for the wall to have a curvature that can resist blast forces. The present invention therefore extends to a wall that can use its curvature to resist blast forces, wherein the wall has a two-dimensional projection defined by a height L and a curvature defined by a maximum lateral displacement x in a direction perpendicular to its projection and towards a source of a blast, wherein $0.001 \le x/L \le 0.5$. Such curved walls may form the basis of a new generation of blast resistant structures including military and civilian buildings. Thus a further aspect of the present invention provides a blast resistant structure formed of one or more walls that use its curvature to resist blast forces, the wall(s) having a two-dimensional projection defined by a height L and a curvature defined by a maximum lateral displacement x in a direction perpendicular to its projection and towards a source of a blast, wherein $0.001 \le x/L \le 0.5$. The blast resistant structure may be a building or shelter, e.g. for military or civilian use.

[0009] The panel or wall may have any suitable geometry. The two-dimensional footprint or projection may be e.g. triangular, rectangular (including square), oval, or elliptical (including circular). The width or height L may correspond to a side length of the two-dimensional footprint or projection. The orientation of the curved surface may be determined by selecting the side length L used to define the curvature. For example, if the two-dimensional footprint or projection is rectangular with a shorter side length L_1 and a longer side length $L_2 > L_1$ then defining a displacement x relative to the side length L_2 will result in a higher degree of curvature. In some embodiments it may be preferable to define a displacement x relative to a shorter side length L_1. The direction of curvature of the wall is convex towards the source of a blast i.e. the panel or wall is curved outwardly to face the direction of an incoming blast wave.

[0010] In one set of embodiments wherein the two-dimensional footprint or projection is rectangular, the curvature is preferably defined by x/L being about 0.015.

[0011] The concept of curved panels or walls (rather than conventional flat walls) to form blast resistant structures can revolutionize the capability of e.g. buildings to resist blast impact. Another aspect of the present invention relates to use of a curved panel or wall to resist blast forces, for example use of a curved wall to form a blast resistant structure such as a building. As is described above, the panel or wall preferably has a two-dimensional footprint or projection defined by a width or height L and a curvature defined by a maximum displacement x in a direction perpendicular to its footprint or projection and towards a source of a blast, wherein $0.001 \le x/L \le 0.5$.

[0012] The degree of curvature of the panel or wall may be selected depending on various factors including the expected magnitude of the blast forces and/or the distance from a source of the blast. In a set of embodiments it is preferable that $0.001 \le x/L \le 0.05$. In another set of embodiments it is preferable that $0.001 \le x/L \le 0.03$. In yet another set of embodiments it is preferable that $0.005 \le x/L \le 0.025$ and further preferably $0.01 \le x/L \le 0.02$. The degree of curvature may also be selected depending on the material used.

[0013] In one set of embodiments the degree of curvature may be defined by: (i) $0.001 \le x/L \le 0.4$; (ii) $0.001 \le x/L \le 0.3$; (iii) $0.001 \le x/L \le 0.2$; (iv) $0.001 \le x/L \le 0.1$; (vi) $0.001 \le x/L \le 0.09$; (vii) $0.001 \le x/L \le 0.08$; (viii) $0.001 \le x/L \le 0.07$; or (ix) $0.001 \le x/L \le 0.06$. In one set of embodiments the degree of curvature may be defined by: (i) $0.001 \le x/L \le 0.05$; (ii) $0.001 \le x/L \le 0.04$; (iii) $0.001 \le x/L \le 0.03$; (iv) $0.001 \le x/L \le 0.02$; (v) $0.001 \le x/L \le 0.01$; (vi) $0.002 \le x/L \le 0.05$; (vii) $0.002 \le x/L \le 0.04$; (viii) $0.002 \le x/L \le 0.03$; (ix) $0.002 \le x/L \le 0.02$; (x) $0.002 \le x/L \le 0.01$; (xi) $0.003 \le x/L \le 0.05$; (xii) $0.003 \le x/L \le 0.04$; (xiii) $0.003 \le x/L \le 0.03$; (xiv) $0.003 \le x/L \le 0.02$; (xv) $0.003 \le x/L \le 0.01$; (xvi) $0.004 \le x/L \le 0.05$; (xvii) $0.004 \le x/L \le 0.04$; (xviii) $0.004 \le x/L \le 0.03$; (xix) $0.004 \le x/L \le 0.02$; (xx) $0.004 \le x/L \le 0.01$; (xxi) $0.005 \le x/L \le 0.05$; (xxii) $0.005 \le x/L \le 0.04$; xxiii) $0.005 \le x/L \le 0.03$; (xxiv) $0.005 \le x/L \le 0.02$; (xxv) $0.005 \le x/L \le 0.01$; or (xxvi) $0.005 \le x/L \le 0.025$. In one set of embodiments the degree of curvature may be defined by: (i) $0.01 \le x/L \le 0.02$; (ii) $0.012 \le x/L \le 0.02$; (iii) $0.014 \le x/L \le 0.02$; (iv) $0.01 \le x/L \le 0.018$; (v) $0.01 \le x/L \le 0.016$; (vi) $0.011 \le x/L \le 0.019$; (vii) $0.012 \le x/L \le 0.018$; (viii) $0.013 \le x/L \le 0.017$; or (ix) $0.014 \le x/L \le 0.016$.

[0014] In embodiments according to any aspect of the invention, the panel or wall may have a permanent curvature that can resist blast forces. For example, the panel or wall may be manufactured so as to have a set curved configuration. It will be appreciated that curvature is one geometrical property of a panel or wall. The curvature may be interrelated with other geometrical properties such as length, height, width, etc. However the Applicant has recognised that it may be advantageous in various situations to be able to selectively put a panel or wall into a curved configuration e.g. when it is determined that blast resistance may be required. Thus in a preferred set of embodiments the panel or wall is arranged to be actively deformed from an initial configuration to a curved configuration having a curvature defined by x/L that can resist blast forces. Actively deforming the panel or wall may comprise changing its geometry to result in the curved configuration. The initial configuration may itself be at least partly curved, albeit with x/L outside the bounds defined herein. However in many embodiments it is envisaged that x=0 in the initial configuration. In other words, the panel or wall may be actively deformed from a substantially planar configuration (e.g. a conventional flat panel or wall) to a curved configuration that can resist blast forces.

[0015] This is considered novel and inventive in its own right, and thus when viewed from a further aspect of the present invention there is provided a method of forming a blast resistant structure, comprising actively deforming a panel or wall of the structure from an initial configuration to a curved configuration that can use its curvature to resist blast forces. When viewed from a yet further aspect of the present invention there is provided a system for forming a blast resistant structure, comprising one or more actuators arranged to actively deform a panel or wall of the structure from an initial configuration to a curved configuration that can use its curvature to resist blast forces. Actively deforming the panel or wall may comprise changing its geometry to result in the curved configuration. Preferably x=0 in the initial configuration i.e. the panel or walls starts in a generally planar configuration before it is actively deformed. In embodiments according to either aspect, the curved configuration of the panel or wall preferably has a two-dimensional footprint or projection defined by a width or height L and a curvature defined by a maximum displacement x in a direction perpendicular to its footprint or projection and towards a source of a blast, wherein $0.001 \le x/L \le 0.5$ (preferably $0.001 \le x/L \le 0.05$ and further preferably $0.005 \le x/L \le 0.03$).

[0016] It will be appreciated that actively deforming a panel or wall into a blast resistant configuration can be highly useful for responding to the threat or occurrence of an explosion. For example, the panel(s) or wall(s) may be used to construct a structure such as a building having conventional flat walls in normal use, but which can be converted to a blast resistant building as and when required. The panel(s) or wall(s) may be used to replace the normal structural walls, or they may provide a cladding for the building. In case of specific terrorism or bombing threat level given by the authorities, the system can be operated to put the whole building into a state of “alertness” by deforming the panel(s) or wall(s). When the threat is cleared by the authorities the panel(s) or wall(s) may resume their initial configuration, as is discussed in more detail below.

[0017] A manual operation may be used to deform the panel or wall between its initial and curved configurations. For example, one or more deformation actuators may act, e.g. to push or pull, the wall or panel into its curved configuration in response to manual operation or input. However this would rely on a human response to a blast threat and could result in a delay when a rapid response is required. In preferred embodiments there is provided an automated system for deforming the panel or wall. Accordingly the system may comprise one or more automated actuators. The automated system preferably responds to an indication or detection of a blast. A corresponding method may comprise automatically acting to actively deform the panel or wall in response to an indication or detection of a blast. In such a “smart” system the panel or wall may be automatically put into its curved configuration as soon as blast protection is required. Such a dynamic response to external factors can provide for a high level of blast safety.

[0018] It is envisaged that the automated system may detect when a blast wave arrives at the blast resistant structure and then act to put the panel or wall into a curved configuration that can resist blast forces. For example, advanced magnetic actuators can act almost instantaneously to put the panel or wall into a curved configuration. However deformation of the panel or wall may not happen fast enough for optimal mitigation of a blast, without advance detection of a blast wave so that the system has time to make a decision to act before the blast wave hits the panel or the wall. In a preferred set of embodiments the automated system comprises one or more sensors remote from the panel or wall that can detect an approaching blast. Such a system provides advance warning so that the panel or wall can be moved into its curved configuration before the blast arrives. Accordingly the remote blast sensor(s) may be arranged to detect an approaching blast and at least one actuator may be arranged to actively deform a panel or wall of the structure into a curved configuration before the blast arrives. A corresponding method may comprise remotely detecting an approaching blast. The blast resisting efficiency is therefore maximised.

[0019] This is considered novel and inventive in its own right, and thus when viewed from a further aspect of the present invention there is provided an automated system for forming a blast resistant structure, comprising one or more remote blast sensors connected to at least one actuator arranged to actively deform a panel or wall of the structure from an initial configuration to a curved configuration in response to sensing a blast. When viewed from a yet further aspect the invention provides a method of forming a blast resistant structure, comprising sensing a blast in advance and actively deforming a panel or wall of the structure from an initial configuration to a curved configuration in response to sensing a blast. The curved configuration is preferably one that can use its curvature to resist blast forces, e.g. as is described above.

[0020] The remote or advanced sensing may be carried out by any appropriate blast sensor(s). In a set of embodiments one or more pressure and/or sound sensors may be provided to measure shock wave pressure and/or sound associated with an explosion. In other embodiments, alternatively or in addition, witness screens may be used to detect a blast, for example witness screens arranged at a set distance from the structure provided with blast protection. In other embodiments, again alternatively or in addition, video surveillance may be used to detect a blast. The blast sensing may be used to inform manual operation of the actuator(s) that deform the panel or wall into a curved configuration, but preferably the system is automated so that the advance sensing automatically acts to move the panel or wall out of its initial configuration. The remote blast sensor(s) may be connected to the actuator(s) by any suitable communication means, wired or wirelessly, but in one set of embodiments wireless communication is preferred.

[0021] The panel or wall must be flexible enough to deform into the curved configuration without compromising its own structural integrity. In some embodiments the action of the blast response system/method, whether manual or automated, may result in the panel or wall being permanently deformed into the curved configuration. This can enable panels, or walls, to be manufactured and transported flat for reasons of economy and then be deformed in situ into a curved configuration that can resist blast forces.

[0022] However in other embodiments it is preferable to avoid plastic deformation otherwise the panel or wall can not return to its initial configuration, thereby preventing the system from being re-used on multiple occasions. It may be preferred for the panel or wall to undergo elastic deformation so that it can return to its initial configuration, for example if the actuator(s) are released after a blast has passed or after a predetermined period of time when blast protection is no longer required. This may be particularly beneficial for manual operation. In a set of embodiments the maximum lateral displacement x may be limited to $0.001 \leq x/L \leq 0.005$ (preferably $0.001 \leq x/L \leq 0.004$ and further preferably $0.001 \leq x/L \leq 0.003$), depending on the material used to manufacture the wall or panel e.g. concrete or mortar. This can help to ensure that the deformation is elastic. Of course the maximum lateral displacement x may fall within a wider range, for example $0.001 \leq x/L \leq 0.5$, e.g. if the material used to manufacture the wall or panel has a relatively high elastic modulus.

[0023] The thickness of the wall or panel may depend on its material. The wall or panel is preferably thin enough to enable its curvature to be formed, but thick enough for use in a blast resistant structure. The wall or panel may be thick enough to support its own weight e.g. so that it can hold its curvature without sagging. In one set of examples the wall or panel has a thickness of about 10 mm, 15 mm, 20 mm or 25 mm. The wall or panel may have a thickness in the range of: (i) 5-25 mm; (ii) 10-25 mm; or (iii) 10-20 mm. In other examples, the wall or panel may be made thicker e.g. when forming a blast resistant structure such as building. For example, the wall or panel may have a thickness in the range of: (i) 25-100 mm; (ii) 30-100 mm; (iii) 40-100 mm; (iv) 50-100 mm; (v) 60-100 mm; (vi) 70-100 mm; (vii) 80-100 mm; or (viii) 90-100 mm.

[0024] In embodiments of any of the aspects of the invention outlined above, the panel or wall may be made from any suitable material that can be deformed between initial and curved configurations, or at least formed to have a configuration that uses its curvature to resist blast forces. The material may be polymeric, concrete, metallic or composite. A suitable composite material may be fibre-reinforced plastic (FRP). In one set of examples, the panel or wall may be formed from steel, aluminium, brass, or any other structural metal or alloy. In a preferred set of embodiments the panel or wall is made of mortar or concrete, or a composite material comprising mortar or concrete.

[0025] A concrete-based material typically comprises cement and coarse aggregate e.g. stone or gravel. A mortar-based material typically comprises cement and only fine aggregate such as sand e.g. of size less than 5 mm. A concrete or mortar composite material may be a fibre-reinforced material comprising metal e.g. steel and/or polymer fibres. In addition, or alternatively, the fibre-reinforced material may comprise glass or carbon fibres. Steel-reinforced concrete materials are known to be unstable when exposed to fire e.g. following a blast, with failure often resulting from explosive spalling. It has been proposed that the fire resistance of concrete materials can be improved by adding polymer fibres to the cement mix. It is thought that when the fibres melt under high temperatures they develop pores or pathways in the cement through which steam or water can escape to avoid the build-up of pressure that is known to result in spalling. As a blast often results in fire, it is desirable for a blast resistant structure to also be fire resistant. It is therefore preferable for the panel or wall to be formed of a concrete or mortar material comprising polymer fibres (and optionally also metal fibres).

[0026] The Applicant has recognised that the ductility of a mortar- or concrete-based material may determine its ability to be formed with a curvature or deformed into a curved configuration. A concrete or mortar composite material including metal e.g. steel fibres can be more ductile than a material without such fibre reinforcement. It is therefore preferable for the panel or wall to be formed of a concrete or mortar material comprising metal e.g. steel fibres (and optionally also polymer fibres, e.g. for the reasons outlined above). Preferably the concrete or mortar composite material includes at least 1-3 wt % and preferably at least 1-6 wt % metal e.g. steel fibres. The concrete or mortar composite material may comprise: (i) 1-3 wt %; (ii) 1-4 wt %; (iii) 1-5 wt %; (iv) 1-6 wt %; (v) 1-7 wt %; (vi) 1-8 wt %; (vii) 1-9 wt %; (viii) 1-10 wt %; (ix) 1-11 wt %; (x) 1-12 wt %; (xi) 1-13 wt %; (xii) 1-14 wt %; or (xiii) 1-15 wt % of metal e.g. steel fibres. In at least some embodiments it is desirable for a mortar- or concrete-based material to contain at least 3 wt % metal e.g. steel fibre reinforcement. The concrete or mortar composite material may comprise: (i) 3-4 wt %; (ii) 3-5 wt %; (iii) 3-6 wt %; (iv) 3-7 wt %; (v) 3-8 wt %; (vi) 3-9 wt %; (vii) 3-10 wt %; (viii) 3-11 wt %; (ix) 3-12 wt %; (x) 3-13 wt %; (xi) 3-14 wt %; or (xii) 3-15 wt % of metal e.g. steel fibres.

[0027] In practice, a wall or panel suitable for being deformed into a curved configuration may be made from any mortar- or concrete-based material that is able to adopt a curvature without undergoing rupture. Fibre-reinforced mortar or concrete materials may be more flexible than non-reinforced materials. A suitable mortar or concrete material may be assessed based on its moment of material cracking M_{crc}. Preferably a panel or wall in its curved configuration meets the criterion:

$$M_{crc}>M_a,$$

where M_{crc} is the moment of crack appearance of the material and M_a is the applied bending moment due to the induced curvature in the panel. As long as the material parameter M_{crc} is higher than the moment created due to the induced curvature in the panel then the a curvature can be achieved. A materials engineer will be able to use this criterion to select or design suitable materials. In one example, a suitable concrete or mortar composite material includes at least 1-6 wt % metal e.g. steel fibres, as is discussed above.

[0028] Compared to concrete, a mortar-based composite material may be more suitable for forming a curved panel or wall. Due to the fine aggregate content the mortar can have better flowability and be more readily moulded or cast into curved shapes. Further, the Applicant has recognised that some mortar-based composites (described in more detail below) can be made significantly more ductile than other conventional construction materials, which means that they can be actively deformed into a curved configuration with a lower risk of undergoing brittle fracture.

[0029] In various embodiments where the panel or wall is made of mortar, or a composite material comprising mortar, the two main constituents of the mortar-based material are preferably cement binder and sand. In one set of examples the mortar-based material may comprise at least 25 wt % sand and up to 40 wt %, 45 wt % or 50 wt % sand. Although the ductility of such material may be mainly dictated by its reinforcement, for example fibre reinforcement as discussed above, the sand content may also contribute by being limited to 25-30 wt %. In addition, the mortar-based material may comprise up to about 10 or 12 wt % silica fume e.g. to enhance the strength and durability of the composition. In one set of examples the silica fume content may be limited to less than about 5 wt %. For example, the mortar-based material may comprise up to about 1, 2, 3, 4, or 5 wt % silica fume.

[0030] Where a mortar-based material contains polymer fibres to enhance the explosive spalling resistance, preferably polypropylene fibres are used. In one set of embodiments, the polypropylene fibres are of 12 mm length, 18 micron diameter and 160° C. melting temperature. In embodiments where a mortar-based material contains metal fibres they are preferably steel fibres, and further preferably micro steel fibres. The micro steel fibres have a diameter <1 mm, for example a diameter of 0.2 mm. The steel fibres may be 10-20 mm in length, for example around 13 mm long. Using a hybrid of polymer and steel fibres to reinforce mortar has been found to be particularly effective in increasing the mortar strength and preventing cracks from appearing. While the polymer fibres make the panels less susceptible to explosive spalling, the addition of steel fibres significantly reinforces the surface layers that normally suffer from fragmentation under blast effect. A typical mix may contain around 1-3% or 1-4% (of mortar volume) of steel fibres and around 1-3 kg per m^3 (of mortar volume) of polypropylene fibres.

[0031] The Applicant has developed a mortar-based material construction that has been found particularly effective for use in blast resistant panels and walls. Further details are described in PCT/GB2012/052481, published as WO 2013/050783, the contents of which are hereby incorporated by reference. In such embodiments there is provided a mortar panel or wall containing metal fibres (and optionally polymer fibres), wherein a core volume of the panel or wall is reinforced by a 3D network of wire cells. Such a construction has been found to improve the material's ductile response to explosions. By confining a network of 3D wire cells to a core volume of the panel or wall, the bulk metal reinforcement does not reach the surface(s) of the panel where it could result in spalling in the presence of a fire. Instead, the optional polymer fibre reinforcement in the surface layers can ensure that the panel has sufficient fire resistance. The metal fibres outside the core volume can help to significantly reinforce the surface layers that might otherwise be fragmented by blast effects.

[0032] An embedded 3D network of wire cells has been found particularly beneficial in providing a "spring" effect that absorbs shock wave energy induced by a blast. The wire cells can be formed from any metal wire, for example steel. The infrastructure provided by a 3D network of metal wires also has a significant effect in maintaining the integrity of the construction, which increases the fire resistance and prevents explosive spalling when exposed to high temperatures. Such a construction is therefore ideally suited for use in fire-blast protection systems which provide protection for buildings, tunnels, industrial premises (or any other structures) against events of: a) blast only (including terrorist attacks); b) fire only; or c) fire and blast at the same time.

[0033] Furthermore, a mortar-based material construction as described above has been found to provide a superior "panel/wall thickness to blast resistance" ratio. Such panels or walls have shown very high ductility when compared with other types of concrete, behaving more like steel rather than concrete. Tests have shown that such panels have approximately 12 times higher ductility than standard concrete panels, including Ultra-High Performance Fibre Reinforced Concrete (UHPFRC).

[0034] This allows for a significant reduction in panel thickness, and consequently a reduction in weight and cost. The panels can be produced in various thicknesses to resist a wide range of blast forces. For example, if a blast resistant system is used for cladding or protecting existing walls, the panels can be 10-25 mm thick. If the system is to be used to erect a new building, the panels can be manufactured in larger thicknesses such as 50-100 mm. The relatively small thickness of the panels makes them lightweight and logistically efficient. Their ability to resist fire and blast forces, their low cost, their light weight and narrowness, make the panels unique.

[0035] The fibre content can be adjusted e.g. depending on the composition of the mortar and its strength. It may be preferred that the fibre content is not too high, so that the fibres do not unduly hinder the cement mortar in impregnating the network of 3D wire cells. However the fibre content may be higher than in known UHPFRC compositions. In one exemplary embodiment, a mortar-based material is made from 970 kg of dry cement, 156 kg of steel fibres and 1.5 kg of polypropylene fibres per m^3 of panel. Thus the fibre content may be around 10-20%, e.g. around 15%, by weight as compared to the dry cement in the mix. Of course other ingredients may be added to the mortar mix, as well as water, including sand, silica, GGBS and plasticizer.

[0036] In a set of examples the panel or wall is formed of a mortar-based material comprising mortar (that is, cement binder and sand) containing metal e.g. steel fibres and an optional core reinforcement consisting of a 3D network of wire cells that is impregnated with the mortar. The mortar may contain: (i) 5-20 wt %; (ii) 10-20 wt %; (iii) 10-15 wt %; or (iv) 15-20 wt % of metal e.g. steel fibres.

[0037] The mortar preferably has a high strength, e.g. in the range of 90-200 MPa, to provide good resistance to compressive and tensile stresses. An exemplary mortar has a strength of 92 MPa. However, the main component that has been found to provide strength against blast and fire is the metal reinforcement provided by the network of 3D wire cells in a core volume. It has been found that the cellular reinforcement shifts the material's behaviour from the brittle zone to the ductile zone.

[0038] Preliminary tests at the University of Ulster have shown that 25 mm thick mortar panels as described above can withstand an impact equivalent to a blast of 500 kg of TNT at a 30 m standoff distance, making them compliant with US Department of Defense UFC 3-340-02 blast deflection response criteria. The panels can withstand higher blast pressures by increasing their thickness. The panels also preferably provide fire resistance as they are immune to the explosive spalling that conventional concrete is prone to under extreme heat. The panels are non-combustible, which makes them ideal for fire situations. Their ability to slow the progress of fire is one advantage over existing blast-proof materials. In addition, the panels have very good thermal insulation properties, enabling them to function as fire wall barriers.

[0039] Regardless of the material chosen, curved panels according to embodiments of the present invention may find a wide variety of uses, fitted as cladding to existing structures (including reinforcing and rehabilitating damaged structural elements) or used to build new structures. The panels described herein may find use in fire protection as well as blast protection.

[0040] For blast protection, the panels described herein may find use as walls or wall coverings, claddings, linings, etc. The panels may be fitted on building facades, internal walls or ceilings which are considered to be vulnerable to explosion and/or fire. In cases of cladding or protecting existing walls, the blast protection system can be provided onsite by fitting the panels into a frame. According to a preferred set of embodiments there is provided a surface protection system comprising one or more blast resistant panels as described above, the panels being fitted in a supporting frame. The supporting frame makes it easier to fit the panels in place, especially when applying cladding to an existing structure. The frame may comprise a female connection arrangement designed to mate with the male profile of the panels. The male profile may be provided by the panel itself, but to avoid risk of damage the panel is preferably provided with a male frame, e.g. fitted to one face of the panel, that connects with the female frame. A "click to fit" system may be provided, e.g. wherein the female connection comprises snap-fit means for fixedly connecting a panel to the frame, preferably in an irremovable manner. Advantageously, the "female" frame can be attached to an existing wall or other structure in advance and then the "male" panels can be fitted into the frame when they are ready to be installed. The panels may be manufactured on site and fitted one-by-one.

[0041] In embodiments where panels are actively deformed into a curved configuration, either due to manual actuation or advance blast sensing, the male and/or female frame may be provided with the actuator(s) that cause the deformation. The actuator(s) may be arranged to act to actively deform the panel(s) from an initial configuration to a curved configuration having a curvature defined by x/L that can resist blast forces. The panels fitted in the frame may have an initial non-planar configuration, but this may make it more difficult to mount the panels in a frame. It is therefore preferable that x=0 in the initial configuration. The actuator(s) may act to actively deform the panels by changing the geometry of the panels. If a panel becomes permanently deformed or damaged then it can easily be removed from its supporting frame and replaced with a new panel, for example one that can be moved into a curved configuration upon actuation.

[0042] In many cases it may be desirable to construct or retrofit a blast resistant structure that can take advantage of advance blast sensing. This may be facilitated by forming a blast resistant structure from one or more panels fitted in a supporting frame. This is considered novel and inventive in its own right, and thus when viewed from a further aspect the present invention provides a surface protection system comprising one or more blast resistant panels fitted in a supporting frame and at least one actuator arranged to actively deform the panel(s) from an initial configuration to a curved configuration in response to sensing a blast. From a yet further aspect the present invention provides a method of protecting a surface, comprising: fitting one or more blast resistant panels in a supporting frame on the surface; and actively deforming the panel(s) from an initial configuration to a curved configuration in response to sensing a blast. Any of the features described hereinabove may equally be applied to these aspects of the invention.

[0043] In designing a surface cladding system that is particularly suitable for providing blast resistance, the Applicant has recognised that the frame connection can itself be used to help absorb the shock of an explosion. Thus in a preferred set of embodiments the frame and its connection means and/or the panels are provided with one or more shock absorbing means, for example in the form of fuse bolts. The shock absorbing means is preferably ductile, thereby absorbing blast impact by bending. One or more metal bolts may be used as shock absorbing means. The shock absorbing means may be provided on the frame, and/or arranged between the frame and panels, and/or provided on the panels.

[0044] Some embodiments of the present invention will now be described, by way of example only, and with reference to the accompanying Figures, in which:

[0045] FIG. **1** shows the increase in flexural stiffness of curved walls compared to flat walls;

[0046] FIG. **2** shows the decrease in bending moments of curved walls compared to flat walls;

[0047] FIG. **3** shows the decrease of wall thickness for curved walls compared to flat walls;

[0048] FIG. **4** shows the increase and decrease of stresses in curved walls compared to flat walls;

[0049] FIG. **5** is a schematic side view of a wall or panel in planar and curved configurations defined by x and L;

[0050] FIG. **6** compares the deformation and stresses under 1 N/mm^2 reflected pressure (equivalent to 2 Tons of TNT at 25 m standoff) for a flat wall (left side) and a curved wall (right side), in which (a) is the wall in its initial configuration, (b) is an FEM model, (c) is the displacement due to blast wave pressure, and (d) is the von Mises stress due to blast wave pressure;

[0051] FIG. **7** compares the deformation and stresses under 0.2 N/mm^2 reflected pressure (equivalent to 1 Ton of TNT at 35 m standoff) for a conventional shelter (left side) and a shelter with curved walls (right side), in which (a) is the shelter before it is subject to a blast, (b) is an FEM mapped model, (c) is the deflection due to blast wave pressure, and (d) is the von Mises stress due to blast wave pressure;

[0052] FIG. **8** is a schematic illustration of a "smart" blast protection system;

[0053] FIG. **9** shows a reinforced mortar panel according to one example;

[0054] FIG. **10** is a cross-sectional view of the panel of FIG. **9**;

[0055] FIG. **11** is a graph showing deflection of Group 1 reinforced mortar panels during impact tests indicating the high ductility as compared with conventional UHPFRC slabs;

[0056] FIG. **12** is a graph showing deflection of Group 2 reinforced mortar panels during impact tests indicating the high ductility as compared with conventional UHPFRC slabs;

[0057] FIG. **13** shows the capacity of the tested reinforced mortar panels to absorb the energy of impact compared with UHPFRC slabs;

[0058] FIG. **14** shows the central deflection of the reinforced mortar panels tested under static loading compared with UHPFRC slabs;

[0059] FIG. **15** is a schematic diagram of a cladding system; and

[0060] FIG. **16** shows some details of such a cladding system.

[0061] A case study for a 2500 mm×1000 mm wall with 25 mm thickness and subjected to blast pressure=1 N/mm^2 has shown that a curved wall with a curvature defined by x/L=0.015 increases the flexural stiffness by a factor of 15 (FIG. **1**) and reduces the bending moment by 92% (as shown in FIG. **2**) as compared with a conventional flat wall. This advantageously corresponds to a possibility to reduce the wall thickness by 60%, as shown in FIG. **3**. The curved geometry of the wall induces additional compressive stresses equivalent to 10% of the overall compressive flexural stresses of the flat wall, as shown in FIG. **4**. The dashed line in FIG. **4** shows tension, in particular a decrease of tensions stresses, for stress of curved wall at extreme section fibre/stress of flat wall at extreme section fibre. The solid line in FIG. **4** shows compression, in particular an increase of compression stresses, for induced stress of curved wall/stress of flat wall at extreme section fibre. Advantageously, these compressive stresses cancel out the tensile stresses and change them to compressive stresses. This effect can be advantageous in asymmetric behaviour materials like concrete.

[0062] FIG. **5** illustrates how the curvature of a wall or panel can be calculated. The wall is seen from a side view in an initial planar configuration (solid line) and in a curved configuration (dashed line). In both configurations the wall has a two-dimensional footprint defined by a width L. In its curved configuration the wall has a curvature defined by a maximum lateral displacement x in a direction perpendicular to its footprint and towards a source of a blast, the large arrows representing the direction of an incoming blast wave. The lateral displacement x can be chosen to have any value in the range of 0.001≤x/L—0.5.

EXAMPLE 1

Blast Resistant Walls

[0063] A finite element analysis was carried out on 4000×2500 mm standalone walls of 50 mm thickness (see FIG. **6**). The first model is a conventional flat wall and the other is a curved wall having a curvature that can resist blast force. The curved wall height is 2500 mm with a 200 mm deflection x at mid height. Both models had identical material and mechanical properties, namely a yield strength of 250 N/mm^2 and a Young Modulus of 210 kN/mm^2, and were subjected to the same reflected blast pressure=1 N/mm^2. This is equivalent to a pressure generated by 2 Tons of TNT detonated at 25 m standoff. The two walls were modelled as being simply supported at two edges only—top and bottom as shown in FIGS. **6** and **7**.

[0064] The analysis has shown that the curved wall outperformed the conventional flat wall in all parameters. Table 1 shows the results obtained for the conventional and curved walls with the improvement factor. The maximum deflection of the curved wall was approximately 15.47 times less than that of the conventional flat wall, as shown in Table 1. The von Mises and mean stresses were also much lower as shown in Table 1. A full contour line based graphic comparison of the finite element analysis is shown in FIG. **6**.

TABLE 1

Parameter	Conventional flat walls	Curved walls	Improvement factor
Max. Deflection (mm)	795.67	51.43	15.47
Max. Mean stress (MPa)	69.35	19.73	3.51
Max. von Mises stress (MPa)	359.60	69.98	5.14
Principal Strain	0.0328	0.00733	4.47

EXAMPLE 2

Blast Resistant Shelters

[0065] A finite element model was built to simulate 4000×3000×2500 mm shelters. One shelter was built with conventional flat walls and the second was built with curved blast resistant walls. All the shelter's walls and roof had a 50 mm thickness. Both models had identical material and mechanical properties, namely a yield strength of 250 N/mm^2 and a Young Modulus of 210 kN/mm^2, and were subjected to the same blast impact pressure acting on the left side wall shown in FIG. **7**. The intensity of the blast pressure=0.2 N/mm^2, which is equivalent to the reflected blast pressure generated from detonating 1 Ton of TNT at 35 m standoff. The Finite Element analysis confirmed the outstanding performance of the curved wall of a shelter as compared with a conventional shelter having a flat wall. Table 2 shows the superior performance of the curved walls in deformability and stresses, providing an improvement factor of 4.68 as compared with conventional flat walls. A full contour line based graphic comparison of the finite element analysis is shown in FIG. **7**.

TABLE 2

Parameter	Conventional flat walls	Curved walls	Improvement factor
Max Deflection (mm)	36.37	7.77	4.68
Max Mean stress (MPa)	6.87	3.8	1.81
Max von Mises stress (MPa)	52.65	11.77	4.47
Principal Strain	0.00391	0.00125	3.13

EXAMPLE 3

Smart Blast Protection Systems

[0066] It can be seen from FIG. **8** that curved, blast resistant walls or panels can also be used to create a "smart" blast protection system. The system is capable of sensing a blast occurrence and the direction of the progressing impact blast wave. The system uses smart remote sensors **2** positioned in the surrounding area of a building being protected against blast. When a blast **1** occurs the pressure and vibration sensors **2** detect the blast wave **3** and send a signal wirelessly or using fibre optics to an actuator **4** fitted to a cladding panel **5**. Upon receiving a signal from the sensors **2**, the actuator **4** acts to bend the cladding panel **5** by pushing it towards and in the direction of the incoming blast wave **3**. The ratio of the lateral displacement x created by the actuator **4** to the height L of the cladding panel should be between about L/400 to L/70. In other words, the degree of curvature may be defined by $0.0025 \leq x/L \leq 0.015$. Changing the initial configuration of the cladding panel **5** from flat to a curved configuration **6** increases its blast resistance by 15 times. The smart system will be able to bend the cladding panel in both directions, that is to the left and right, depending on the direction of the approaching blast wave. This can be achieved by using smart actuators which work in pushing and pulling.

[0067] The curved, blast resistant walls can be used in a manually operated mode as well. That is in case of specific terrorism or bombing threat level given by the authorities the system can be operated manually to put the whole building into a state of "alertness" by bending all the cladding panels. When the threat is cleared by the authorities the cladding system can be put back to its initial position. In the case of the manual mode of operation the amount of lateral displacement may be limited to a certain range, e.g. L/250-L/300, depending on the material used to manufacture the wall or panels, so as to avoid plastic deformation in the cladding panels.

EXAMPLE 4

Materials

[0068] In one set of examples the panels described above are made from fibre-reinforced concrete or fibre-reinforced mortar. The mix contents per m^3 are provided below for two different examples. The weight percentage of steel fibres is relatively high, at least about 9 or 10 wt %, so as provide the material with ductility. Polymer fibres, for example polypropylene fibres, may optionally be added to provide a hybrid fibre reinforcement.

Mix 1. Ingredients/m^3:

[0069]

Cement	955 kg
Water	168 kg
Sand	1100 kg
Silica fume	143 kg
Superplasticizer	66 kg
Steel fibres	260 kg

Mix 2. Ingredients/m^3:

[0070]

Cement	1050 kg
Water	292 kg
Sand	960 kg
Silica fume	120 kg
Superplasticizer	76 kg
Steel fibres	360 kg

EXAMPLE 5

Materials

[0071] In one set of examples the panels described above are made from ultra-high performance, fibre-reinforced concrete (UHPFRC) or fibre-reinforced mortar.

[0072] This example uses mortar of ultra-high strength e.g. 90-200 MPa that is reinforced with a hybrid of polypropylene fibres (12 mm length, 18 μm diameter and 160° C. melting temperature) and micro steel fibres (13 mm length and 0.2 mm diameter, tensile strength 2000 MPa). The mix contents in one m^3 are shown in Table 3 for two different examples. In one example, the mixing time is: 5 minutes for dry ingredients (cement+sand+silica fume)+2 minutes with water+2 minutes with steel fibres+2 minutes with polypropylene fibres+1 minute all materials. Total mixing time=12 minutes. In another example, the mixing time is: 4 minutes for dry ingredients (cement+sand+silica fume)+3 minutes with water+3 minutes with steel fibres+3 minutes with polypropylene fibres+2 minutes all materials. Total mixing time=15 minutes. Curing the panels can be either in water with room temperature for a period of 3-28 days or more. The strength of the panels can be increased by curing in hot water up to 90° C. for 3-7 days or more.

TABLE 3

Ingredients	Quantity	Unit
Mix one		
Cement	970	kg
Water	243	kg
Sand	668	kg
Silica fume	245	kg
Superplasticizer (based on polycarboxylate polymers)	73	litre
Steel fibres	156	kg
Polypropylene fibres	1.5	kg

TABLE 3-continued

Ingredients	Quantity	Unit
Mix two		
cement	628	kg
water	251	kg
sand	680	kg
silicafume	258	kg
GGBS (Ground Granulated Blast-furnace Slag)	330	kg
Superplasticizer (based on polycarboxylate polymers)	72	litre
Steel fibres	79	kg
Polypropylene fibres	0	kg

[0073] The steel fibres are used to increase the mortar strength, increase ductility and reduce the appearance of cracks. This will significantly reinforce the external layers that normally suffer from fragmentation under blast effect. The addition of polypropylene fibres makes the panels less susceptible to explosive spalling normally encountered in concrete materials exposed to fire.

[0074] In addition, panels made from such a mortar mix can be reinforced with a network of wire cells, for example formed from integrated layers of steel wire mesh. The core of the panels is reinforced with a galvanised steel wire network (gauge 19=1 mm wire diameter) which defines a 3D network of wire cells impregnated with the mortar as a covering on all sides. There is seen in FIGS. **9** and **10** a mortar-based panel **1** formed of ultra high strength mortar with polypropylene and steel fibres. The core **2** consists of a network of 3D wire cells. The core **2** may be an integrally formed cellular structure. The wire network ensures an interactive performance between the cells. It is seen from the cross-sectional view of FIG. **10** that the wire network in the core **2** is impregnated and covered by the mortar forming the surfaces of the panel **1**.

[0075] The steel wire network can be of different opening sizes between 13 mm and 25 mm. In one example a 16 mm (square) opening size is recommended for optimum performance. For example, for 25 mm thickness panels the network of 3D wire cells should form around 75% of the thickness of the slab leaving 12.5% of mortar cover from edges, top and bottom surfaces (see FIG. **10**). The thickness of the steel wire core **2** is determined by the cover thickness for a given panel depth d. The cover should not be less than 3 mm and not greater than 10 mm. The steel wire network core thickness is the remaining depth after deducting the cover for both of the top and bottom sides of the panel. In Table 4 below are some examples of the core and cover thickness.

TABLE 4

Panel thickness (mm)	Cover thickness each side (mm)	Core of 3D network of steel wire cells (mm)	No. of 1 mm diameter wire layers (gauge 19)
10	3	7	4
20	3	14	9
25	4	17	12
50	7.5	35	22
100	10	80	52

Tolerance ±0.5 mm

Blast/Impact Tests

[0076] Performing real blast tests requires special facilities and resources. Drop weight impact tests can be performed to simulate blast effect and to give a primary assessment of a panel's resistance to explosions. However, conducting drop weight impact tests also requires expensive equipment and devices which were not available at the University of Ulster. Alternative test arrangements were adopted to fit within the project budget. The tests were performed by dropping a steel mass of 27.13 kg from two heights (1.5 m and 2 m) to simulate explosion energy. Six weight drop tests were performed in total. Two groups of panels each consisting of three specimens were involved in the impact tests. Panels **17**, **18**, **19** and **20** were made from a mortar mix containing steel fibres with a core reinforcement provided by a 3D network of wire cells, e.g. as seen in FIGS. **9** and **10**. Each group was subjected to impact energy by dropping a 27.13 kg mass from a calculated height to simulate the energy and pressure exerted by explosion. Table 5 shows details of the impact tests.

[0077] The tests showed an unprecedented performance of the core-reinforced panels as compared with control panels **23** and **24** (reinforced with steel fibres only). The test showed a remarkable success in shifting the behaviour of a concrete-type material from the brittle zone to the ductile zone. This makes the panels very efficient to resist and absorb blast energy.

TABLE 5

	Slab ref.	Reinforcement type	Drop Height (m)	Kinetic Energy (J)	Equivalent blast load	Equivalent reflected pressure (MPa)	Time (ms)	Reflected Impulse (MPa · ms)
Gro. 1	Slab 17	network 12 × 13 mm	1.52 m	404.5	500 kg of TNT at 30 m standoff	0.172	13.2	1.13
	Slab 19	network 12 × 25 mm						
	Slab 23	no network						
Gro. 2	Slab 18	network 12 × 13 mm	2.02 m	537.6	800 kg of TNT at 30 m standoff	0.262	10.80	1.41
	Slab 20	network 12 × 25 mm						
	Slab 24	no network						

[0078] The panels showed an outstanding "spring" (ability to bounce back impact objects) indicating a high elasticity behaviour of the mortar panels which is important in blast shock absorption. The panels showed an approximately 10 times bouncing/spring effect capacity as compared with the control panels. The panels were observed to bounce back the 27 kg drop weight to a height of approximately 500 mm compared with 50 mm for the control panels. The tests also showed a high ductile deformability of the panels compared with the control panels, making them ideal for blast absorption.

Group 1

[0079] Drop weight height: 1.5 m.
Equivalent blast: 500 kg of TNT @ 30 m distance or well above EXV(10) of ISO 16933:2007(E).

[0080] The tested panels performed remarkably and efficiently by resisting 13 impacts for slab **17** (12 layers of 13 mm mesh) and 11 impacts for slab **19** (12 layers of 25 mm mesh) with high strength capacity residual in the slabs after the tests. The control slab **23** which had no mesh but steel fibres failed in the first impact by deflection and was completely destroyed in the second impact. FIG. **11** is a graph showing deflection of the slabs in Group 1 during impact tests indicating the high ductility as compared with conventional UHPFRC panels. Line **1** relates to slab **23** (control, no core reinforcement) and shows complete failure by fragmentation. Line **2** relates to slab **19** with a 3D wire network formed by 12×25 mm mesh. Line **3** relates to slab **17** with a 3D wire network formed by 12×13 mm mesh. FIG. **11** confirms the efficiency and the ductility of the panels compared with the control slab. Furthermore FIG. **11** shows that slab **17** (13 mm mesh opening size) has shown higher stiffness than slab **19** (25 mm mesh opening size) while the control UHPFRC slab **23** showed very weak stiffness with a failure after first impact.

Group 2

[0081] Drop weight height: 2 m.
Equivalent blast: 800 kg of TNT @ 30 m distance.

[0082] This group was subjected to blast/impact energy higher than Group 1 as shown in Table 5 above. The slabs performed remarkably well: slab **18** (12 layers of 13 mm mesh) resisted seven impacts, and slab **20** (12 layers of 25 mm mesh) resisted five impacts. The outstanding performance of the slabs can be compared with the control UHPFRC slab **24** which failed in the first impact and was completely shattered into pieces in the second impact. FIG. **12** is a graph showing deflection of the slabs in Group 2 during the impact tests. Line **1** relates to slab **24** (control, no core reinforcement) and shows complete failure by fragmentation. Line **2** relates to slab **20** with 12×25 mm mesh. Line **3** relates to slab **18** with 12×13 mm mesh.

[0083] An overall assessment of the absorption capacity of the mortar panels made as described above, compared to UHPFRC, is shown in FIG. **13**. In FIG. **13**, area **1** is slab **18** tested for energy absorption and area **2** is a comparison with a slab of standard UHPFRC.

Static Loading Tests

[0084] Three static tests were performed on 500×500×25 mm slabs. The tests involved applying a concentrated load at the central point of the surface of a 480×480 mm slab simply supported (on all four edges). One slab **26** contained a 3D network of wire cells formed from 12 layers of mesh with a 25 mm opening size. The second slab **27** did not contain a 3D network of wire cells, while the third one was a plain mortar slab **28**.

[0085] FIG. **14** shows the development of the central deflection of the panels with load increase for the three types of panels. The central deflection of the tested slab **26** (line **1**) is compared to a standard UHPFRC slab (line **2**) and a plain mortar slab (line **3**). FIG. **14** clearly shows that the core-reinforced panels (line **1**) demonstrate a spectacular ductility with a stress-deflection curve similar to steel behaviour. The outstanding performance of the slabs, exceeding standard UHPFRC by around 2.2 times on load capacity and deformability, is shown in Table 6 below.

TABLE 6

Slab ref.	Reinforcement type	Max load KN	Max deflection mm
Slab 26	3D network of wire cells 12 × 25	26.82	47.03
Slab 27	UHPFRC	12.88	21.16
Slab 28	Plain mortar	2.27	0.46

EXAMPLE 6

Blast Protection Cladding Systems

[0086] As is seen from FIGS. **15** and **16**, a blast protection system can be assembled on site by fitting "male" panels **1** into a "female" light frame **8** fitted on an existing wall **10** that needs to be protected e.g. using a "click to fit" technique. The female light steel frame **8** can be fitted on the existing wall or ceiling e.g. using DIY bolts and plastic plugs. The "male" panels **1** are then fitted by clicking into the corresponding profiles of the "female" frame **8**. Other methods of fitting can be utilized depending on the blast risk assessment. During casting the panels **1** are fitted with a light galvanized "male" steel frame **6** at the back face (leaving 1 cm from the edges of the panel). This frame **6** then clicks into the "female" frame **8** that has been permanently fitted on the existing wall **10** on site. Furthermore the "male" plate **6** can be designed to work as a "fuse" by bending in cases of excessive blast shock.

[0087] The system robustness against explosions can be enhanced by using "fuse" bolts **12** (that can be part of the "click to fit" mechanism) as supports for the panels **1**. The fuse bolts **12** are designed to fail under high explosion impact, thereby relieving the blast pressure on the panel face. It is recommended that 6-12 bolts **12** are used on the perimeter of the rear face (away from blast) of the panel **1** depending on the panel's fitting procedure, as shown in FIG. **16**. In case of high explosion load the bolts fail under the impact impulse. A failed bolt **12'** is seen in close-up after the blast. This will absorb the blast impact energy and relieve the blast pressure on the panels **1** and significantly increase the system's blast resistance capacity. The bolts' diameter and quantity are determined to ensure that they fail under the impact load by bending. Table 7 below shows some diameters of the bolts for some blast intensities.

TABLE 7

Blast load intensity	Bolts
500 kg of TNT @ 30 m standoff	10 bolts of 6 mm diameter
500 kg of TNT @ 40 m standoff	10 bolts of 4 mm diameter
500 kg of TNT @ 50 m standoff	10 bolts of 3 mm diameter

[0088] In such a cladding system the panels **1** may be made from mortar with fibre and/or core reinforcement, for example as described above. However the cladding system can provide benefits in terms of absorbing a blast impact regardless of the material of the panels **1**. The panels **1** may be formed from conventional concrete or other materials such as metal and/or plastic.

1. An automated system for forming a blast resistant structure, comprising one or more remote blast sensors connected to at least one actuator arranged to actively deform a panel or wall of the structure from an initial configuration to a curved configuration in response to sensing a blast.

2. The system as claimed in claim **1**, wherein the one or more remote blast sensors are arranged to detect an approaching blast and the at least one actuator is arranged to actively deform a panel or wall of the structure into a curved configuration before the blast arrives.

3. The system as claimed in claim **1**, wherein the direction of curvature of the panel or wall is convex towards a source of a blast.

4. The system as claimed in claim **1**, wherein the at least one actuator is arranged to actively deform the panel or wall by changing the geometry of the panel or wall.

5. The system as claimed in claim **1**, wherein the remote blast sensor(s) comprise one or more pressure or sound sensors to measure shock wave pressure or sound associated with an explosion.

6. The system as claimed in claim **1**, wherein the remote blast sensor(s) communicate wirelessly with the at least one actuator.

7. The system as claimed in claim **1**, wherein the panel or wall is permanently deformed into a curved configuration.

8. The system as claimed in claim **1**, wherein the panel or wall is elastically deformed into a curved configuration.

9. The system as claimed in claim **1**, wherein the blast resistant structure is formed of one or more panels or walls that are arranged to be actively deformed to a curved configuration having a curvature that can resist blast forces.

10. The system as claimed in claim **9**, wherein the panel(s) or wall(s) have a two-dimensional projection defined by a height L and a curvature defined by a maximum lateral displacement x in a direction perpendicular to the projection and towards a source of a blast, wherein $0.001 \le x/L \le 0.5$.

11. The system as claimed in claim **10**, wherein $x=0$ in the initial configuration.

12. The system as claimed in claim **10**, wherein the two-dimensional projection is rectangular.

13. The system as claimed in claim **10**, wherein the curvature is defined by x/L being about 0.015.

14. The system as claimed in claim **10**, wherein the degree of curvature is defined by: (i) $0.001 \le x/L \le 0.4$; (ii) $0.001 \le x/L \le 0.3$; (iii) $0.001 \le x/L \le 0.2$; (iv) $0.001 \le x/L \le 0.1$; (vi) $0.001 \le x/L \le 0.09$; (vii) $0.001 \le x/L \le 0.08$; (viii) $0.001 \le x/L \le 0.07$; or (ix) $0.001 \le x/L \le 0.06$.

15. The system as claimed in claim **10**, wherein the degree of curvature is defined by: (i) $0.001 \le x/L \le 0.05$; (ii) $0.001 \le x/L \le 0.04$; (iii) $0.001 \le x/L \le 0.03$; (iv) $0.001 \le x/L \le 0.02$; (v) $0.001 \le x/L \le 0.01$; (vi) $0.002 \le x/L \le 0.05$; (vii) $0.002 \le x/L \le 0.04$; (viii) $0.002 \le x/L \le 0.03$; (ix) $0.002 \le x/L \le 0.02$; (x) $0.002 \le x/L \le 0.01$; (xi) $0.003 \le x/L \le 0.05$; (xii) $0.003 \le x/L \le 0.04$; (xiii) $0.003 \le x/L \le 0.03$; (xiv) $0.003 \le x/L \le 0.02$; (xv) $0.003 \le x/L \le 0.01$; (xvi) $0.004 \le x/L \le 0.05$; (xvii) $0.004 \le x/L \le 0.04$; (xviii) $0.004 \le x/L \le 0.03$; (xix) $0.004 \le x/L \le 0.02$; (xx) $0.004 \le x/L \le 0.01$; (xxi) $0.005 \le x/L \le 0.05$; (xxii) $0.005 \le x/L \le 0.04$; xxiii) $0.005 \le x/L \le 0.03$; (xxiv) $0.005 \le x/L \le 0.02$; (xxv) $0.005 \le x/L \le 0.01$; or (xxvi) $0.005 \le x/L \le 0.025$.

16. The system as claimed in claim **10**, wherein the degree of curvature is defined by: (i) $0.01 \le x/L \le 0.02$; (ii) $0.012 \le x/L \le 0.02$; (iii) $0.014 \le x/L \le 0.02$; (iv) $0.01 \le x/L \le 0.018$; (v) $0.01 \le x/L \le 0.016$; (vi) $0.011 \le x/L \le 0.019$; (vii) $0.012 \le x/L \le 0.018$; (viii) $0.013 \le x/L \le 0.017$; or (ix) $0.014 \le x/L \le 0.016$.

17. The system as claimed in claim **1**, wherein the blast resistant structure is formed of one or more panels fitted in a supporting frame.

18. A surface protection system comprising one or more blast resistant panels fitted in a supporting frame and at least one actuator arranged to actively deform the panel(s) from an initial configuration to a curved configuration in response to sensing a blast.

19. The system as claimed in claim **18**, further comprising one or more remote blast sensors connected to the at least one actuator and arranged to detect an approaching blast.

20. The system as claimed in claim **17**, wherein the frame comprises a female connection arrangement designed to mate with a male profile of the panel(s).

21. The system as claimed in claim **20**, wherein the male profile is provided by a male frame, e.g. fitted to one face of the panel(s), that connects with the female frame.

22. The system as claimed in claim **20**, wherein the female connection arrangement comprises snap-fit means for fixedly connecting a panel to the frame.

23. The system as claimed in claim **17**, wherein the frame or the panel(s) are provided with one or more shock absorbing means.

24. A method of forming a blast resistant structure, comprising:

sensing a blast in advance; and

actively deforming a panel or wall of the structure from an initial configuration to a curved configuration in response to sensing a blast.

25. A method as claimed in claim **24**, comprising: using one or more remote blast sensors to detect an approaching blast.

26. A method as claimed in claim **24**, comprising: actively deforming a panel or wall of the structure into a curved configuration before the blast arrives.

27. A method as claimed in claim **24**, comprising: actively deforming a panel or wall of the structure into a curved configuration having a curvature that is convex towards a source of the blast.

28. The method as claimed in claim **24**, comprising: using one or more witness screens to detect a blast.

29. The method as claimed in claim **24**, comprising: using video surveillance to detect a blast.

30. The method as claimed in claim **24**, comprising: wirelessly communicating with the blast resistant structure when a blast is sensed.

31. The method as claimed in claim **24**, comprising: permanently deforming the panel or wall into a curved configuration.

32. The method as claimed in claim **24**, comprising: elastically deforming the panel or wall into a curved configuration.

33. The method as claimed in claim **24**, comprising: fitting one or more panels fitted in a supporting frame to form the blast resistant structure.

34. The method as claimed in claim **33**, comprising: removing a panel from the supporting frame after it has been deformed and replacing the panel.

35. A method of protecting a surface, comprising:
- fitting one or more blast resistant panels in a supporting frame on the surface; and
- actively deforming the panel(s) from an initial configuration to a curved configuration in response to sensing a blast.

36. The method as claimed in claim **35**, comprising: sensing a blast in advance.

37. A method as claimed in claim **36**, comprising: using one or more remote blast sensors to detect an approaching blast.

38. A method as claimed in claim **36**, comprising: actively deforming the panel(s) into a curved configuration before the blast arrives.

39. A method as claimed in claim **36**, comprising: actively deforming the panel(s) into a curved configuration having a curvature that is convex towards a source of the blast.

40. The system as claimed in claim **17**, wherein the panel(s) or wall(s) have a thickness in the range of: (i) 5-25 mm; (ii) 10-25 mm; or (iii) 10-20 mm.

41. The system as claimed in claim **17**, wherein the panel(s) or wall(s) comprise a polymeric, concrete, metallic or composite material.

42. The system as claimed in claim **17**, wherein the panel(s) or wall(s) are formed of a composite material comprising concrete or mortar.

43. The system as claimed in claim **42**, wherein the composite material comprises metal fibres.

44. The system as claimed in claim **43**, wherein the concrete or mortar composite material comprises: (i) 1-3 wt %; (ii) 1-4 wt %; (iii) 1-5 wt %; (iv) 1-6 wt %; (v) 1-7 wt %; (vi) 1-8 wt %; (vii) 1-9 wt %; (viii) 1-10 wt %; (ix) 1-11 wt %; (x) 1-12 wt %; (xi) 1-13 wt %; (xii) 1-14 wt %; or (xiii) 1-15 wt % of metal fibres.

45. The system as claimed in claim **43**, wherein the concrete or mortar composite material comprises: (i) 3-4 wt %; (ii) 3-5 wt %; (iii) 3-6 wt %; (iv) 3-7 wt %; (v) 3-8 wt %; (vi) 3-9 wt %; (vii) 3-10 wt %; (viii) 3-11 wt %; (ix) 3-12 wt %; (x) 3-13 wt %; (xi) 3-14 wt %; or (xii) 3-15 wt % of metal fibres.

46. The system as claimed in claim **42**, wherein the panel(s) or wall(s) comprise a core volume reinforced by a 3D network of wire cells.

47. The system as claimed in claim **17**, wherein the panel(s) or wall(s) are formed of a mortar-based material comprising mortar containing metal fibres and a core reinforcement consisting of a 3D network of wire cells that is impregnated with the mortar.

48. The system as claimed in claim **47**, wherein the mortar contains: (i) 5-20 wt %; (ii) 10-20 wt %; (iii) 10-15 wt %; or (iv) 15-20 wt % of metal fibres.

49. The panel, wall, system as claimed in claim **43**, wherein the metal fibres are steel fibres.

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