



## Apparatus and method for manufacturing reinforced 3d printed structures

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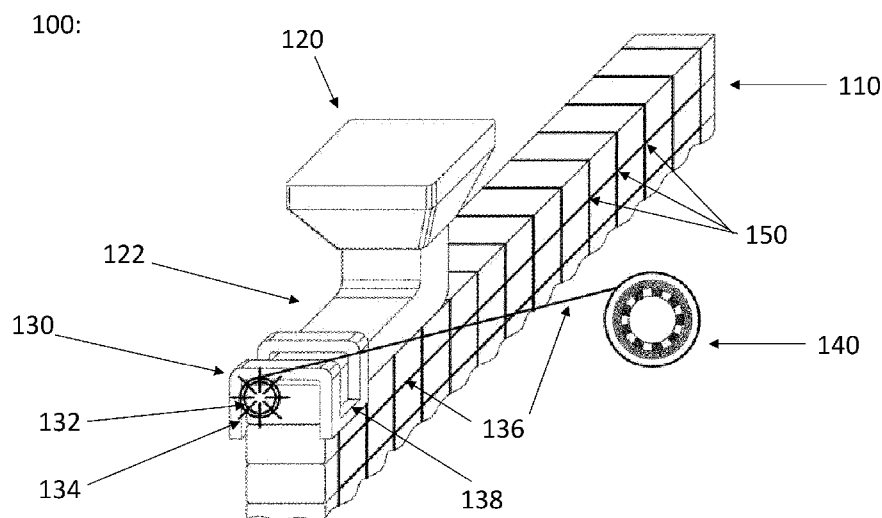


Fig. 1

(57) Abstract: The invention relates to a method of reinforcing a 3D printed structure (110) by interweaving reinforcement (136) with 3D printed substrate layers (122) as the substrate layers are being printed. The method comprising the steps of printing substrate layers (122), supplying reinforcement (136), and interweaving the reinforcement with the printed substrate layers to create a reinforcement grid around, and optionally in between, the printed substrate layers. The reinforcement is connected at nodes (150). The invention also relates to an apparatus (100) comprising a 3D printer (120) and a reinforcement tool (130). The reinforcement tool comprises at least one weaving tool (132) with at least one needle (134) for interweaving the reinforcement (136). It also has at least one arrangement means (138) for moving the reinforcement tool (130) to the position where the reinforcement (136) is to be interwoven with the printed layers (122). By use of the invention, a reinforced 3D printed structure (110) can be designed and manufactured to take into account

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## **APPARATUS AND METHOD FOR MANUFACTURING REINFORCED 3D PRINTED STRUCTURES**

### **FIELD OF THE INVENTION**

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The invention relates to an apparatus and a method for manufacturing reinforced 3D printed structures. In particular, it relates to an apparatus and a method wherein the reinforcement is continuously and simultaneously interwoven with 3D printed substrate layers as the substrate layers are being printed, and wherein the  
10 reinforcement is interconnected at nodes to form a grid arranged around, and optionally in between, the printed substrate layers.

### **BACKGROUND OF THE INVENTION**

15 The present invention has been developed with specific focus on how to reinforce structures made by 3D printing of concrete based materials e.g. for use within the building industry. The following description is therefore related to this technical field. However, the scope of protection is not limited to use for these types of materials or structures.

20

Concrete based structures are known to perform very well under compression whereas the tensile strength is relatively low so that reinforcement is often needed to ensure a satisfactory performance of the structure when applied to tension and/or bending. Such reinforcement is typically provided by arranging  
25 steel bars in a separate process. An example is to print an outer wall forming an inner cavity, arranging steel bars in the cavity and then filling the inner cavity with a third material, which may be similar to the one used for the printing of the walls, to form the final structure. Another example is to arrange the reinforcement as part of an extrusion process, but then the reinforcement is only arranged in the  
30 longitudinal orientation of the component being extruded. This will be sufficient for some but not all types of components.

Another way of reinforcing concrete material is to incorporate short fibres into the concrete as part of the mixing and thereby no reinforcement between layers which  
35 results in the bond between the layers being the weak spot in the structure. The

fibres provide tensile strength to a structure cast from such material, but it can be difficult to control the orientation of the fibres and thereby the strength of the final structure, and a good bonding between the fibres and the concrete is crucial for the overall properties of the structure. Furthermore, the incorporation of such short fibres makes the mixing harder, increases the wear of the tools used, and it may influence the forces needed to perform the 3D printing. Moreover, flexural and tensile properties of this type of material is usually limited.

Hence, an improved apparatus and method for manufacturing a reinforced 3D printed structure would be advantageous.

#### OBJECT OF THE INVENTION

It is an object of the invention to provide a method and an apparatus with which the reinforcement of a 3D printed structure can be performed more efficiently than with known methods.

It is an object of at least some embodiments of the invention to provide a method and an apparatus with which a 3D printed structure can be reinforced in a continuous process without the need for arranging the reinforcement in a separate production step.

It is another object of at least some embodiments of the invention to provide a method and an apparatus with which a reinforced 3D printed structure can be designed and manufactured to take into account the local internal forces expected to arise during use of the structure.

It is a further object of the present invention to provide an alternative to the prior art.

30

In particular, it may be seen as an object of the present invention to provide a method of reinforcing 3D printed structures that solves the above mentioned deficiencies and shortcomings of the prior art.

## SUMMARY OF THE INVENTION

The above-described object and several other objects are intended to be obtained in a first aspect of the invention by providing a method of reinforcing a 3D printed structure by interweaving reinforcement with 3D printed substrate layers as the substrate layers are being printed or as segments of the substrate are being placed, the method comprising the steps of:

- printing substrate layers,
- supplying reinforcement,
- 10 - interweaving the reinforcement with the printed substrate layers to create a reinforcement grid around, and optionally in between, the printed substrate layers by the steps:
  - arranging the reinforcement around, and optionally in between, the printed substrate layers, and
  - 15 - connecting the reinforcement at nodes.

By "interweaving" is meant that one point of the reinforcement material is connected, such as mechanically connected, to one or more other points of this reinforcement material so that at least one coherent structure of reinforcement is formed. Such a connection can also be referred to as a node or a knot. This structure is also referred to as a "reinforcement grid". By "grid" is preferably meant a physical network of reinforcement material, not necessarily forming straight or parallel lines of reinforcement. Examples of different patterns of the arrangement of reinforcement will be shown in the figures. Another term that could be used instead of "interweaving" or "weaving" is "knitting".

The interweaving can be understood as enclosing the layers individually or in groups, wherein the reinforcement is arranged along the interface between the layers. By "interface" is meant the area where two subsequent layers touch each other and are joined together. The reinforcement is typically arranged at the plane of this interface either transversely, i.e. 90 degrees to the printing direction, or longitudinally, i.e. in the printing direction. Thus, by "optionally in between" is meant that the reinforcement is not necessarily arranged between all of the layers having a mutual interface. Furthermore, it will be possible to have all the reinforcement arranged on an outer surface of the structure; e.g. if it only consists of few layers.

By "substrate" is meant the material that is formed in the printing process, i.e. the material to be reinforced in order to perform the intended function. This part of the process is known on its own, and a person skilled in the art will know which equipment and which process parameters to use for a given material and

5 structure. This does not exclude that it may be relevant to make modifications to the printing process, such as to adjust the speed of the printer to match what is optimal for the arrangement of the reinforcement material or the rheology and/or consistency of the substrate material as it is being printed.

10 The step of arranging the reinforcement can be performed in different ways. It can e.g. be done by arranging the reinforcement around one layer at a time. Another option is to arrange it around a plurality of layers at a time, such as around two or three layers printed on top of each other. Yet another option is to first arrange the reinforcement around one layer, typically the actual top layer,  
15 and then around a plurality of layers. The exact way of arranging the reinforcement will be determined as a part of the design process as will be described in further details below.

By "nodes" is meant the points or regions where the reinforcement is  
20 interconnected to form the grid. It could also be referred to as "knots". In the context of the invention, "node" may be understood as a connection allowing a mechanical transfer of tensile forces in the reinforcement, preferably by tying a knot, wherein "knot" may be understood as a point where the reinforcement is tied or twisted together, and preferably pulled tight. The nodes  
25 thereby mechanically facilitate a direct force transfer within the reinforcement connected at the nodes. The nodes might thereby be an anchoring of the reinforcement to itself, wherein a load can be mechanically transferred.

In some embodiments of the invention, the step of arranging the reinforcement is  
30 around each layer.

In some embodiments of the invention, the steps are being repeated. Hereby is preferably meant that the method can be considered a stepwise process, e.g. in the sense that one layer is printed while being reinforced, and then another layer  
35 is subsequently being formed on top thereof. Hereby different designs of the

structure can be made that do not necessarily have the same geometry in all of the layers.

The steps of arranging and connecting the reinforcement around, and optionally in  
5 between, the printed substrate layers may be synchronized with the substrate printing process. Hereby the method can be performed as a continuous process wherein the reinforcement is typically arranged shortly after the substrate material leaves an extrusion nozzle of the 3D-printer to form a layer.

Alternatively, a layer or segments of a layer may be printed before that layer is  
10 provided with reinforcement, and then the subsequent layer is being printed, reinforced and so on.

The process of weaving the reinforcement around each layer or group of layers does not rely on maintaining an external support of the reinforcement as each  
15 layer is being printed, since the reinforcement is in contact with, and thereby supported by, the printed substrate material itself. This is different from known methods wherein loops of reinforcement must be kept elevated above each layer until a connection with subsequently arranged reinforcement is established at a later stage in the process.

20

The printed substrate layers may be made of mineral and cementitious composite material, polymer, metal and/or any moldable material. A substrate made from mineral and cementitious composite material could e.g. be based on cement mortar without or with large aggregates, also referred to as concrete. The  
25 substrate may also include short fibres. By "any moldable material" is meant any material that has sufficient internal coherence to form a layer, typically without the need for a mould. However, the scope of protection also covers methods wherein the substrate material needs some kind of support, such as from a supporting formwork, to maintain the desired shape until solidified. Such support  
30 could e.g. be applied before or after the reinforcement has been arranged.

The reinforcement may be made of any type of material with the required physical reinforcing properties, such as:

- Synthetic, which includes polymeric: e.g. PE, PP, Nylon, Carbon, Aramid
- 35 • Mineral: Glass, Basalt

- Metal: Steel
- Natural

The reinforcement will e.g. be applied in order to provide the structure with a  
5 higher tensile and/or flexural strength, but it could also be used for providing  
higher stiffness or impact toughness, as compared to the structure without  
reinforcement.

In some embodiments of the invention, the type and/or direction of arrangement  
10 of the reinforcement is adjustable, and the type and/or direction may be  
predetermined based on the expected internal forces in the reinforced structure  
under service and ultimate loading conditions. Such adjustment may take place  
while the process is running e.g. to provide a larger amount of reinforcement  
and/or change the orientation of the reinforcement to some parts of a structure.  
15 The expected forces and stresses for a given structure can e.g. be determined  
based on computer simulations, such as finite element analysis. Such an analysis  
may be an iterative process.

In the context of the invention, "direction" may also be referred to as orientation.  
20

In some embodiments of the invention, the method comprises the step of  
receiving requirements of the type and/or direction of the reinforcement from a  
predetermined weaving-plan based on structural analysis, such as analytical  
and/or numerical calculations. Such a structural analysis may be part of the  
25 analysis used to determine the expected internal forces and ultimate loading  
conditions. However, it may also be a separate analysis being applied as part of  
the design process e.g. in order to determine a specific way of achieving  
reinforcement matching a predetermined expected pattern of forces.

30 In some embodiments of the invention, the interwoven reinforcement is the only  
reinforcement so that no further anchoring elements are needed to keep the  
reinforcement in place. This may simplify a manufacturing process, since only one  
element is to be supplied, and since no additional interconnecting elements are  
necessary.

In any of the embodiments as described above, the 3D-printed structure may be in straight and/or curved shape, preferable being in the shape of: a beam, a wall, a slab, a column and/or a curved shell. The method may e.g. be used for the manufacturing of optimized structures for use in the building industry.

5

The reinforcement may be in a continuous form, preferably being any of the types: thread, yarn and/or wire. In an alternative embodiment, the reinforcement grid is created from a combination of reinforcement in continuous form and smaller sections of reinforcement used for the connection of continuous reinforcement at the nodes. An example of such an embodiment will be shown in the figures.

10

The method may be partly or, preferably, fully automatic.

15 The method may be a digitally controlled process, such as controlled by a computer.

The above-described object and several other objects may also be obtained in a second aspect of the invention by providing an apparatus for manufacturing of a reinforced 3D printed structure, the apparatus comprising:

20

- a 3D printer for printing substrate in layers,
- a reinforcement tool for reinforcing the 3D printed substrate layers, the reinforcement tool comprising:
  - at least one weaving tool comprising at least one needle for
  - 25 interweaving the reinforcement,
  - at least one arrangement means for moving the reinforcement tool to the position where the reinforcement is to be interwoven with the printed layers,
- a reinforcement supplier for supplying reinforcement to the weaving tool
- 30 during use of the apparatus,
- a controller for controlling the reinforcement tool, and

wherein the reinforcement tool is adapted to interweave the reinforcement with the 3D printed substrate layers as the substrate layers are being printed or as segments of the substrate are being placed, by:

- arranging the reinforcement around, and optionally in between, the printed layers, and
- connecting the reinforcement at nodes, the nodes being formed by the at least one needle of the weaving tool.

5

In presently preferred embodiments of the invention, the at least one weaving tool comprises a plurality of needles, such as two or more needles, preferably between three and ten needles. The at least one needle should be designed to interact with the reinforcement in order to interweave it by forming nodes in a  
10 predetermined pattern or grid as described above. Thus, a needle could also be called a hook or a tweezer depending on its shape and working principle.

In some embodiments of the invention, the arrangement means is bridging across the printed substrate layers enabling the at least one weaving tool to move across  
15 the printed substrate layers via the arrangement means. An example of such an embodiment will be shown in the figures. Alternatively, the weaving tool could be suspended over the substrate layer being reinforced e.g. by a robotic arm which in that case would form the arrangement means.

20 The arrangement means may be mounted to at least one rail making it movable along the printed layers. The speed of the movement along the rail could then be adjusted to match the speed of the 3D-printer. The movement would match the actual arrangement of the reinforcement being made. So it might include both back and forth movement as well as periods of no movement, e.g. during the  
25 forming of the nodes.

In some embodiments of the invention, the weaving tool is substantially circularly shaped with a plurality of needles radially arranged, and the needles are adapted to move back and forth with respect to a central region of the weaving tool to  
30 establish the nodes. An example of such a tool will be described in relation to the figures.

In some embodiments, the weaving tool has three needles which are arranged in a triangular configuration, and the needles are adapted to move back and forth  
35 with respect to a central region of the weaving tool and/or rotate around it to

establish the nodes. An example of such a tool will be described in relation to the figures.

A weaving tool may alternatively have other numbers of needles, and they may  
5 be arranged in other configurations. In any of the embodiments, the needles may be arranged in frames provided with fixation points as well as guides or hinges along and/or around which the needles can move.

Each of the at least one needle may have a front end comprising a gripping device  
10 adapted to grip the reinforcement and tie it into nodes. Such a gripping device may e.g. be a hook or a tweezer.

The weaving tool may be movable and rotatable in any direction. Hereby a large freedom in the design of the reinforcement grid is obtained. Alternatively, the  
15 weaving tool may be designed for a specific application that only requires the movement to take place in some orientations and/or directions.

The type and/or direction of arrangement of the reinforcement may be adjustable, and the type and/or direction may be predetermined based on the expected  
20 internal forces in the structure under service and ultimate loading. Hereby a given apparatus can be adjusted to meet the requirements of different manufacturing processes to be performed so that it is flexible with respect to different uses.

As described above for the method according to the first aspect of the invention,  
25 the interweaving of the reinforcement with the printed substrate layers may be synchronized with the substrate printing process. The interweaving of the reinforcement may be a digitally controlled process. The reinforcement may be interwoven with the printed substrate layers according to a weaving-plan, the weaving-plan resulting from structural analysis.

30

In a third aspect, the present invention relates to a reinforced 3D printed structure comprising:

- 3D printed substrate layers, and
- reinforcement interwoven with the printed substrate layers,

wherein the reinforcement forms a reinforcement grid around, and optionally in between, the printed substrate layers, and

wherein the reinforcement grid is formed by the reinforcement being connected at nodes.

5

Such a 3D printed structure may be manufactured by any of the embodiments of a method or of an apparatus as described above.

The first, second and third aspects of the present invention may each be  
10 combined with any of the other aspects. These and other aspects of the invention will be apparent from and elucidated with reference to the embodiments described hereinafter.

#### BRIEF DESCRIPTION OF THE FIGURES

15

The apparatus and method according to the invention will now be described in more detail with regard to the accompanying figures. The figures show one way of implementing the present invention and is not to be construed as being limiting to other possible embodiments falling within the scope of the attached claim set.

20

Figure 1 schematically shows an apparatus according to an embodiment of the invention.

Figure 2.a schematically shows an example of a design of a weaving tool having a  
25 plurality of needles for interweaving reinforcement.

Figure 2.b schematically shows another example of a design of a weaving tool having a plurality of needles for interweaving reinforcement.

30 Figure 3 schematically shows another embodiment of the invention, wherein the weaving tool is suspended from a robotic arm.

Figure 4 shows a weaving sequence resulting in the reinforcement being arranged with the 3D printed layer in an orthogonal manner.

Figure 5 shows a weaving sequence resulting in the reinforcement being arranged with the 3D printed layer in a uni-directional diagonal manner.

Figure 6 shows an alternative weaving sequence resulting in the reinforcement  
5 being arranged with the 3D printed layer in a uni-directional diagonal manner.

Figure 7 shows a weaving sequence resulting in the reinforcement being arranged with the 3D printed layer in a multi-directional diagonal manner.

10 Figure 8 shows one example of steps of connecting the reinforcement into a node using a circular weaving tool with a plurality of needles.

Figure 9 schematically shows an example of how a node can be formed in eight steps.

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Figure 10 schematically shows another example of forming a node which is an alternative to the one in figure 9.

Figure 11 schematically shows another alternative example of forming a node.

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Figure 12 schematically shows yet another alternative example of forming a node.

Figures 13, 14 and 15 show configurations of simply supported beams with line load, FEM stress results, and resulting force analysis, corresponding reinforcement  
25 layouts and sketches of the resulting reinforced printed concrete element.

Figure 16 shows the load-deformation response of tested prototypes.

#### DETAILED DESCRIPTION OF AN EMBODIMENT

30

Figure 1 schematically shows an apparatus 100 according to a presently preferred embodiment of the invention. The apparatus is used for the manufacturing of a reinforced 3D printed structure 110 in the form of a straight beam. However, the 3D-printed structure may alternatively be in straight and/or curved shape,  
35 preferable being in the shape of: a beam, a wall, a slab, a column and/or a curved

shell. The apparatus comprises a 3D printer 120 for printing a substrate material in layers 122. These substrate layers could e.g. be made of mineral and cementitious composite materials, polymer, metal and/or any moldable material. The apparatus 100 further comprises a reinforcement tool 130 for reinforcing the 3D printed substrate layers 122. The reinforcement tool in figure 1 has one weaving tool 132, but the scope of the invention also covers that there could be more than one such weaving tool. The weaving tool is preferably movable and rotatable in any direction. Figure 1 illustrates a weaving tool 132 with a plurality of needles 134, but a weaving tool comprising e.g. one needle or a weaving tool comprising more needles than illustrated in the figure are also covered in the scope of the invention.

The reinforcement tool 130 furthermore comprises at least one arrangement means 138 for moving the reinforcement tool to the position where the reinforcement 136 is to be interwoven with the printed layers 122. In figure 1, the arrangement means 138 is shown in a presently preferred embodiment, wherein the arrangement means is bridging across the printed substrate layers 122 enabling the weaving tool 132 to move across the printed substrate layers via the arrangement means 138. The weaving tool is movably arranged on the arrangement means so as to allow the weaving tool to interweave reinforcement with the printed layers. Figure 1 thereby also illustrates the reinforcement tool 130 being adapted to interweave the reinforcement 136 with the 3D printed substrate layers 122, as the substrate layers are being printed, by arranging the reinforcement around, and optionally in between, the printed layers, and connecting the reinforcement at nodes 150. The interweaving is preferably synchronized with the 3D printing of the layers 122 as described above. The arrangement means 138 is in a presently preferred embodiment mounted to at least one rail (not shown) or a robot arm 300 (shown in figure 3) making it movable along the printed layers.

30

Figure 1 also illustrates a reinforcement supplier 140 for supplying reinforcement 136 to the weaving tool 132 during use of the apparatus 100, the reinforcement supplier 140 being illustrated as one spool, but there could also be more than one spool or it could be another type of reinforcement supplier than a spool. The reinforcement 136 in figure 1 is in a continuous form. The reinforcement could

e.g. be in any of the types: yarn, thread and/or wire. The reinforcement could e.g. be made of metallic, polymeric, carbon, glass, synthetic and/or other types of materials with the required physical reinforcing properties.

- 5 The reinforcement tool 140 is controlled by a controller (not shown), which could be an integrated part of the apparatus or could be arranged on an associated computer. Furthermore, the apparatus 100 for manufacturing of a reinforced 3D printed structure 110 illustrated in the embodiment in figure 1 is possibly partly or fully automatic. Moreover, the apparatus is possibly partly or fully digitally  
10 controlled.

Figure 2.a schematically shows an example of a design of a weaving tool 132 having a plurality of needles 134 for interweaving the reinforcement 136 with the 3D printed substrate layers 122. The weaving tool is illustrated as being circularly  
15 shaped with the needles radially arranged, and with the plurality of needles being adapted to move back and forth with respect to a central region of the weaving tool to establish the nodes 150. The weaving tool illustrated in figure 2.a comprises a frame 200 to support the tool, the frame having an outer surface 210 and an inner surface 220; the two surfaces are connected e.g. by a plurality of  
20 hinges 230 as illustrated in the figure. Other connection means can be used to directly and/or indirectly connect the inner and outer surfaces. The number of hinges 230 in figure 2.a is corresponding to the number of needles 134 of the weaving tool 132. The illustrated weaving tool has eight needles, but the scope of the invention covers down to one needle and up to an undefined number of  
25 needles. Furthermore, the illustrated weaving tool 132 has two fixation points 240 that allow the weaving tool to be connected to the arrangements means 138. The number of fixation points 240 is not limited to a specific number in the scope of this invention, and the way of connecting the weaving tool 132 and the arrangement means 138 is not limited by the scope of the invention. The scope of  
30 the invention allows the connection to be a direct connection/engagement, but an indirect connection, e.g. through secondary connection means, is also possible. Each of the illustrated needles 134 has a front end comprising a gripping device 250 for gripping the reinforcement and connecting it into nodes e.g. by tying knots in and of the reinforcement 136. The gripping device 250 is in figure 2.a

illustrated as having a spherical shape. The gripping device 250 could be in any suitable form, e.g. a hook, a tweezer, or a clamp.

Figure 2.b schematically shows another example of a design of a weaving tool  
5 132. In this embodiment, the weaving tool 132 has three needles 134 which are arranged in a triangular configuration. The needles are shown as being arranged in a frame 200 comprising two linear profiles having two needles 134 and two hinges 230 arranged in one of the profiles and one needle 134 and one hinge 230 arranged in the other profile. However, other configurations providing the same  
10 possible overall movement patterns for gripping devices 250 would also be covered by the scope of protection. Apart from the overall geometry, the functioning of the components of figures 2.a and 2.b are the same, and the above description therefore also applies to figure 2.b.

15 Figure 3 schematically shows another embodiment of the invention, wherein the weaving tool 132 is suspended from a robotic arm 300 arranged over the substrate layer 122 being reinforced. Thus, such a robotic arm 300, possibly in combination with a guide along which it is movable, forms the arrangement means. In this embodiment, the weaving tool is illustrated as comprising three  
20 curved needles 134 for interweaving the reinforcement 136 while the positioning and movement of the weaving tool is controlled via the robotic arm 300.

Figures 4, 5, 6 and 7 illustrate some preferred weaving sequences 410, 420, 510, 520, 610, 620, 710, 720 for interweaving reinforcement with 3D printed substrate  
25 layers 122 as the substrate layers are being printed. The method used for the interweaving comprises at least the steps of:

- printing substrate layers 122,
- supplying reinforcement 136,
- interweaving the reinforcement 136 with the printed substrate layers  
30 122 to create a reinforcement grid around, and optionally in between, the printed substrate layers 122 by the steps:
  - arranging the reinforcement 136 around, and optionally in between, the printed substrate layers 133, and
  - connecting the reinforcement 136 at nodes 150,

wherein the steps are being repeated and wherein the steps of arranging and connecting the reinforcement 136 around, and optionally in between, the printed substrate layers 122 are synchronized with the substrate printing process.

The method is partly or, preferably, fully automatic and the method is typically a  
5 digitally controlled process.

Figure 4 shows a weaving sequence 410, 420 resulting in the reinforcement 136 being arranged with the 3D printed layer 122 in an orthogonal manner.

10 Figure 5 shows a weaving sequence 510, 520 resulting in the reinforcement 136 being arranged with the 3D printed layer 122 in a uni-directional diagonal manner.

Figure 6 shows an alternative weaving sequence 610, 620 resulting in the  
15 reinforcement 136 being arranged with the 3D printed layer 122 in a uni-directional diagonal manner.

Figure 7 shows a weaving sequence 710, 720 resulting in the reinforcement 136 being arranged with the 3D printed layer 122 in a multi-directional diagonal  
20 manner.

Figure 8 shows one example of possible steps of connecting reinforcement into a node 150 using a weaving tool 132 with a plurality of needles 134. The 14 steps illustrated in this figure show how the needles 134 are adapted to move back and  
25 forth with respect to a central region of the weaving tool 132 to establish the nodes 150 by gripping the reinforcement 136 in an exact predetermined sequence. This illustrated sequence of 14 steps is only one out of many possible sequences of how to connect the reinforcement into a node with a weaving tool of the invention.

30

Figure 9 schematically shows an example of how a node 150 can be formed in eight steps. For clarity, the figure shows only the different movements applied to the reinforcement 136. The movements are applied by needles 134 that are left out in this figure. The corresponding movements of the needles are typically  
35 controlled according to a weaving plan as described above. The bracket in the last

step indicates where to apply a pulling force in order to tie the reinforcement into a node in the form of a knot.

Figure 10 schematically shows an alternative example of forming a node 150 to the one in figure 9. As explained in relation to figure 9, the bracket in the last step indicates where to apply a pulling force.

Figure 11 schematically shows another alternative example of forming a node 150.

10

Figure 12 schematically shows yet another alternative example of forming a node. In this embodiment, smaller sections of reinforcement are used for the connection of continuous reinforcement at the nodes. This might be an advantageous solution for cases where steel wire will be used as the reinforcement.

15

Figures 13, 14 and 15 are illustrating configurations of simply supported beams (BEA) and walls (WAL) with line load (LOA), FEM stress results (FEM), resulting internal force analysis (RES), corresponding reinforcement layouts (LAY) and sketches (SKE) of the resulting reinforced printed substrate element 110.

20 Figures 13 and 14 show a beam (BEA) wherein forces are being applied from above as line load (LOA). Figure 13 shows digital construction of a beam (BEA) in flexure. The beam being relatively long and relatively low and line load (LOA) is applied from above of the beam. Figure 14 shows digital construction of a deep beam (BEA). The beam being relatively slender and relatively high and line load (LOA) is applied from above of the beam. Figure 15 shows digital construction of a wall (WAL) with out-of-plane loading. The wall being applied forces from one side of the wall (WAL). By what external forces and from what direction the printed structure is influenced is not limited to the two examples: from above and from one side. Within the scope of the invention, the application of forces can be in any  
25 direction and anywhere on the printed structure, and it can be any kind of forces  
30 e.g. tension, compression, shear, or flexure.

It is thereby seen from the illustrations in figures 13, 14 and 15 that the dimensions of the structure 110 to be 3D printed and the expected forces to be  
35 applied to the printed structure require very different and varying reinforcement

136 layouts due to the varying force analysis and varying stresses calculated by FEM analysis. Each type of structure combined with each type of expected applied loads results in a unique internal force analysis and unique internal stresses. This therefore causes the need for a method of being able to globally and locally  
5 reinforce every unique structure in a unique manner, which is exactly what the invention allows.

The resulting force analysis can be used for providing a predetermined weaving-plan based on the analysis, so that the method of reinforcing printed substrate  
10 layers 122 comprises the step of receiving requirements of the type and/or direction of the reinforcement 136 from such a predetermined weaving-plan. The weaving-plan is thereby based on a force analysis including expected forces in the reinforced structure under service, the mechanical properties of the reinforcement material, and/or ultimate loading conditions.

15

Figure 16 shows a load-deformation response of tested prototypes corresponding to one embodiment of the invention. This figure illustrates two examples of a result of interweaving reinforcement into 3D printed layers 122. As seen in the figure, the amount of load applied to the structures and the possible deformation  
20 of the structures before the structures collapse is a lot higher than the result of the un-reinforced test structure. Figure 16 thereby illustrates a proved advantageous effect of the invention.

Although the present invention has been described in connection with the  
25 specified embodiments, it should not be construed as being in any way limited to the presented examples. The scope of the present invention is set out by the accompanying claim set. In the context of the claims, the terms "comprising" or "comprises" do not exclude other possible elements or steps. Furthermore, the mentioning of references such as "a" or "an" etc. should not be construed as  
30 excluding a plurality. The use of reference signs in the claims with respect to elements indicated in the figures shall also not be construed as limiting the scope of the invention. Furthermore, individual features mentioned in different claims, may possibly be advantageously combined, and the mentioning of these features in different claims does not exclude that a combination of features is not possible  
35 and advantageous.

## CLAIMS

1. A method of reinforcing a 3D printed structure (110) by interweaving reinforcement (136) with 3D printed substrate layers (122) as the substrate layers are being printed or as segments of the substrate are being placed, the method comprising the steps of:
- printing substrate layers (122),
  - supplying reinforcement (136),
  - interweaving the reinforcement with the printed substrate layers to create a reinforcement grid around, and optionally in between, the printed substrate layers by the steps:
    - arranging the reinforcement (136) around, and optionally in between, the printed substrate layers (122), and
    - connecting the reinforcement (136) at nodes (150).
2. The method according to claim 1, wherein the step of arranging the reinforcement (136) is around each layer.
3. The method according to any of the preceding claims, wherein the steps of arranging and connecting the reinforcement (136) around, and optionally in between, the printed substrate layers (122) are synchronized with the substrate printing process.
4. The method according to any of the preceding claims, wherein the printed substrate layers (122) are made of mineral and cementitious composite materials, polymer, metal and/or any moldable material.
5. The method according to any of the preceding claims, wherein the reinforcement (136) is made of metallic, carbon, glass, basalt, natural and/or synthetic including polymeric material with the required physical reinforcing properties.
6. The method according to any of the preceding claims, wherein the type and/or direction of arrangement of the reinforcement (136) is adjustable and wherein the

type and/or direction is predetermined based on the expected internal forces in the reinforced structure under service and ultimate loading conditions.

7. The method according to any of the preceding claims, wherein the method  
5 comprises the step of receiving requirements of the type and/or direction of the reinforcement (136) from a predetermined weaving-plan based on structural analysis.

8. The method according to any of the preceding claims, wherein the  
10 reinforcement (136) is in a continuous form, preferably being any of the types: thread, yarn and/or wire.

9. The method according to any of the preceding claims, wherein the interwoven reinforcement (136) is the only reinforcement so that no further anchoring  
15 elements are needed to keep the reinforcement in place.

10. An apparatus (100) for manufacturing of a reinforced 3D printed structure (110), the apparatus comprising:

- a 3D printer (120) for printing substrate in layers (122),
- 20 - a reinforcement tool (130) for reinforcing the 3D printed substrate layers (122), the reinforcement tool comprising:
  - at least one weaving tool (132) comprising at least one needle (134) for interweaving reinforcement (136),
  - at least one arrangement means (138) for moving the  
25 reinforcement tool (130) to the position where the reinforcement (136) is to be interwoven with the printed layers (122),
- a reinforcement supplier (140) for supplying reinforcement (136) to the weaving tool (132) during use of the apparatus (100),
- a controller for controlling the reinforcement tool (130), and  
30

wherein the reinforcement tool (130) is adapted to interweave the reinforcement (136) with the 3D printed substrate layers (122) as the substrate layers are being printed or as segments of the substrate are being placed, by:

- arranging the reinforcement (136) around, and optionally in between,  
35 the printed layers (122), and

- connecting the reinforcement at nodes (150), the nodes being formed by the at least one needle (134) of the weaving tool (132).

11. The apparatus according to claim 10, wherein the arrangement means (138) is bridging across the printed substrate layers (122) enabling the weaving tool (132) to move across the printed substrate layers via the arrangement means.

12. The apparatus according to claim 10 or 11, wherein the arrangement means (138) is mounted to at least one rail making it movable along the printed layers (122).

13. The apparatus according to any of claims 10-12, wherein the weaving tool (132) is substantially circularly shaped with a plurality of needles (134) radially arranged, and wherein the needles are adapted to move back and forth with respect to a central region of the weaving tool (132) to establish the nodes (150).

14. The apparatus according to any of claims 10-12, wherein the weaving tool (132) has three needles (134) which are arranged in a triangular configuration, and wherein the needles are adapted to move back and forth with respect to a central region of the weaving tool (132) and/or rotate around it to establish the nodes (150).

15. The apparatus according to any of claims 10-14, wherein each of the at least one needle (134) has a front end comprising a gripping device (250) for gripping the reinforcement and connect it into nodes (150).

16. The apparatus according to any of claims 10-15, wherein the weaving tool (132) is movable and rotatable in any direction.

17. The apparatus according to any of claims 10-16, wherein the type and/or direction of arrangement of the reinforcement (136) is adjustable, and wherein the type and/or direction is predetermined based on the expected internal forces in the structure under service and ultimate loading.

18. A reinforced 3D printed structure (110) comprising:
- 3D printed substrate layers (122), and
  - reinforcement (136) interwoven with the printed substrate layers,
- wherein the reinforcement forms a reinforcement grid around, and optionally in
- 5 between, the printed substrate layers, and
- wherein the reinforcement grid is formed by the reinforcement being connected at nodes (150).

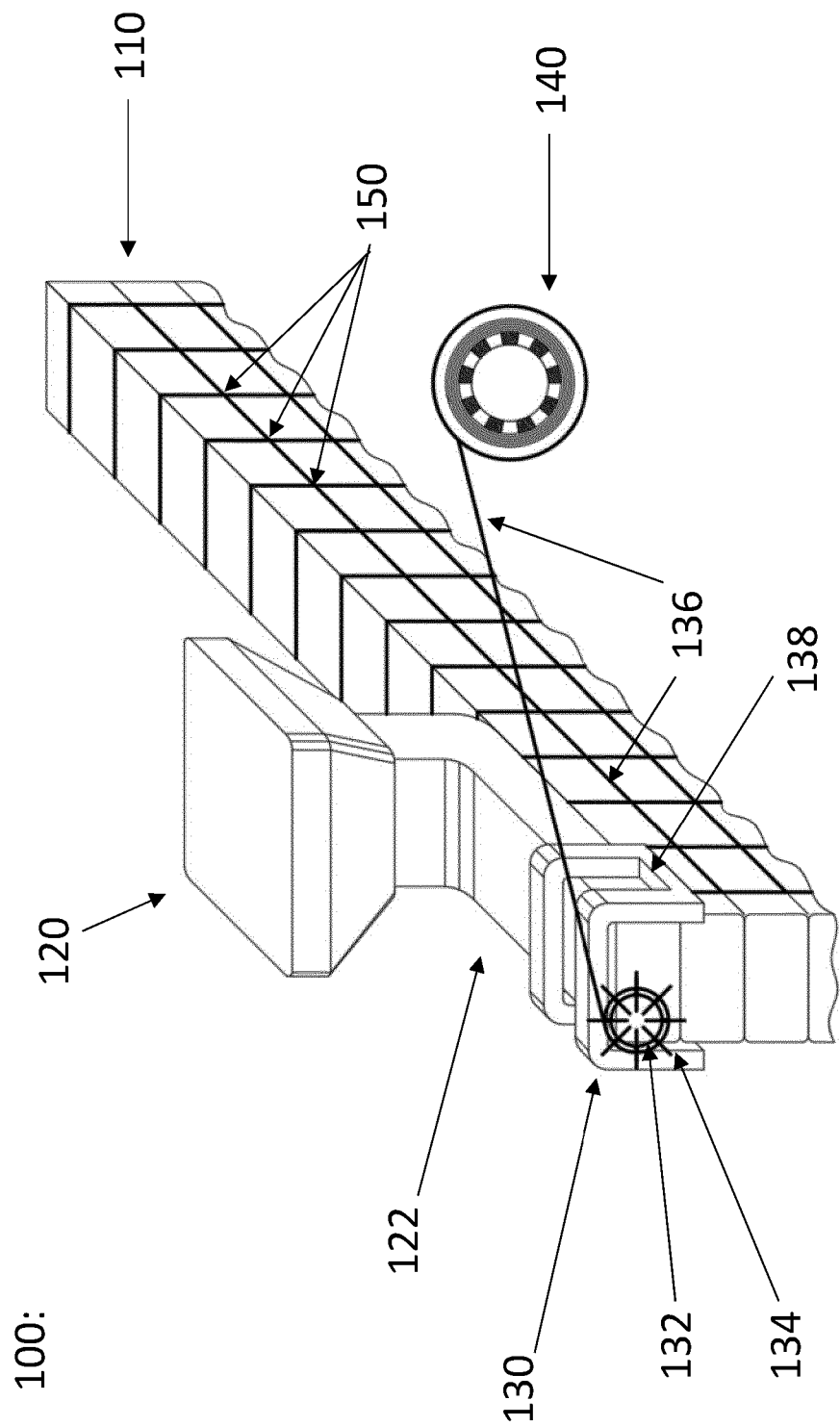


Fig. 1

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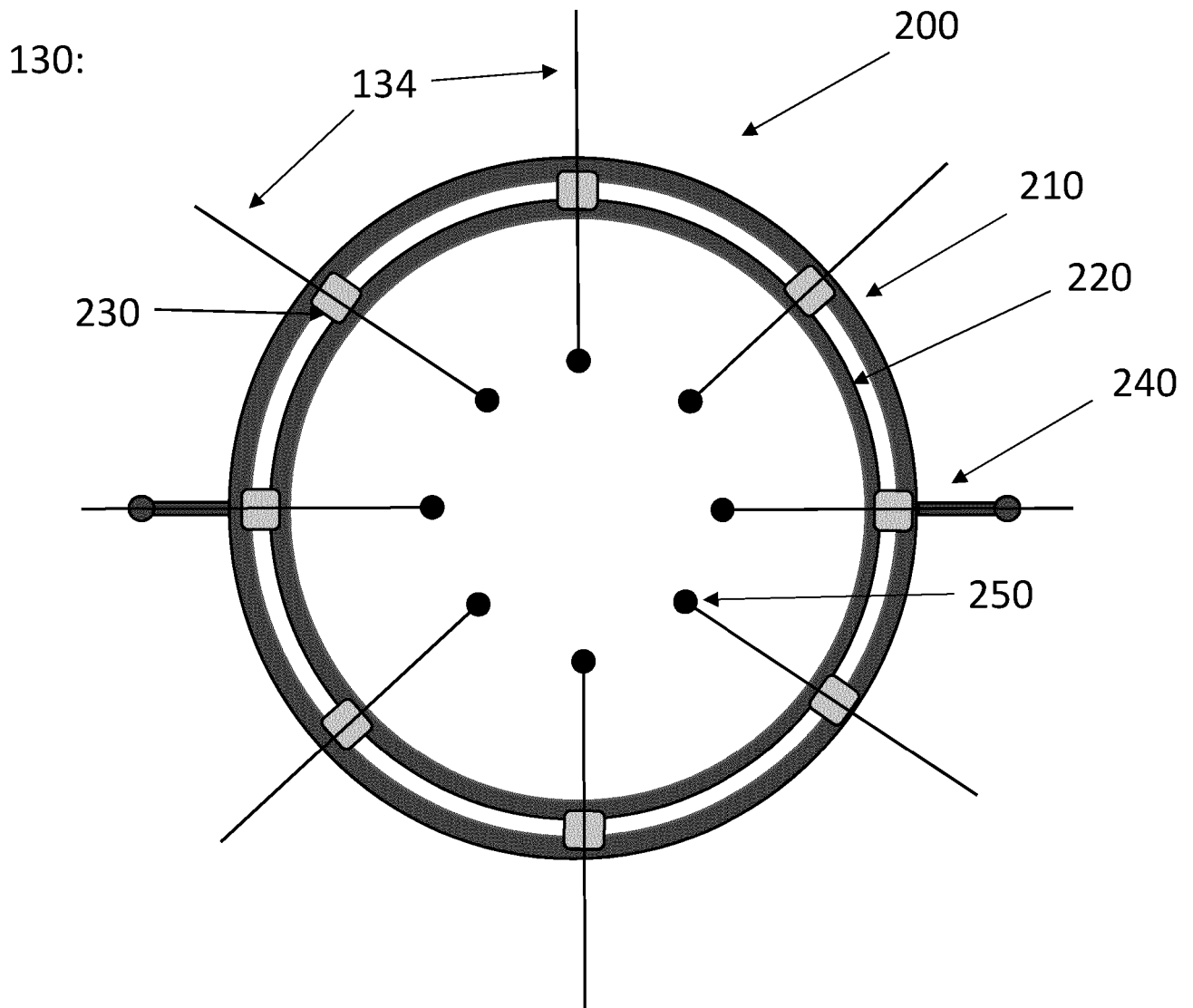


Fig. 2.a

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132:

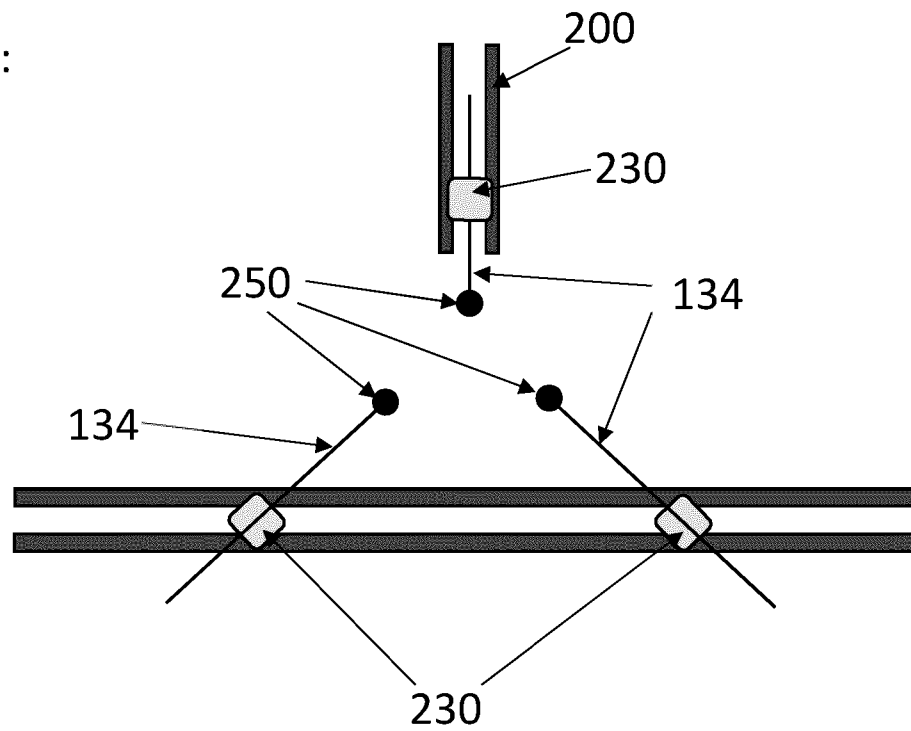


Fig. 2.b

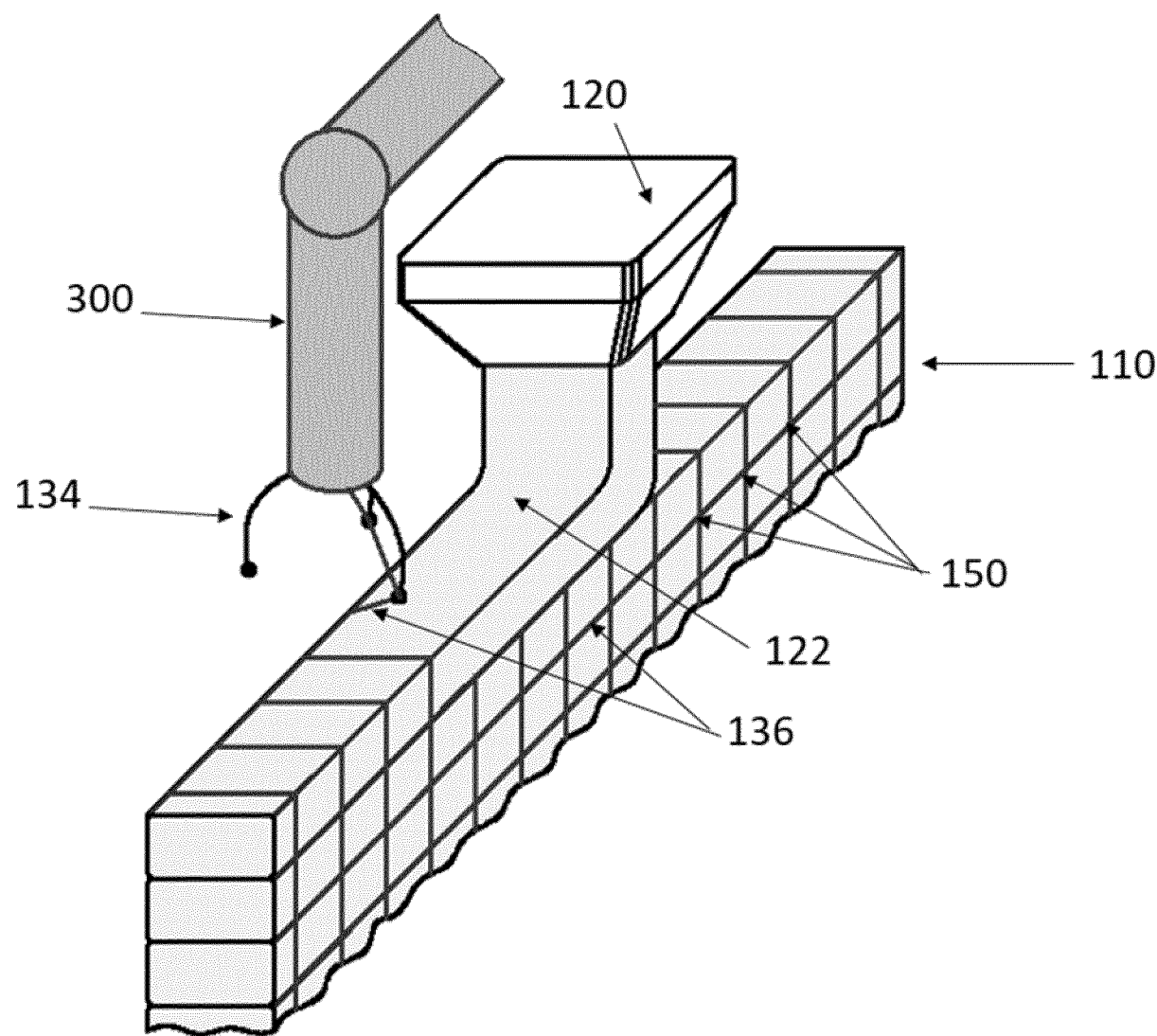


Fig. 3

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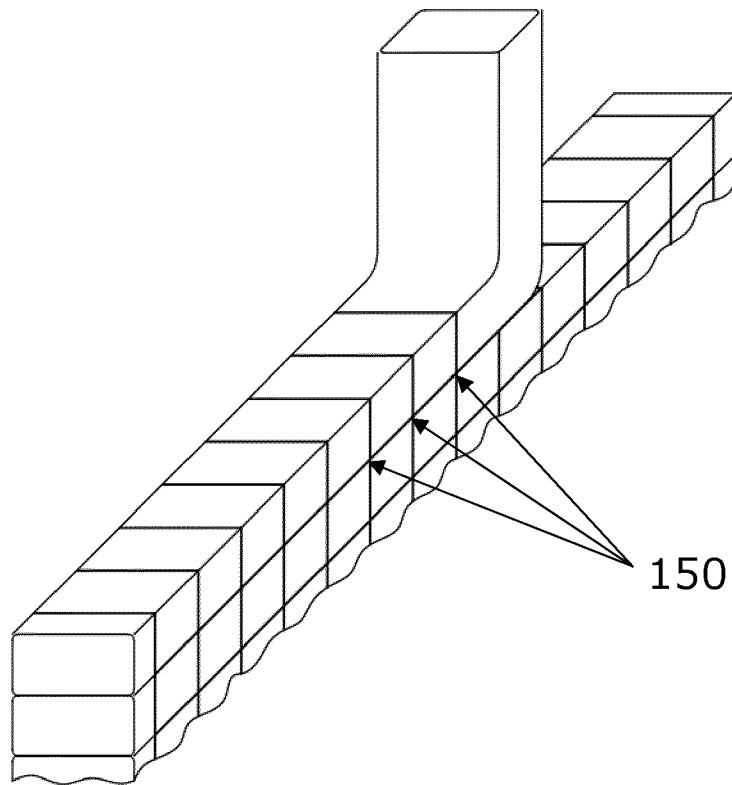


Fig. 4

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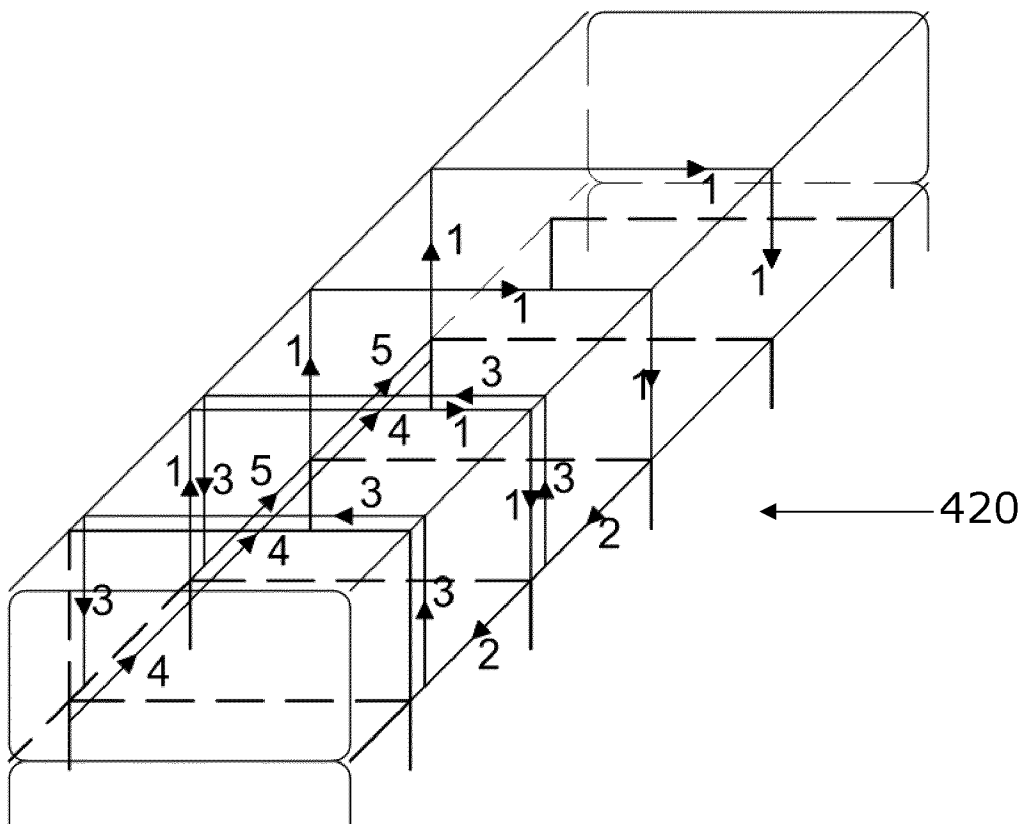
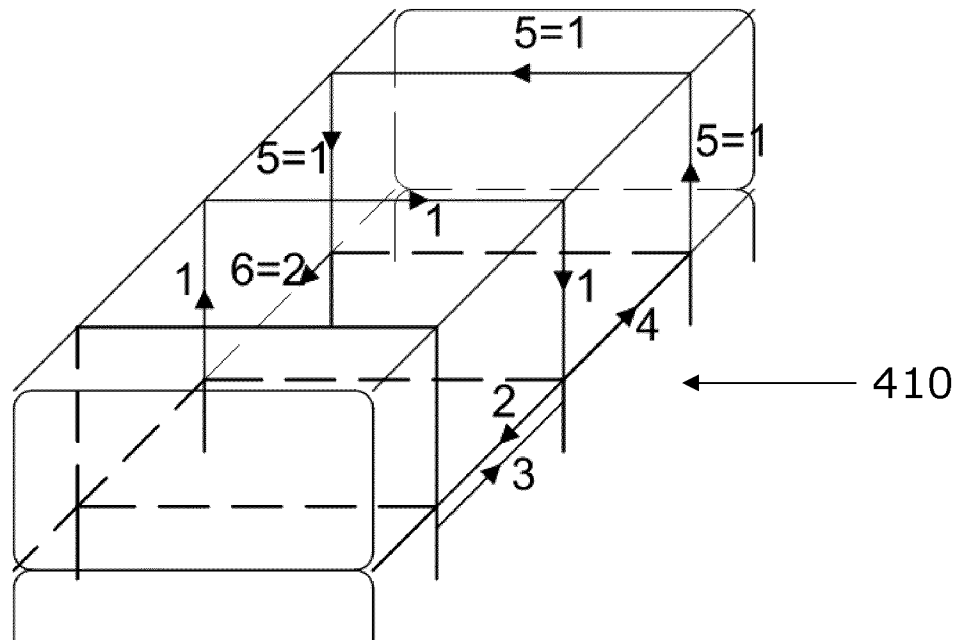


Fig. 4, cont.

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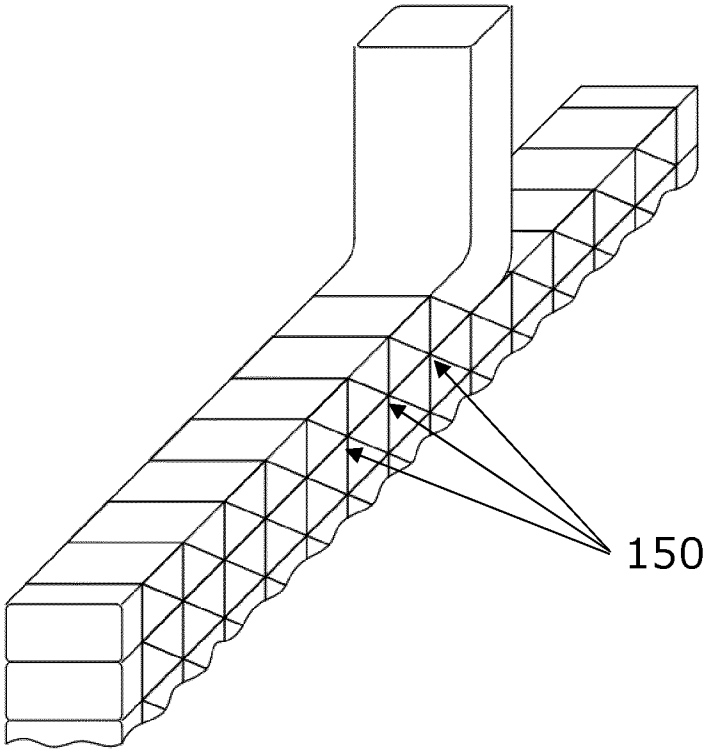


Fig. 5

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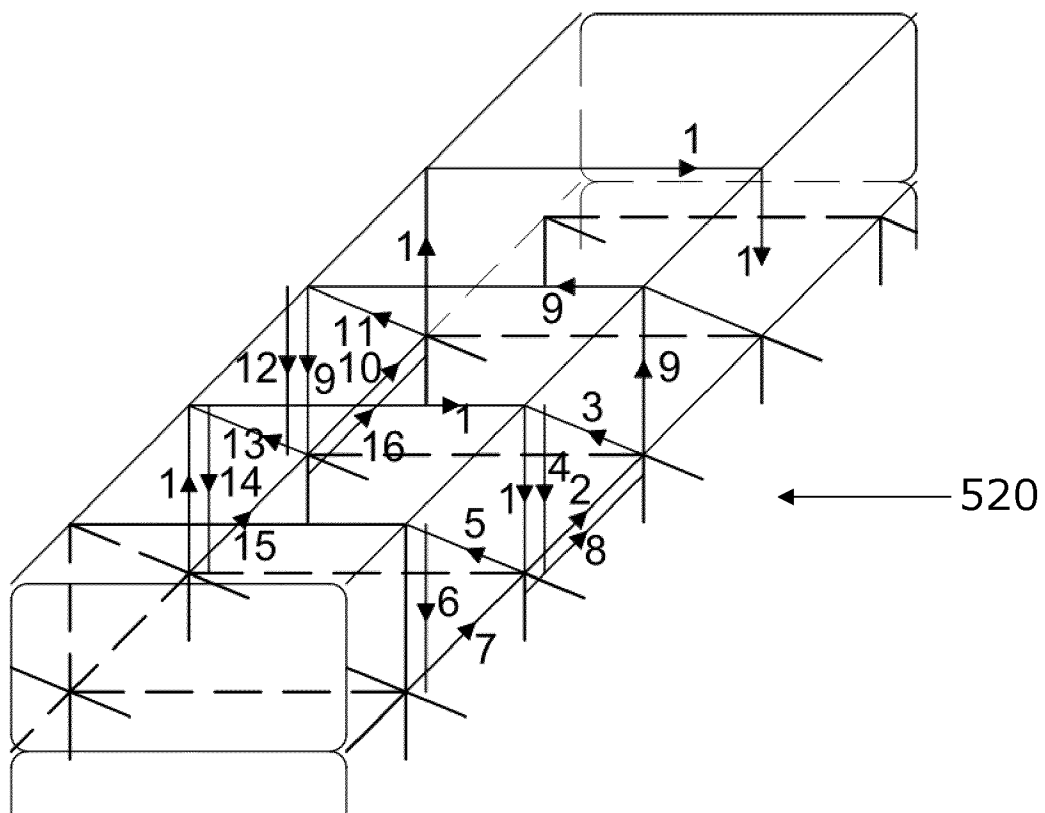
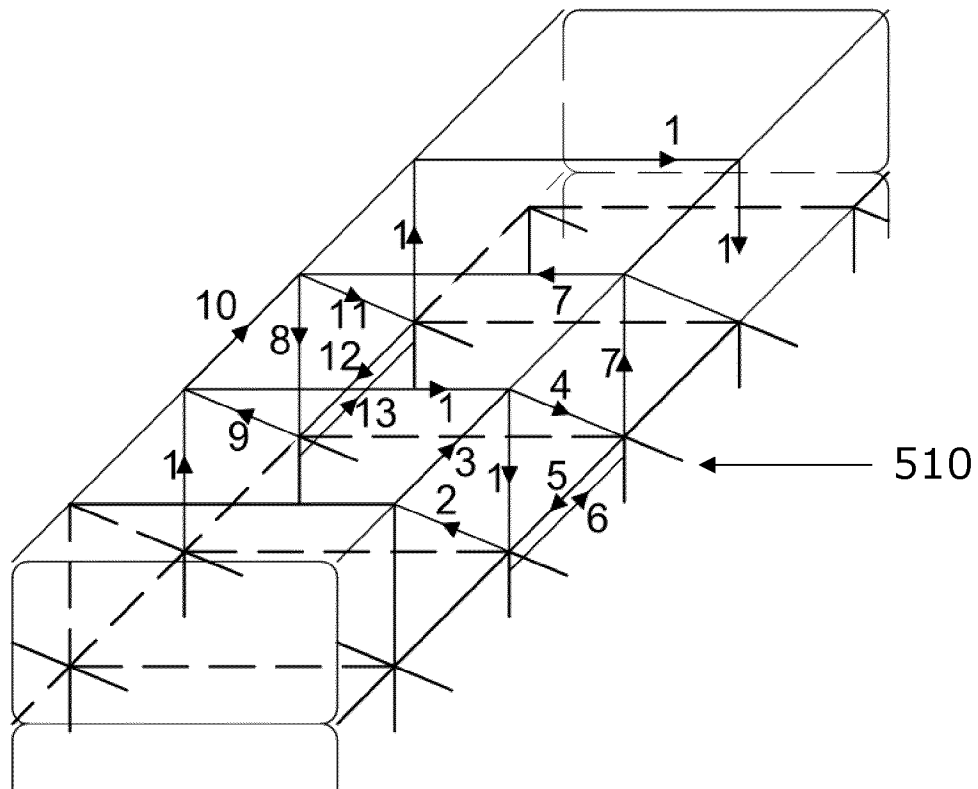


Fig. 5, cont.

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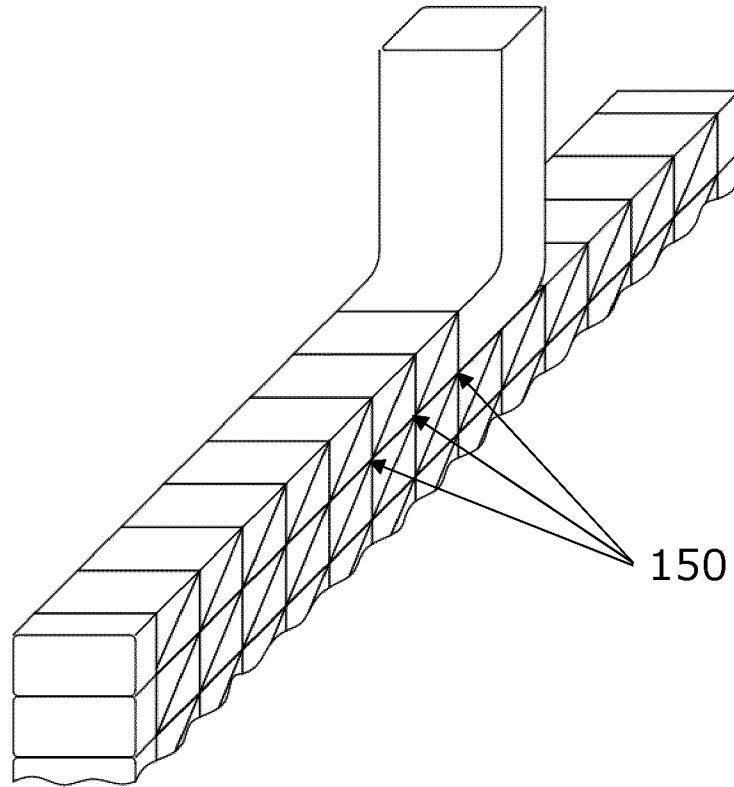


Fig. 6

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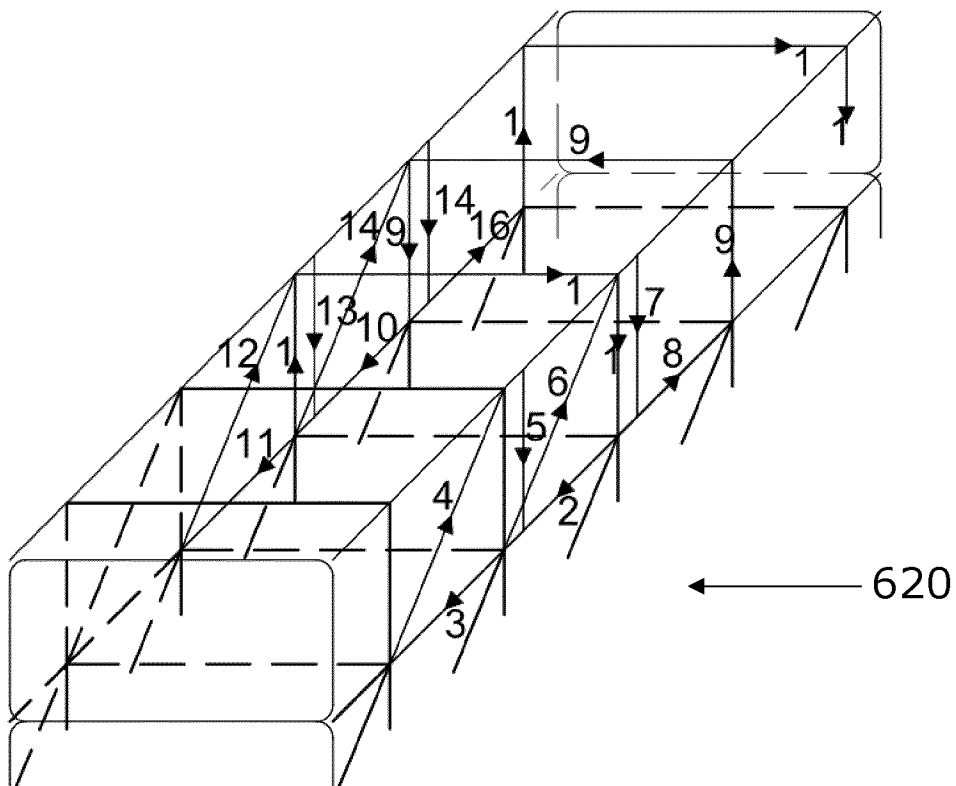
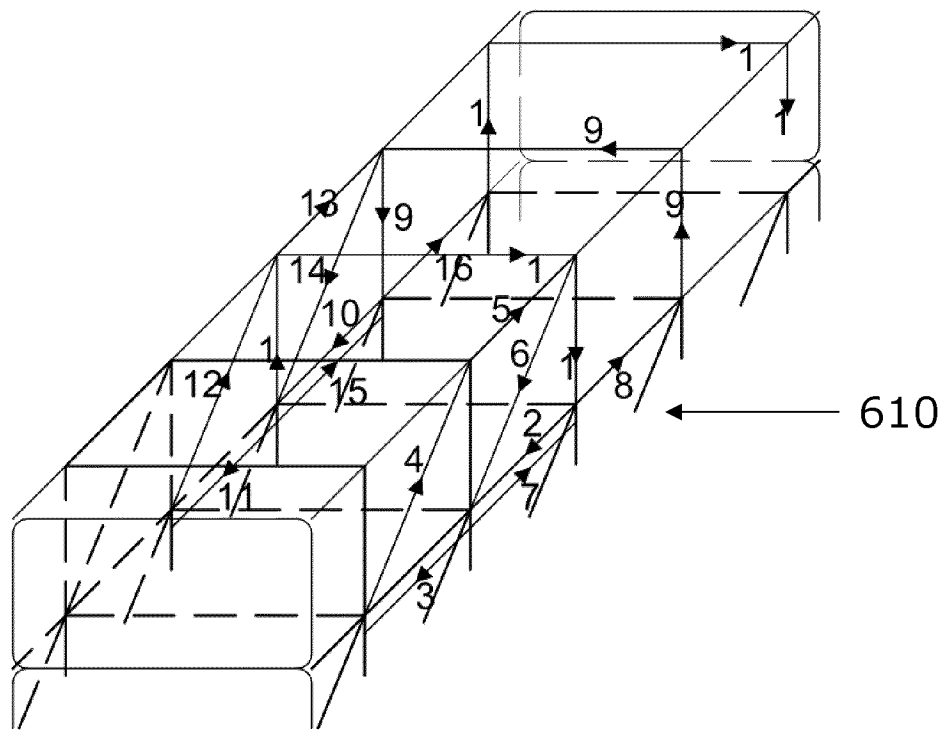


Fig. 6, cont.

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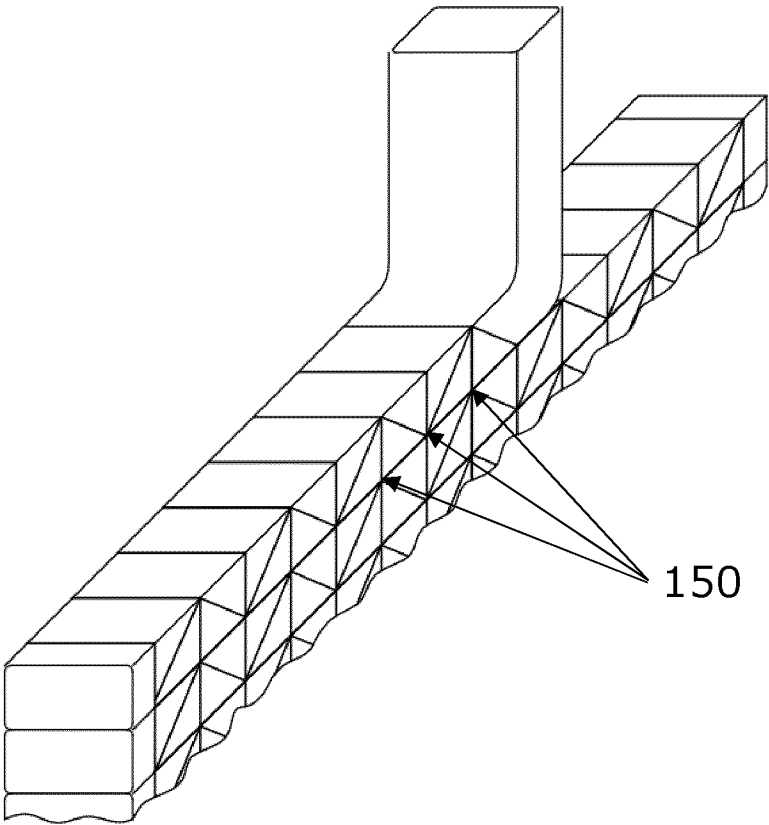


Fig. 7

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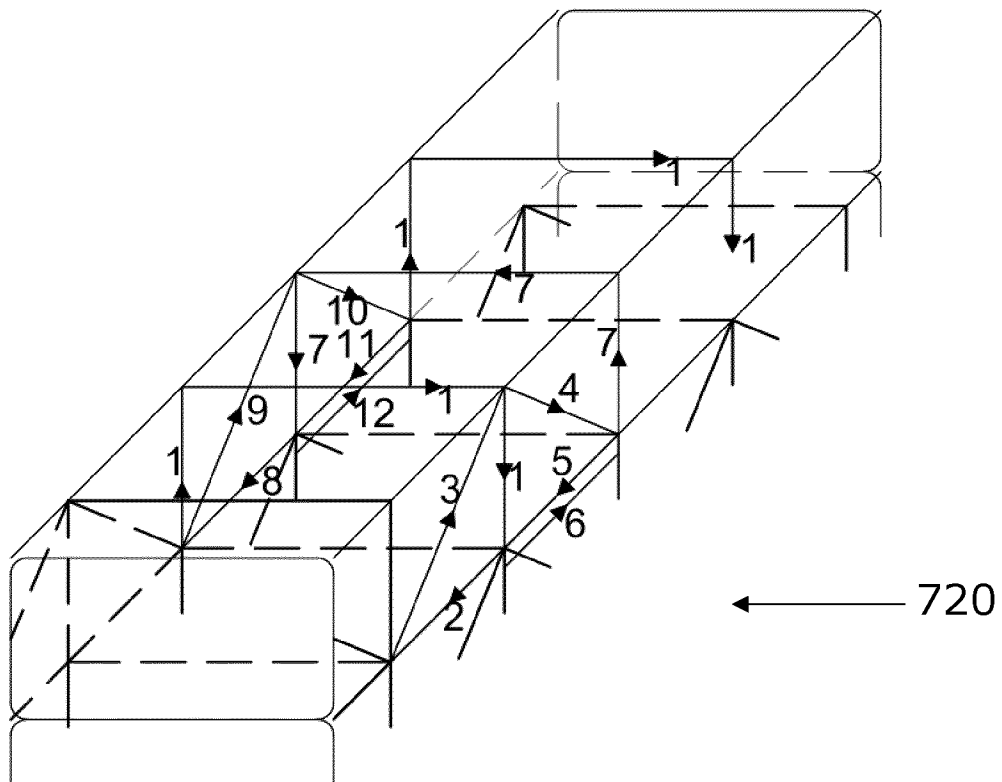
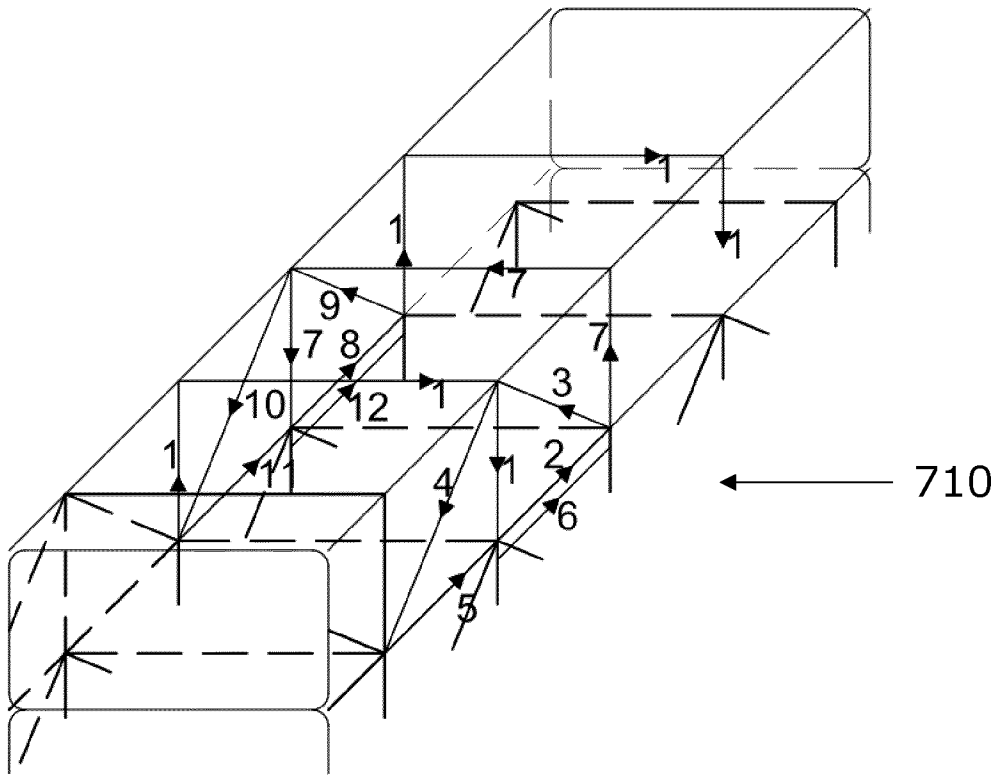


Fig. 7, cont.

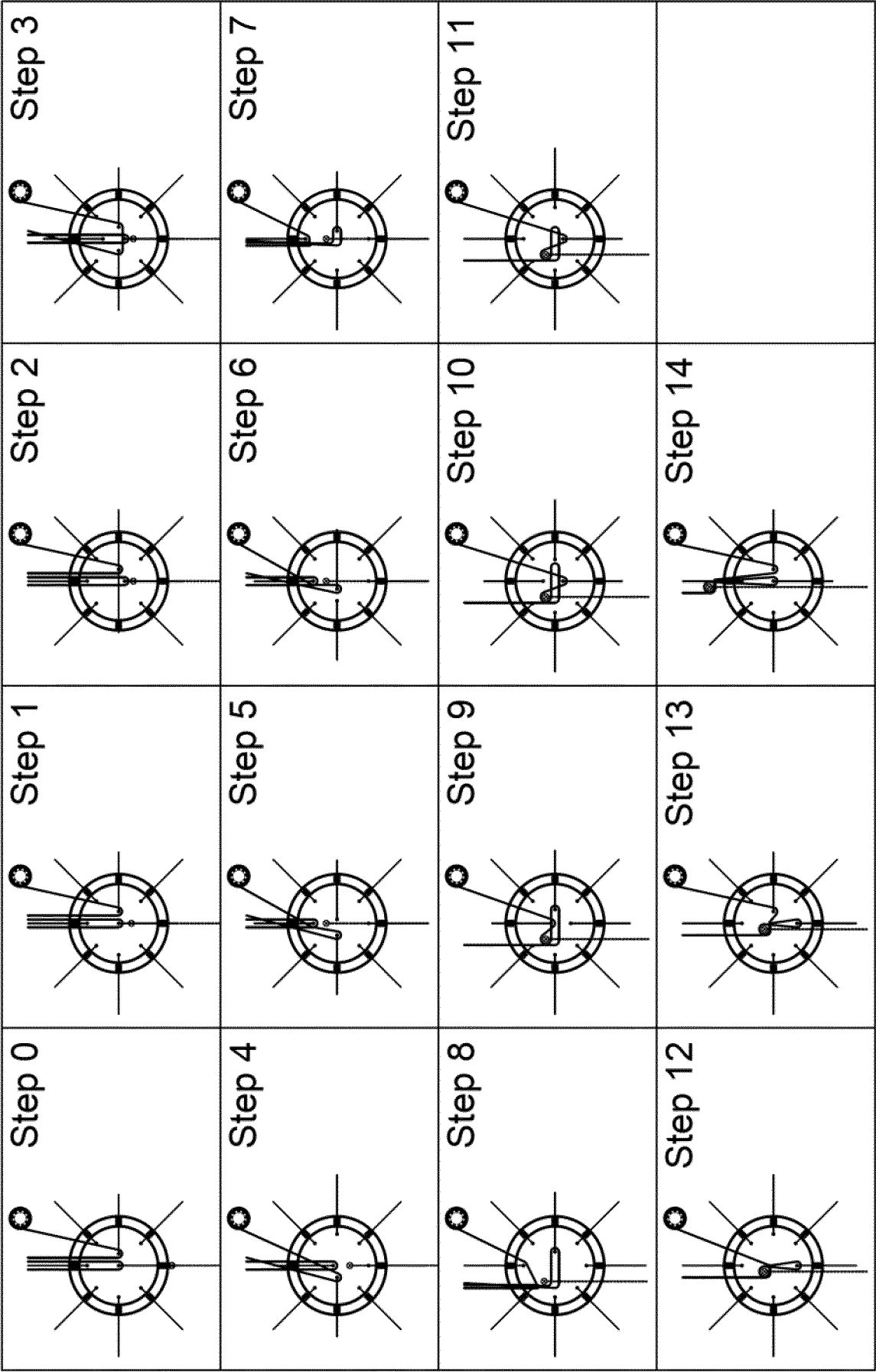


Fig. 8

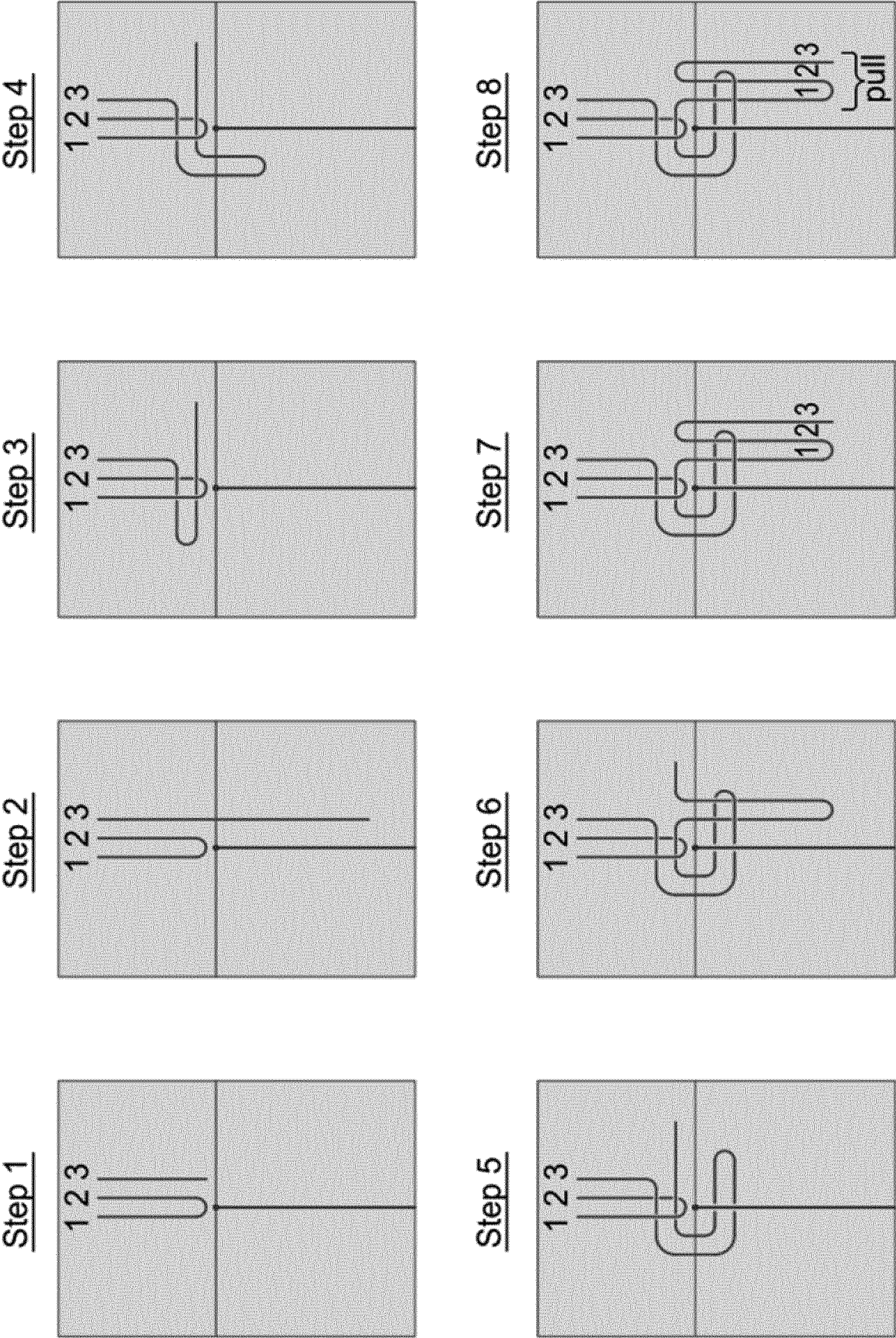
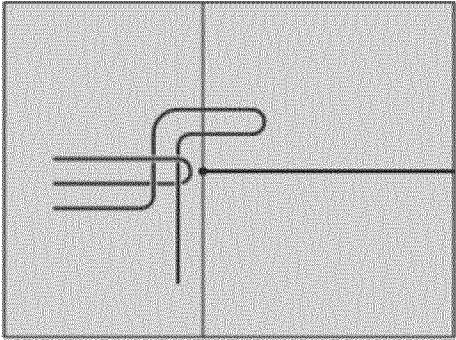
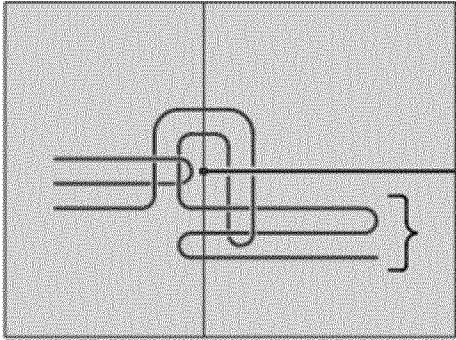


Fig. 9

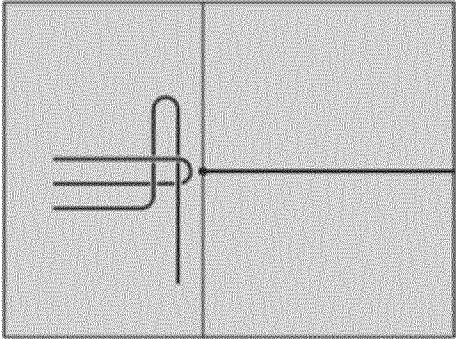
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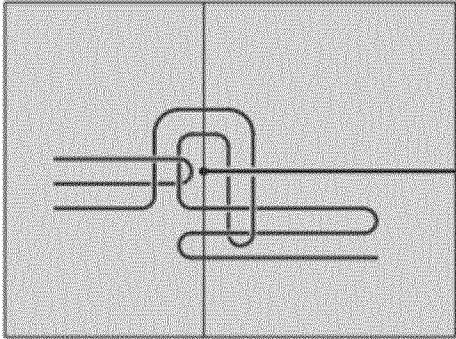
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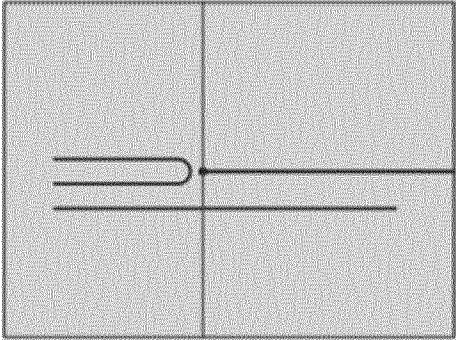
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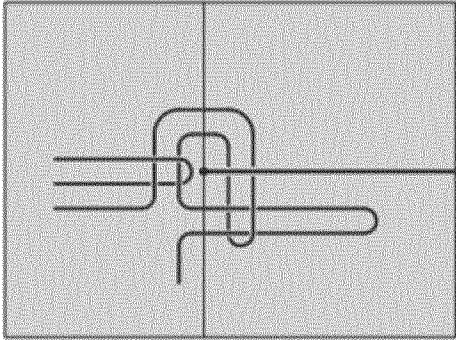
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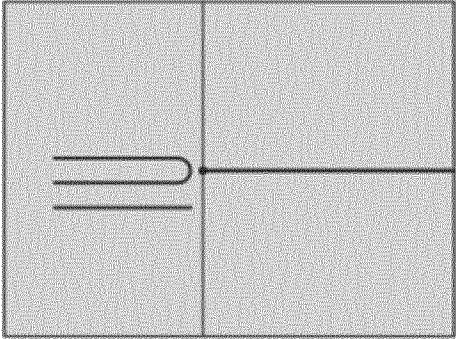
Step 2



Step 6



Step 1



Step 5

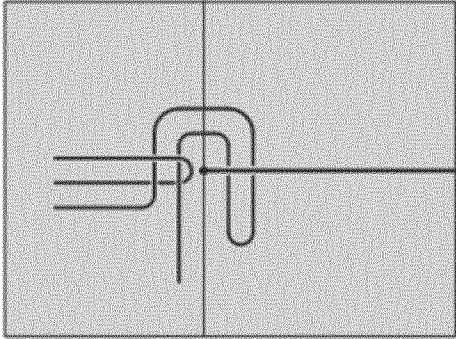


Fig. 10

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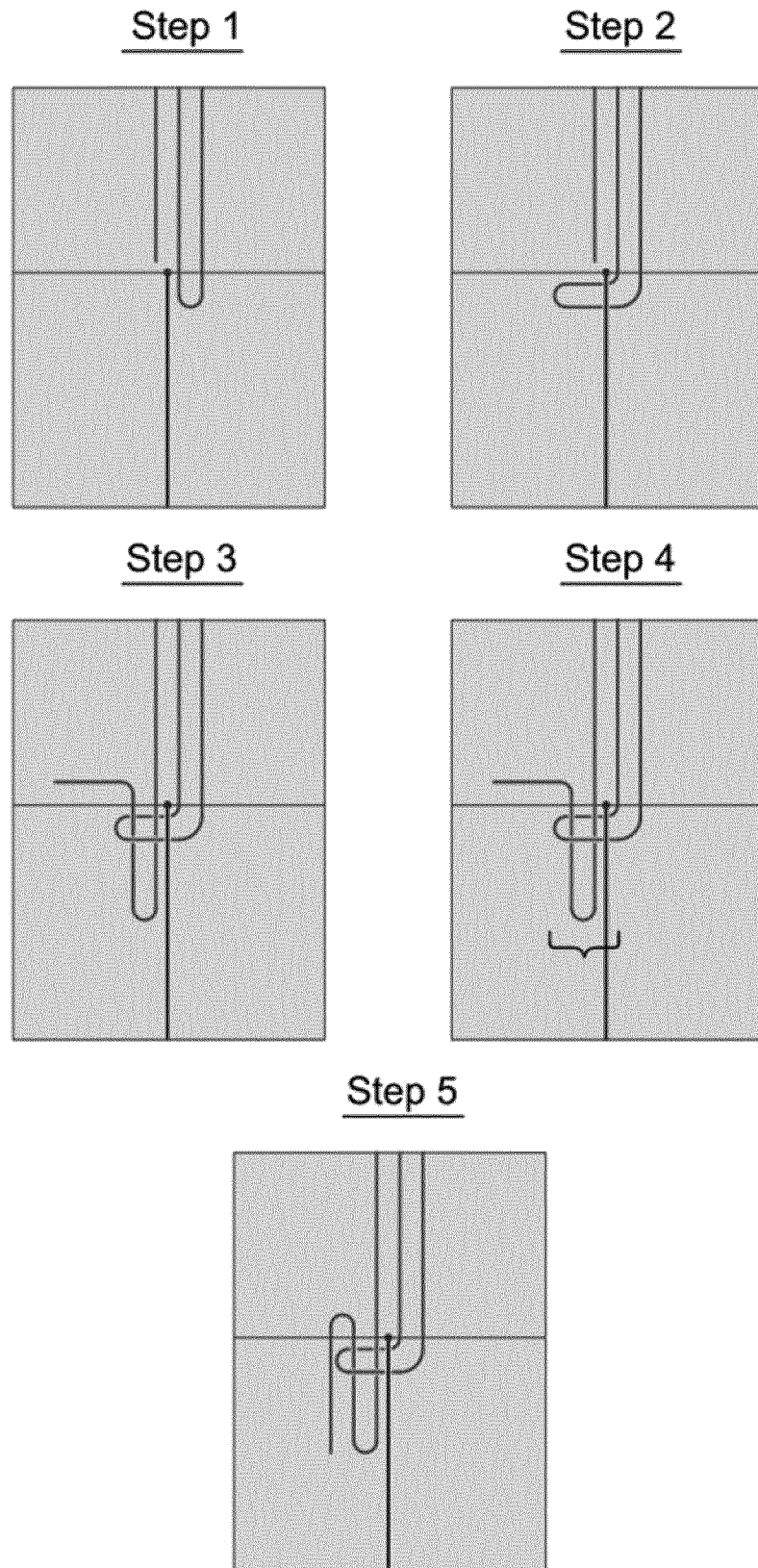
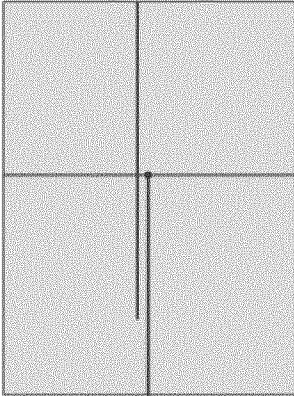


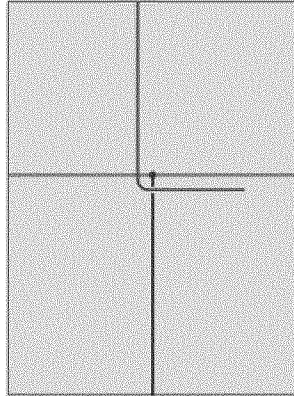
Fig. 11

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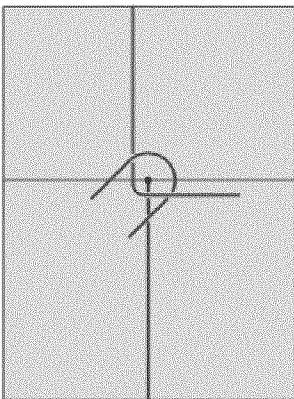
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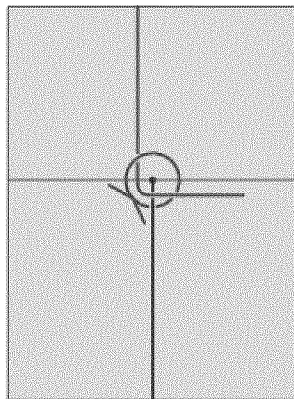
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Step 3



Step 4



Step 5

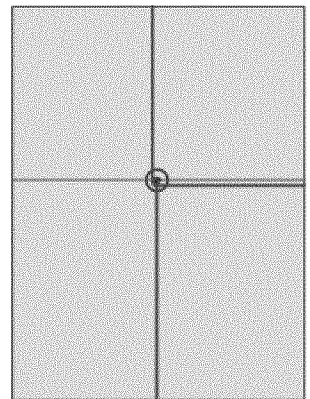


Fig. 12

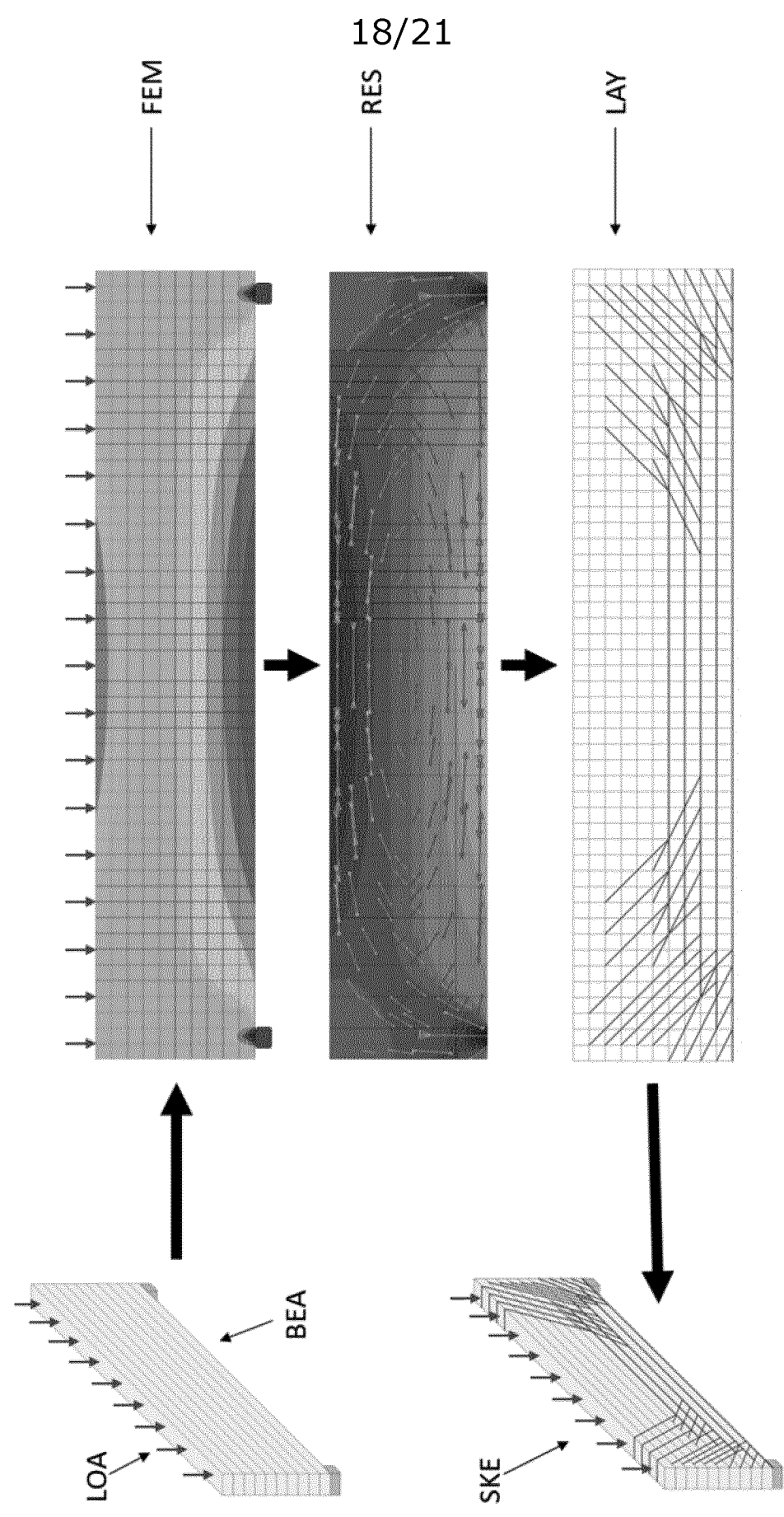


Fig. 13

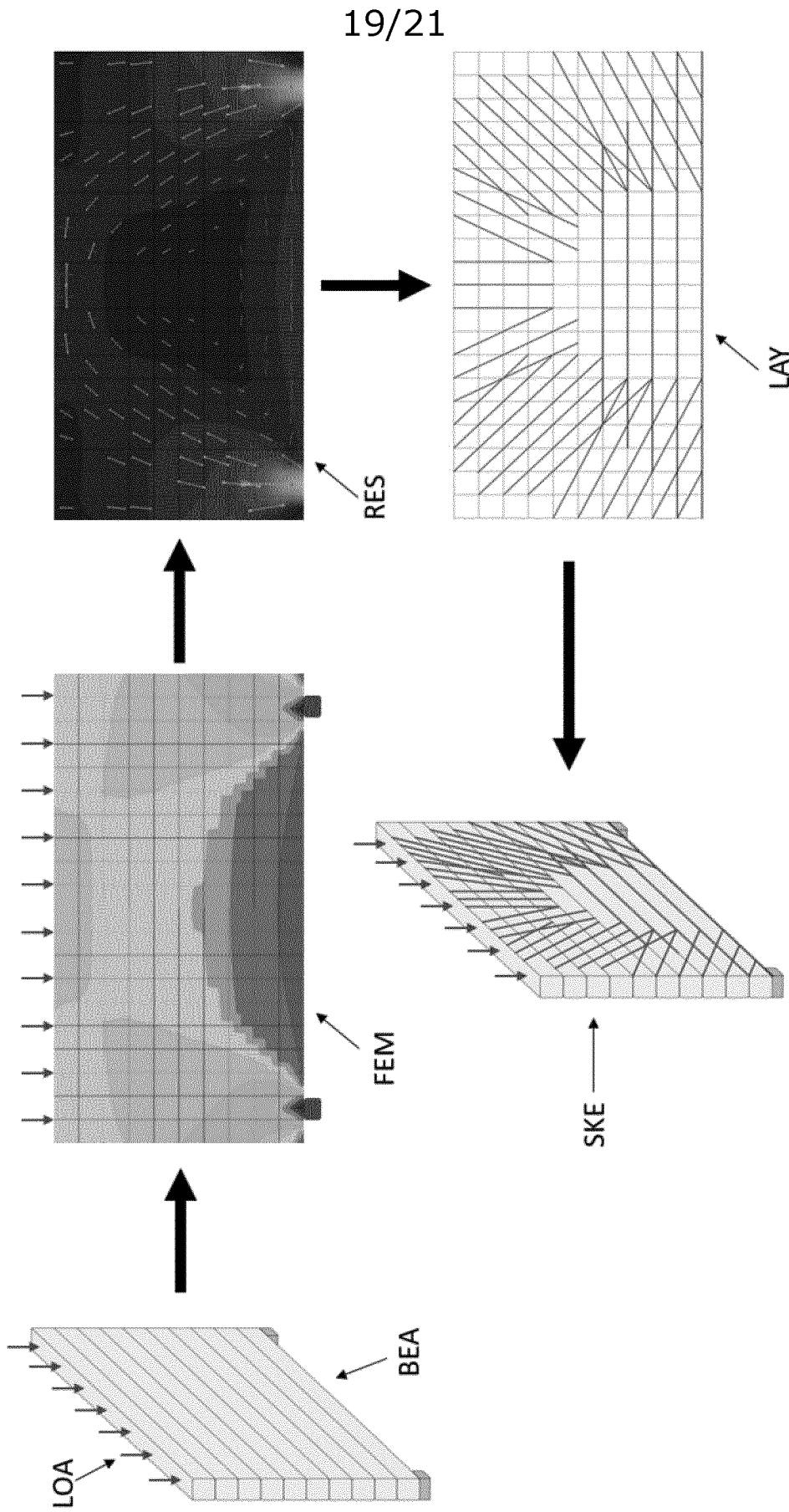


Fig. 14

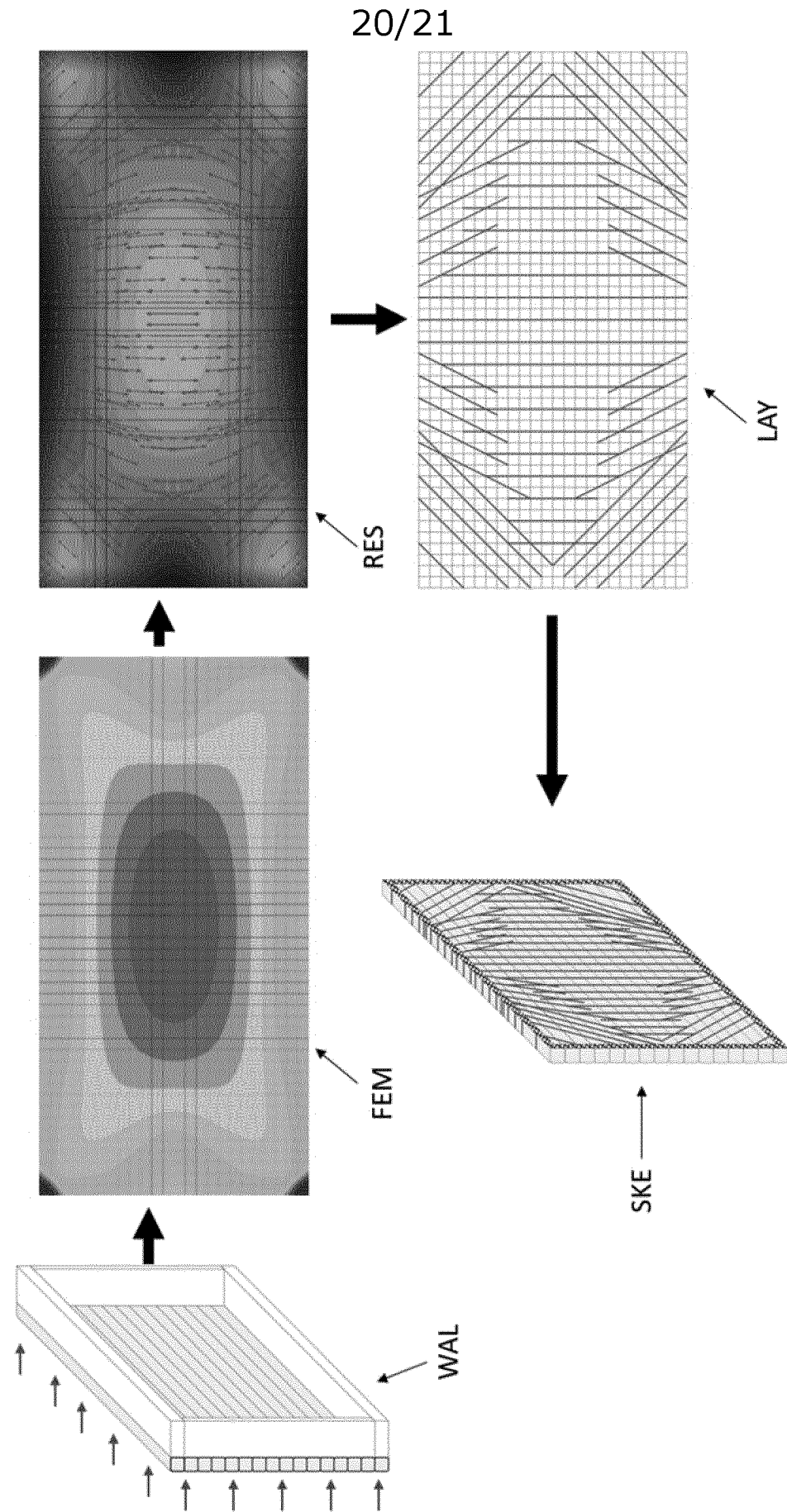


Fig. 15

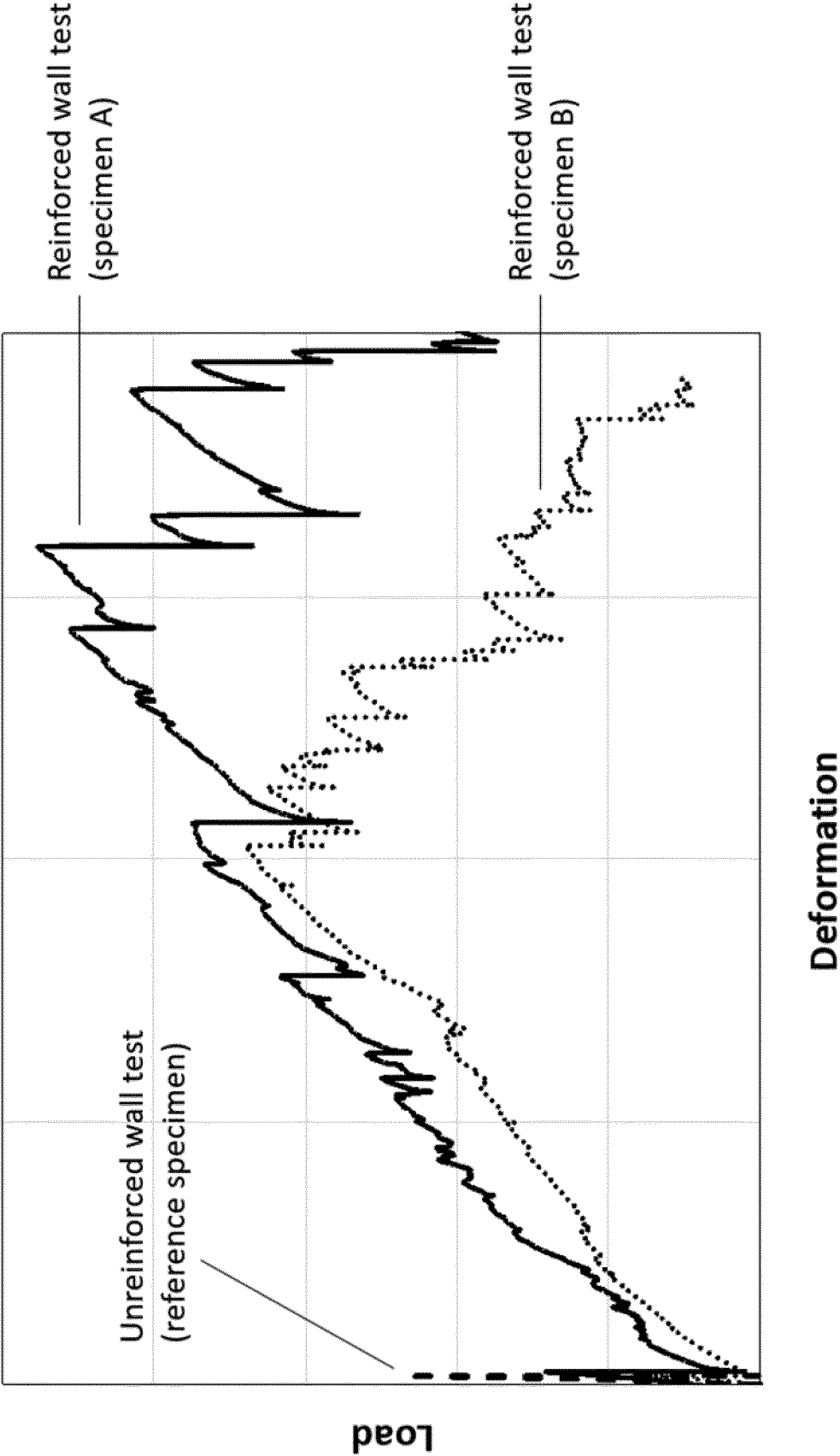


Fig. 16

# INTERNATIONAL SEARCH REPORT

International application No  
PCT/EP2021/063122

<b>A. CLASSIFICATION OF SUBJECT MATTER</b> INV. B28B1/00 B28B23/00 B28B23/02 B28B23/16 B29C64/106 B29C70/24 B29C70/38 B33Y10/00 D04G5/00 ADD. According to International Patent Classification (IPC) or to both national classification and IPC																							
<b>B. FIELDS SEARCHED</b> Minimum documentation searched (classification system followed by classification symbols) B28B B29C B33Y E04C D04G D03D Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched Electronic data base consulted during the international search (name of data base and, where practicable, search terms used) EPO-Internal																							
<b>C. DOCUMENTS CONSIDERED TO BE RELEVANT</b> <table border="1" style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th style="width: 10%;">Category*</th> <th style="width: 70%;">Citation of document, with indication, where appropriate, of the relevant passages</th> <th style="width: 20%;">Relevant to claim No.</th> </tr> </thead> <tbody> <tr> <td style="text-align: center; vertical-align: top;">X</td> <td>CN 108 215 178 A (UNIV XI AN JIAOTONG) 29 June 2018 (2018-06-29)</td> <td style="vertical-align: top;">1-5, 8-12,15, 18</td> </tr> <tr> <td style="text-align: center; vertical-align: top;">Y</td> <td>the whole document</td> <td style="vertical-align: top;">6,7,16, 17</td> </tr> <tr> <td style="text-align: center; vertical-align: top;">A</td> <td style="text-align: center;">-----</td> <td style="vertical-align: top;">13,14</td> </tr> <tr> <td style="text-align: center; vertical-align: top;">X</td> <td>DE 10 2014 019151 A1 (DAIMLER AG [DE]) 23 June 2016 (2016-06-23) paragraphs [0058] - [0060], [0068] figures 1, 2</td> <td style="vertical-align: top;">1-5,8,9, 18</td> </tr> <tr> <td style="text-align: center; vertical-align: top;">Y</td> <td>CN 104 388 848 A (ADVANCED MFT TECH CT CN CAMST) 4 March 2015 (2015-03-04) the whole document</td> <td style="vertical-align: top;">6,7,16, 17</td> </tr> <tr> <td></td> <td style="text-align: center;">----- -/-</td> <td></td> </tr> </tbody> </table>			Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.	X	CN 108 215 178 A (UNIV XI AN JIAOTONG) 29 June 2018 (2018-06-29)	1-5, 8-12,15, 18	Y	the whole document	6,7,16, 17	A	-----	13,14	X	DE 10 2014 019151 A1 (DAIMLER AG [DE]) 23 June 2016 (2016-06-23) paragraphs [0058] - [0060], [0068] figures 1, 2	1-5,8,9, 18	Y	CN 104 388 848 A (ADVANCED MFT TECH CT CN CAMST) 4 March 2015 (2015-03-04) the whole document	6,7,16, 17		----- -/-	
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.																					
X	CN 108 215 178 A (UNIV XI AN JIAOTONG) 29 June 2018 (2018-06-29)	1-5, 8-12,15, 18																					
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<div style="display: flex;"> <div style="flex: 1;"> <p>* Special categories of cited documents :</p> <p>"A" document defining the general state of the art which is not considered to be of particular relevance</p> <p>"E" earlier application or patent but published on or after the international filing date</p> <p>"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)</p> <p>"O" document referring to an oral disclosure, use, exhibition or other means</p> <p>"P" document published prior to the international filing date but later than the priority date claimed</p> </div> <div style="flex: 1;"> <p>"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention</p> <p>"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone</p> <p>"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art</p> <p>"&amp;" document member of the same patent family</p> </div> </div>																							
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## INTERNATIONAL SEARCH REPORT

International application No  
PCT/EP2021/063122

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	CN 110 774 407 A (UNIV ZHEJIANG) 11 February 2020 (2020-02-11) the whole document -----	1-18
A	US 2020/149269 A1 (CRUMP S SCOTT [US] ET AL) 14 May 2020 (2020-05-14) paragraphs [0032], [0036], [0037] figures 1, 2 -----	1-18
A	CN 106 393 684 A (ZHEJIANG SCI-TECH UNIV) 15 February 2017 (2017-02-15) the whole document -----	1-18

# INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/EP2021/063122

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