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(54) **LIMITING VISIBLE DAMAGE IN MODULAR BUILDINGS**

(57) A method for limiting visible damage such as cracking within 3D modules of a modular building by maintaining level across storeys is described. The method comprises determining an axial force for each column element, with a given cross-sectional area, in a stack forming a column traversing a modular building with a plurality of storey. Each storey of the building is occupied by a plurality of column elements of different columns. The method comprises determining an individual Force-Area Ratio for each of the column elements, successively summing cumulative Force-Area Ratios from the column elements at the base to the top of a given column and adjusting individual Force-Area Ratios of the column elements within a given storey to be within a specified target range of the cumulative Force-Area Ratios of the other column elements within a given storey.

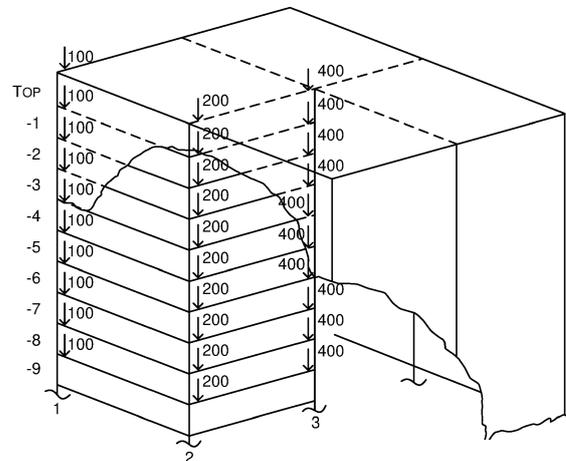


FIG. 1

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Description

[0001] The present disclosure relates to improvements in managing vertical movement in modular construction.

5 BACKGROUND

[0002] Modular buildings comprise prefabricated building sections or modules that may be manufactured off-site and transported to a construction site. On-site, the modules may be assembled to form part or all of a building structure. These modules may be assembled in any suitable manner to yield a robust and safe building. Typically, in order to increase the height of a building such modules may be stacked on top of each other.

[0003] The effect of vertical forces over time causes all buildings to experience shortening of their vertical elements such as walls and columns. This effect is particularly noticeable in taller buildings as the magnitude of vertical deflection increases with height. As a result, the stacking of modules can yield an increase in the magnitude of vertical deflection experienced by a modular building.

[0004] The embodiments described below are provided by way of example only and are not limiting of implementations which solve any or all of the disadvantages of managing vertical movement in modular construction.

[0005] The examples described herein are not limited to examples which solve problems mentioned in this background section.

20 SUMMARY

[0006] Examples of preferred aspects and embodiments of the invention are as set out in the accompanying independent and dependent claims.

[0007] This Summary is provided to introduce a selection of concepts in a simplified form that are further described below in the Detailed Description. This Summary is not intended to identify key features or essential features of the claimed subject matter, nor is it intended to be used to limit the scope of the claimed subject matter.

[0008] A first aspect of the disclosed technology comprises a method for limiting visible damage such as cracking within 3D modules through the control of vertical, flexural and racking deflections. The method comprises determining an individual axial force for each of a plurality of column elements that are stacked to form a column, wherein: each of the plurality of column elements links a lower storey to an adjacent upper storey of a modular building such that the column traverses a plurality of storeys of the modular building, each of the plurality of column elements has a cross-sectional area, the axial force of a column element in any given storey is the sum of the loads entering the column element from all of the storeys above in that column, and each storey comprises a plurality of column elements of different columns; determining an individual Force-Area Ratio (FAR) for each of the plurality of column elements based on the determined axial force for each of the plurality of column elements divided by the cross-sectional area of each of the plurality of column elements; determining a cumulative FAR for each of the plurality of column elements, each cumulative FAR respectively comprising the sum total of each of the determined individual FARs for each of the plurality of column elements summed successively from the column element at the base of the column to the column element at the top of the column; and adjusting the determined individual FAR of at least one column element to adjust the cumulative FAR of the at least one column element within a specified target range of the cumulative FARs of the other column elements of the storey that the at least one column element occupies.

[0009] In this way, FARs across storeys are balanced within a specified target range thereby maintaining the level of the storeys. This allows vertical, flexural and racking deflections in a modular building to be controlled, thereby limiting damage such as cracking.

[0010] In some preferred example embodiments, adjusting at least one determined individual FAR of at least one column element comprises adjusting the nominal storey-to-storey height of the modular building by one or more of: adding a first shim of a specified size to at least one of the plurality of column elements; adjusting a thickness of at least one tie-plate; and adjusting a length of at least one of the plurality of column element to adjust the cross-sectional area of the at least one column element. In this way, determined individual FARs of given column elements can be manipulated in order to subsequently adjust the cumulative FARs of the given column elements.

[0011] In some preferred example embodiments, the method comprises adjusting the cumulative FAR of the at least one column element to within a FAR tolerance range of the average cumulative FAR of the storey that the at least one column element occupies. In this way, the cumulative FARs as summed successively up each storey lie within a FAR tolerance range.

[0012] In some preferred example embodiments, the FAR tolerance range of the average cumulative FAR of the storey that the at least one column occupies is up to 25 per cent of a permitted deformation available to the at least one column element. In this way, the FAR contribution to the permitted deformation of the column element is limited.

[0013] In some preferred example embodiments, the method comprises adjusting for poor tolerances of length of the

plurality of column elements by using a second shim. In this way, poor tolerances in length of column elements can be compensated, contributing to maintaining level across storeys.

[0014] In some preferred example embodiments, the method comprises offsetting deflections experienced in an upper cluster of co-located column elements by sandwiching at least one tie-plate between lower cluster of co-located column elements and the upper cluster of co-located column elements, wherein the lower cluster of co-located column elements comprises a plurality of columns elements occupying a first storey, the upper cluster of co-located column elements comprises a plurality of column elements occupying a second storey immediately above the first storey and the lower cluster of co-located column elements and the upper cluster of co-located column elements are substantially aligned. In this way, forces arising from residual column shortening can be redistributed.

[0015] In some preferred example embodiments, the method comprises offsetting variable vertical displacements between at least one core element of the modular building and at least one of the plurality of column elements by using a compliant element, wherein: the at least one core element comprises a fixed structure within the modular building and the compliant element is arranged substantially perpendicular to the axis of the variable vertical displacements and is configured to: adjoin the at least one core element and at least one of the plurality of column elements; transfer lateral forces that are applied to the modular building along its length via axial forces in the compliant element; deform plastically in flexure to offset variable vertical displacements as a result of a differential vertical movement between the core element and the at least one of the plurality of column elements; and deform elastically to offset variable vertical displacements as a result of at least one of lateral or vertical forces applied to the building. In this way, variable vertical displacements between core elements and column elements can be offset during construction and thereafter.

[0016] In some preferred example embodiments, the compliant element is configured to deform elastically within a predetermined range. In this way, small variable vertical displacements that occur after stacking of modules can be offset.

[0017] In some preferred example embodiments, adjoining the at least one core element and at least one of the plurality of column elements comprises affixing a first end of the compliant element to the one of the at least one tie-plates and affixing a second end of the compliant element to a plate affixed to the at least one core element, wherein the first end and the second end of the compliant element are substantially opposite. In this way, variable vertical displacements experienced between the core element and the column elements are able to be offset.

[0018] In some preferred example embodiments, the compliant element is any of one of a bar, a sectional profile or a plate.

[0019] In some preferred example embodiments, the compliant element is manufactured of metal.

[0020] In some preferred example embodiments, the method comprises compensating for elastic shortening of at least one column element by attaching at least one headed stud to a structure that moves with the uppermost surface of at least one column element in the at least one column, wherein the headed stud is configured to move within a ceiling rail from a first position to a second position independently of the uppermost surface of the at least one column element by traversing an opening in the ceiling rail. In this way, elastic shortening of column elements can be compensated by allowing a ceiling rail to move independently of the ceiling of the column element.

[0021] In some preferred example embodiments, the magnitude of the movement of the ceiling rail is within a predetermined range of movement to accommodate the effects of column axial shortening, structural flexure under in-service loads and cumulative manufacturing tolerances.

[0022] In some preferred example embodiments, the diameter of the opening of the ceiling rail exceeds that of the shaft of the headed stud and is less than that of the diameter of the headed stud. In this way, the stud can traverse the opening of the ceiling rail.

[0023] In some preferred example embodiments, the stiffness of the ceiling rail enables the ceiling rail to deflect within a predetermined threshold level for a specified span of the ceiling rail. In this way, the relative stiffness of the ceiling rail allows the ceiling rail to deflect only within a specified range across its span.

[0024] It will also be apparent to anyone of ordinary skill in the art, that some of the preferred features indicated above as preferable in the context of one of the aspects of the disclosed technology indicated may replace one or more preferred features of other ones of the preferred aspects of the disclosed technology. Such apparent combinations are not explicitly listed above under each such possible additional aspect for the sake of conciseness.

[0025] Other examples will become apparent from the following detailed description, which, when taken in conjunction with the drawings, illustrate by way of example the principles of the disclosed technology.

BRIEF DESCRIPTION OF THE DRAWINGS

[0026]

FIG. 1 illustrates an isometric cut-away of an exemplary building with column elements;
 FIG. 2 is a table illustrating how the maximised individual Force-Area Ratio is obtained at every storey in the building of FIG. 1;

FIG. 3 is a table showing the effects of using a reduced number of column elements of different sizes on the cumulative Force-Area Ratios within a given storey of the building of FIG. 1;

FIG. 4 is a table showing the balanced Force-Area Ratios for column element adjusted to obtain a balanced Force-Area Ratio within a given storey of the building of FIG. 1;

FIG. 5A illustrates the isometric cut-away of the exemplary building of FIG.1 with the addition of shims on given column elements and provides an expanded view illustrating the addition of a shim on a given column element; FIG. 5B is table showing the effects on individual and cumulative FARs as a result of adding shims to given column elements;

FIG. 6A is a table illustrating the average cumulative FARs across storeys for an exemplary unshimmed building;

FIG. 6B is a table illustrating the average cumulative FARs across storeys for an exemplary shimmed building;

FIG. 7 is table showing the sum total of all of the cross-sectional areas of each of the buildings represented in the tables of FIGs. 2, 3, 4 and 5B;

FIG. 8 is a simplified flow diagram of an exemplary method for limiting damage in 3D modules;

FIG. 9A is a simplified angular view diagram of a tie-plate in use with a cluster of column elements;

FIG. 9B is a simplified frontal view diagram of a tie-plate in use with a cluster of column elements;

FIG. 10 is an exemplary diagram of a compliant element in use with a core element and a cluster of column elements;

FIG. 11A illustrates a schematic section through a column element; and

FIG. 11B shows an expanded schematic section of the ceiling of the column element as depicted in FIG. 11A.

[0027] The accompanying drawings illustrate various examples. The skilled person will appreciate that the illustrated element boundaries (e.g., boxes, groups of boxes, or other shapes) in the drawings represent one example of the boundaries. It may be that in some examples, one element may be designed as multiple elements or that multiple elements may be designed as one element. Common reference numerals are used throughout the figures, where appropriate, to indicate similar features.

DETAILED DESCRIPTION

[0028] The following description is made for the purpose of illustrating the general principles of the present technology and is not meant to limit the inventive concepts claimed herein. As will be apparent to anyone of ordinary skill in the art, one or more or all of the particular features described herein in the context of one embodiment are also present in some other embodiment(s) and/or can be used in combination with other described features in various possible combinations and permutations in some other embodiment(s).

[0029] This disclosure relates to a method for managing vertical movement in modular buildings. In particular, but not exclusively, it relates to maintaining level of storeys within modular buildings and offsetting any further effects of differential vertical movement.

[0030] The following description is presented by way of example to enable a person skilled in the art to make and use the invention. The present invention is not limited to the embodiments described herein and various modifications to the disclosed embodiments will be apparent to those skilled in the art.

[0031] Modular construction is typically a form of construction in which building components, which may be alternatively referred to as modules, are manufactured off-site before being assembled on-site. Social, political, economic, environmental and financial factors mean that modular construction is becoming more common as there is need to quickly and consistently construct good quality buildings, whilst minimising waste and pollution.

[0032] All buildings experience axial shortening of their vertical elements over time. Differential axial shortening may alternatively be referred to as differential shortening or shortening. It is appreciated that whilst columns are specifically discussed hereafter, that the methods described may be applicable to any suitable vertical element of a module in a modular building.

[0033] The axial shortening of a column can be described by:

$$\text{Axial Shortening} = \frac{\{\text{Height of Column} \times \text{Axial Force on Column}\}}{\{\text{Elastic Modulus} \times \text{Cross - Sectional Area of Column}\}}$$

(1)

[0034] Columns in a modular building can shorten by different amounts. This leads to differential axial shortening, which can be described by:

Differential Axial Shortening

= Axial Shortening of First Column – Axial Shortening of Second Column

5

(2)

[0035] Various factors influence differential axial shortening; as such, there are numerous ways that differential axial shortening may be corrected or compensated for in a building.

[0036] In conventional concrete frame construction, the effects of differential axial shortening may be corrected during construction as each storey of the building is constructed and levelled sequentially. Surveys are performed at every column position in every storey to identify differential shortening, which is then corrected for at higher storeys as construction progresses. Such surveys are time-consuming and prone to human error.

[0037] In contrast, the objective of modular construction is to minimise the amount of work that is to be completed on site. In order to minimise the effects of shortening in a modular building, vertical elements in a modular building therefore may be manufactured to nominally the same length. As some tolerances in the lengths of these elements may remain, there is still a need to survey and check the level of storeys and vertical elements at approximately every five storeys.

[0038] Differential axial shortening in conventional concrete frame building can occur as additional storeys are added. This may cause lower storeys to become out-of-level. This can be corrected for by the application of screed. Any shortening occurring after the application of screed is corrected for by the fitting of finishes and elements such as internal walls to correspond to the deflected shape of the building. Such finishes are only used to correct for shortening that occurs at a late stage of construction.

[0039] In contrast, in modular construction, finishes are applied early in the modular construction process, so cannot be used in the same corrective manner as conventional construction. Further, the differential shortening as a result of stacking can cause module finishes to be damaged, which results in unsightly finishes.

[0040] Foundation settlement is also problematic for modular construction. Foundation settlement occurs under load and over time. In conventional construction, differential vertical movement as a result of foundation settlement can be corrected as construction progresses as such construction is typically quite a lengthy process. In contrast, foundation settlement is problematic for modular construction due to the typical sequence it follows. It is usual to build the core or fixed elements of the building prior to assembly of the modules. The core may be concrete such that it is subject to shortening as a result of shrinkage, creep and self-weight. The majority of shortening that is experienced by the core is prior to installation of the modules. As the modules are stacked, the modules experience shortening which results in a differential vertical movement between the core and the module.

[0041] Similar issues may arise when a modular building is instead constructed atop a transfer slab. Modules may not align with vertical elements beneath the transfer slab, thereby experiencing flexural deflections of slab, resulting in differential vertical deflections between adjacent columns in the module. As the modules are stacked, there is a corresponding increase in the differential vertical deflections as the load entering the columns from above increases. This effect is particularly pronounced if the transfer slab is constructed from concrete as it will also undergo creep.

[0042] Due to the numerous contributory factors and associated problems with differential axial shortening and differential vertical movements, it is desirable to find means to minimise differential axial shortening in modular buildings. One such method relates to the maintaining the Force-Area Ratio within given storeys of a modular building.

[0043] With reference to equation (1), the height of a given column and the elastic modulus are generally constant. As such, it follows that:

45

$$Axial\ Shortening \propto \frac{\{Axial\ Force\ on\ Column\}}{\{Cross - Sectional\ Area\ of\ Column\}}$$

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(3)

[0044] Columns may be comprised of stacked column elements. Each column element may occupy a given storey, alternatively referred to as levels or floors. As such, a column may traverse multiple storeys of a building. Each storey may include a plurality of column elements from different columns.

[0045] Differential axial shortening can cause the column elements and subsequently, the storeys they occupy, to become out-of-level as the column elements of different columns are compressed along their axes at different rates. If the Force-Area Ratio (FAR) is kept constant for every column element in the building, then each column shortens by

the same amount. As a result, all of the storeys in the building remain level as all of the columns move vertically downwards by the same margin.

[0046] In practice, keeping the FAR constant is challenging due to the complex and often interdependent relationships between various factors. Firstly, the axial force experienced by a column varies with the height of the building. The axial force in a column is the sum of all of the individual forces entering the column from above. By way of example, a column element occupying a lower storey will experience a greater axial force than a column element occupying an upper storey. As a result, the lower column element requires a higher cross-sectional area than the upper column, thereby changing the FAR.

[0047] Balancing FAR for all of the column elements within a given storey is further complicated as the axial force experienced by a column element varies based on its position within the storey. For example, a column element of a fully internal column may experience twice the load of a perimeter mid-side column element in the same storey. The perimeter mid-side column element may experience twice the load of a corner column element in the same storey. Further, perimeter column elements may be subject to additional loads due to the need to support external features such as cladding and balconies.

[0048] Further additional superimposed dead and live loads are problematic for maintaining the constancy of FAR within storeys as they can be unpredictable. Modular buildings tend to be more sensitive to variations in live loads than concrete or steel-framed buildings. Modular buildings can typically tolerate a lower dead load to live load ratio than so-called conventional buildings. As such, the level of the floorplates forming at least part of the floors of storeys of modular buildings tends to depart from level more than a counterpart concrete framed building. It is therefore desirable for the initial level of the floorplate in a modular building to be better than that of a concrete framed building.

[0049] FAR may further be affected by alternative load paths. In modular construction, an alternative load path may see the transfer of the load into upper beams, through wall studs, into lower beams and back into the column. As such, the construction and plan of the building and the amount of axial force on a column element has a large effect on the proportion of the load that alternative load paths can tolerate.

[0050] It would be desirable to provide an improved method for managing vertical movement in modular construction, such that a survey is not required at every storey during construction of the modular building. As the vertical displacement experienced by a column element is proportional to its FAR, maintaining the constancy of the FARs of column elements within the same storey provides a means of managing vertical movement.

[0051] FIG. 1 of the accompanying drawings shows an isometric cut-away of an exemplary building. The diagram shows the top ten storeys of the exemplary building. Each storey is labelled sequentially, starting with the top storey denoted as 'TOP', the penultimate storey as (-1) etc. The building extends to a reference storey, denoted as (-9). In other examples, it is appreciated that any storey other than the top storey could be the reference storey. It is appreciated that the building could be constructed of any suitable number of storeys and be of any suitable height.

[0052] In FIG. 1, three columns are visible, a corner column (1), a mid-side column (2), and a fully internal column (3). The columns traverse all ten of the storeys shown. Whilst in the depiction shown the columns only traverse the upper ten storeys, it is appreciated that in other examples the columns may traverse the whole length of the building, or any other number of storeys of the building.

[0053] The columns shown are formed by the stacking of column elements on top of each other. Each module has an uppermost surface, alternatively referred to as a ceiling, a lowermost surface, alternatively referred to as a floor, and lateral surfaces, alternatively referred to as walls. In this example, each individual column element occupies a single given storey.

[0054] In FIG. 1, ten column elements are stacked to respectively form each of the three columns (1, 2, 3). Three column elements from each of the different columns (1, 2, 3) occupy each given storey. By way of example, storey -1 is occupied by the column elements of each of the corner (1), mid-side (2) and internal (3) columns.

[0055] The individual axial forces experienced by each column element are shown at the corresponding location they are experienced on building 100. The individual axial forces may describe the loads added from the individual module floors and ceilings.

[0056] FIG. 2 is a table corresponding to the exemplary building in FIG. 1. The table is split into three sections, each indicating respective columns (1), (2) and (3). Each row in the table corresponds to each storey of the building in FIG. 1.

[0057] Each of the sections of the table are split into four columns. The first column describes the cumulative axial force experienced by a given column element within a storey. The cumulative axial force is calculated by sequentially summing the individual axial forces experienced by the column element from the top storey down to storey (-9).

[0058] The second column describes the cross-sectional area of the given column element.

[0059] The third column describes the individual Force-Area Ratio of the given column element. The individual FAR is calculated using the cumulative axial force and the cross-sectional area of the column.

[0060] The fourth column describes the cumulative FAR experienced by the given column element. The cumulative FAR is calculated by sequentially summing the individual FARs from the lowest storey (-9) to the top storey (TOP).

[0061] For ease of discussion, the maximum permitted value of FAR in the following examples is 100, wherein the

limit is related to the capacity of the column.

[0062] In FIG. 2, the cross-sectional areas of the column elements of the building in FIG. 1 have been adjusted in order to yield the maximum individual FAR for each given column element. FIG. 2 shows the optimal design for maintaining FAR within storeys, as the achieving the maximum individual FAR at each column element within a given storey results in the cumulative FAR being maintained across the storey. As the vertical displacement of each column element is proportional to its individual FAR, if the cumulative FAR summed up the building is the same for all columns across each storey and has this condition at every storey, then each storey will maintain level assuming that the base of each column element in a given storey lies in the same horizontal plane.

[0063] Whilst FIG. 2 highlights the optimal design for maintaining FAR, in practice, it is unrealistic, impractical and expensive. In FIG. 2, by way of example, a total of twenty different cross-sectional areas are required in order to maintain the FARs within given storeys. In practice, the number of column sizes may be significantly higher. As such, it is therefore disadvantageous to use such a design in order to manage vertical displacement.

[0064] FIG. 3 is a table showing the effects of using a reduced number of column elements of different sizes on the cumulative Force-Area Ratios within a given storey of the building of FIG. 1. The arrangement of the table in FIG. 3 is the same as that of FIG. 2. In this example, as in practice, there is a limit on the number of different sizes of column element that are available. In this example, there are eight different cross-sectional areas of column element available, in contrast to the twenty available in the optimally designed building of FIG. 2.

[0065] Referring more specifically to the cross-sectional area columns in FIG. 3, it can be seen that the smallest cross-sectional area available is 5, the largest being 40, increasing in increments of 5. The smallest-sized cross-sectional area that achieves a FAR of ≤ 100 has been selected for each given column element, as can be seen in the individual FAR columns of each section.

[0066] Comparing columns 1, 2 and 3 of FIG. 3 shows that the cumulative FARs for a given storey vary. By way of example, consider the top storey where the cumulative FAR for the corner column (1) is 700, for the mid-side column (2) is 803 and for the internal column (3) is 890. This yields a difference of 190 for the cumulative FARs for the top storey.

[0067] Consider that a difference of 100 for cumulative FARs typically represents a 3mm shortening of a fully loaded steel column. A difference of 190 as depicted in the top storey of the building in FIG. 3 may result in a difference in shortening of columns 1 and 3 by approximately 5.7mm. Such a difference in shortening may be the entire deflection allowance of the module, such there is no margin allowing for additional deflection, resulting in modules that would deform to such an extent that finishes would crack, and remedial work would be required. It would therefore be beneficial to introduce improved and alternative means for maintaining FAR within a given storey.

[0068] FIG. 4 is a table showing matching individual Force-Area Ratios wherein the column elements of the building of FIG. 1 have been adjusted to obtain matching individual FARs across a given storey. The arrangement of the table in FIG. 4 is the same as that of FIGs. 2 and 3. The cross-sectional areas of the column elements of the mid-side column (2) are adjusted to give individual FARs that are equal to the individual FARs of the corresponding column element in the corner column (1). The cross-sectional areas of the column elements of internal column (3) are also adjusted to match the individual FARs of the corresponding column elements of the corner column (1). By way of example, the individual FAR of the corner column element in the top storey is 20. The individual FARs of mid-side and internal column elements are also 20, as the cross-sectional areas of the mid-side and internal columns have been adjusted in order to achieve this correspondence across the top storey. This can be seen in each of the remaining storeys in FIG. 4.

[0069] It is noted that for both of the buildings described by FIGs. 3 and 4, a limited number of cross-sectional areas are available. In FIG. 3, cross-sectional areas of column elements are selected to achieve an individual FAR as close to the maximum as possible. In contrast, in FIG. 4, the cross-sectional areas are selected from an even more limited pallet of cross-sectional areas, but the selection ensures that the sum of the individual FARs up the columns is similar across storeys. This achieves a much more consistent range of cumulative FARs across storeys. The effects of adjusting cross-sectional area of column element in terms of volume of material used will be discussed in greater detail later with respect to FIG. 7.

[0070] FIG. 5A illustrates the isometric cut-away of the exemplary building of FIG. 1 with the addition of shims on given column elements and provides an expanded view of the addition of a shim on a given column element. A shim may be of any suitable material or shape to effectively adjust the FAR without the need to adjust the cross-sectional areas of the columns themselves. A shim is typically applied to the underside of a module. As such, the shim may additionally be in contact with the uppermost surface of the stacked lower adjacent module. Alternatively, a shim may be in contact with a tie-plate, which will be discussed in greater detail later.

[0071] Whilst the building in FIG. 5A is the same building as shown in FIG. 1 and is arranged in the same manner, shims have been added to given column elements. FIG. 5A provides a simplified expanded view 500 of the addition of a shim 502 to column element 504a occupying storey -1 for column (2), where the shim is sandwiched between the upper column element 504a at storey -1 and the lower column element 504b occupying storey -2.

[0072] FIG. 5B is table showing the effects on individual and cumulative FARs as a result of adding shims to given column elements as in FIG. 5A. The arrangement of the table in FIG. 5B is the same as that of FIGs. 2, 3 and 4 with the

exception of the individual FAR columns. The boxed column elements are the column elements that have been fitted with a shim. As the shim is intended to maintain level in a building, the shim reduces the individual FAR. As such, in the boxed columns in the individual FAR column of FIG. 5B, the individual FAR without a shim is shown and the effect of the shim reduction is subtracted to obtain the shimmed individual FAR. The cumulative axial forces, cross-sectional areas and individual FARs without the shims are the same as those depicted in FIG. 3, such that FIG. 5B depicts a shimmed version of the building of FIG. 3.

[0073] Adding a shim will reduce the effective axial shortening of a column element at a given level as individual FAR is proportional to axial displacement. The adjustment to FAR value used in figure 5B is related to shim thickness as follows:

$$FAR = \{Stress\ in\ Column\} = \frac{\{Axial\ Force\ in\ Column\}}{\{Cross\ Sectional\ Area\ of\ Column\}} \quad (4)$$

and

$$Column\ Shortening = FAR \times \frac{\{Axial\ Force\ in\ Column\}}{\{Column\ Modulus\ of\ Elasticity\}} \quad (5)$$

[0074] Where a shim is used, it is to give the same effect as column shortening (or lengthening). Equation (5) is rearranged to give the FAR adjustment resulting from a given shim thickness:

$$FAR\ Adjustment = \{Shim\ Thickness\} \times \frac{\{Column\ Modulus\ of\ Elasticity\}}{\{Height\ of\ Column\ Element\}} \quad (6)$$

[0075] The FAR adjustment is subtracted from the normally calculated FAR for any given column element whenever a shim is deployed to that column element.

[0076] By way of example, assume that an individual FAR of 100 represents a 3mm displacement. It follows that a cumulative FAR of 1000 represents an axial displacement of 30mm. The axial displacement of the top of an upper column element relative to the top of a vertically adjacent lower column element is proportional to the individual FAR of the upper column element. The addition of a shim between the upper and lower column elements in the stack reduces that axial displacement of the top of the upper column relative to the top of the lower column element. As axial displacement is proportional to FAR, the reduction in the relative axial displacement as a result of adding the shim is equivalent to reducing the FAR.

[0077] A 1mm shim may reduce the individual FAR of a column element by 33. Specifically, and by way of example, the individual FAR of the top column element of the mid-side column 2 in FIG. 5B is 40 without the addition of a shim. With the addition of a 1mm shim the individual FAR is reduced by 33 to 7.

[0078] Additional 1mm shims have been added to the -1 and -6 column elements of the mid-side column. This has an impact on the cumulative FARs experienced within a given storey as it reduces the individual FARs of each of these column elements. This effect can be seen with reference to FIGs. 3 and 5B, in which FIG. 5B is the shimmed version of FIG. 3. By way of example, the cumulative FAR of the top storey column element of the mid-side column in FIG. 3 is 803. In the shimmed version of FIG. 5B, this cumulative FAR has been reduced to 704

[0079] Reading the cumulative FARs across storeys in FIG. 5B, it is shown that the cumulative FARs can sit within a range of 19. This maximum range can be seen in storey -2. It is therefore possible to keep the adjustment of the cumulative FAR across a storey within a range that is approximately half of the thickness of a shim by varying the location of the shims. As an example, to maintain storey level within 1mm, a shim of 2mm could be used.

[0080] The benefits of adjusting the individual FARs of given column elements can be explained by averaging the cumulative FARs of all the column elements within a given storey and determining the percentage difference for each of the cumulative FARs for each of the column elements within a given storey.

[0081] FIG. 6A is a table illustrating the average cumulative FARs across storeys for the exemplary un-shimmed

building as described in FIG. 3. The absolute difference between the average cumulative FAR for a given storey and the cumulative FARs for each of the column elements within a given storey is shown for each of columns 1, 2 and 3.

[0082] FIG. 6B is a table illustrating the absolute difference between the average cumulative FAR for a given storey and the cumulative FARs for each of the column elements within a given storey for the exemplary shimmed building as described in FIG. 5B. FIG. 6B is arranged in the same manner as FIG. 6A.

[0083] The objective of equalising cumulative FARs at each storey is to maintain level across each storey such that module finishes are not damaged when a module is placed. The damage limit for a given module may be defined in terms of the differential level between adjacent columns in a given module. The damage limit also needs to allow for module deformations arising from other tolerances and adjustments made during installation. It is reasonable for the FAR contribution to permitted deformation to use up 25% of the total available. As an example, if the maximum differential level between adjacent columns is 6mm, then the FAR contribution should be 1.5mm. Putting this value into equation (6) gives a FAR value, in this case the tolerance range within which the cumulative FARs at each storey should lie.

[0084] By way of example, the cumulative FARs of all of the column elements in the top storey in the non-shimmed building of FIG. 3 and as depicted in FIG. 6A yield an average cumulative FAR of 798. The cumulative FAR of the top storey of column 1 is within a range of 98 of the average cumulative FAR across the storey. The cumulative FAR of the top storey of column 2 is within a range of -5 of the average cumulative FAR across the storey. The cumulative FAR of the top storey of column 3 is within a range of -92 of the average cumulative FAR across the storey.

[0085] In contrast, and with reference to FIG. 6B, averaging the cumulative FARs of all of the column elements in the top storey in the shimmed building as depicted in FIG. 5A gives an average cumulative FAR of 699. The cumulative FAR of the top storey of column 1 is within a range of -1 of the average cumulative FAR across the storey. The cumulative FAR of the top storey of column 2 is within a range of -5 of the average cumulative FAR across the storey. The cumulative FAR of the top storey of column 3 is within a range of 7 of the average cumulative FAR across the storey.

[0086] Comparing the absolute differences of the adjusted building to the non-adjusted building shows that the cumulative FAR within a given storey can be maintained to within a much tighter tolerance than in the non-adjusted building.

[0087] The use of shims is also beneficial in terms of efficiency. The sum of the cross-sectional areas of the column elements in a column is directly proportional to the amount of material that is used to form the column. The amount of material used to form a column provides a measure of efficiency.

[0088] FIG. 7 is table showing the sum total of all of the cross-sectional areas of each of the buildings as described by the tables depicted in FIGs. 2, 3, 4 and 5B. The first column shows the building to which it relates. The sum totalled cross-sectional areas for each of the columns is shown. The sum total of all of the columns in a given building is shown in the final column.

[0089] For the shimmed building of FIG. 5B, the sum total of the cross-sectional areas of all of the column elements is 445. This is the same as the limited column size building depicted in FIG. 3. The sum total of all of the cross-sectional areas of all of the column elements of FIG. 4 is 525. In contrast, in the optimal building design as in FIG. 2, the sum total is 385.

[0090] There is an 18% reduction in material required to construct the shimmed building in FIG. 5B in comparison to the equivalently level non-shimmed building of FIG 4. This shows that with the addition of a limited number of shims, it is possible to balance cumulative FARs within a given storey to within a tight tolerance. This assists in maintaining the level of a given storey by minimising the amount differential shortening that each of the column elements within a given storey undergoes, such that they shorten at substantially the same rate.

[0091] It is noted that whilst in terms of amount of material used, the building in FIG. 2 may be considered to be the most efficient, in practice it is unrealistic and impractical due to the number of different cross-sectional areas required. It is therefore beneficial to combine shims with column elements with varying cross-sectional areas in order to manage variable vertical displacement.

[0092] Imbalances in FAR within a given storey can result in damage to the modules including visible cracks and hairline fractures due to vertical, flexural and racking deflections. Based on the preceding examples, there is a need to provide a method of maintaining cumulative FARs within given storeys of buildings in an efficient and practical manner in order to limit damage to the modules.

[0093] FIG. 8 provides a flow-chart depicting an exemplary method 800 for limiting damage within 3D modules of a building. The method comprises determining an individual axial force for each of a plurality of column elements that are stacked to form a column (block 810). The column element may be a module of the modular building such that it occupies a given storey in the modular building. Each of the plurality of column elements has a defined cross-sectional area and links a lower storey to an adjacent upper storey of a modular building such that the column traverses a plurality of storeys of the modular building. The column may traverse the entire height of the building from the ground storey to the top floor. Alternatively, it is appreciated that the column may span from a first reference storey to the top storey, where the reference storey may be any storey below the top storey including the ground storey.

[0094] Column elements may be stacked to form a plurality of columns such that each storey includes a plurality of column elements from different columns.

[0095] The individual axial force of a column element in any given storey may be determined by calculating the sum of the loads entering the column element from all of the storeys above.

[0096] A cumulative axial force for each of the plurality of column elements may be determined (block 820). Each cumulative axial force of each of the plurality of column elements may comprise the sum total of each of the determined individual axial forces summed successively from the column element at the top of the column to a column element at a reference storey.

[0097] An individual Force-Area Ratio for each of the plurality of column elements is determined (block 830). The individual FAR is based on the determined cumulative axial force for each of the plurality of column elements divided by the cross-sectional area of each of the plurality of column elements.

[0098] A cumulative FAR for each of the plurality of column elements is determined (block 840). Each of the cumulative FARs for each of the plurality of column elements respectively comprises the sum total of each of the determined individual FARs for each of the plurality of column elements summed successively from the column element at the base of the column to the column element at the top of the column.

[0099] An average cumulative FAR for each storey of the modular building is determined (block 850). The average cumulative FAR is based on the determined cumulative FARs of all of the plurality of column elements that occupy a given storey. The determined individual FAR of at least one column element is adjusted (block 860). The determined individual FAR is adjusted to adjust the cumulative FAR of the at least one column element to within a specified target range of the average cumulative FAR of the storey that the at least one column element occupies. The objective of equalising cumulative FARs up the column at each storey is to maintain level across each storey such that module finishes are not damaged when a module is placed. The damage limit for a given module may be defined in terms of the differential level between adjacent columns on that module. This limit also needs to allow for module deformations arising from other tolerances and adjustments made during installation. It is reasonable for the FAR contribution to permitted deformation to use up 25% of the total available.

[0100] The determined individual FAR may be adjusted by varying the cross-sectional area of the column element which may be achieved by adjusting the length of a column element. Alternatively, or additionally, the individual FAR may be adjusted with the addition of a shim. Alternatively, or additionally, the individual FAR may be adjusted by the addition of a tie-plate, positioned on the underside of a column element. The tie-plate may be of any suitable shape provided that it is larger or equal in size to the base of the column element. The tie-plate may be of any suitable material provided that it can withstand the loads entering it from above.

[0101] The adjustment of the individual FAR allows the cumulative FAR to be adjusted in order to maintain the cumulative FARs across column elements within a given storey to within an acceptable range, thereby limiting damage experienced by the 3D modules.

[0102] The exemplary method 800 provides a practical and realistic method for installation of a modular building. The method 800 minimises the amount of material required whilst being realistic and affordable in practice. The method 800 provides a means for balancing FAR within given storeys within a specified target range. This more efficiently and easily maintains level within storey.

[0103] The method 800 may also limit the need to perform level surveys at every storey. In the examples in which the cumulative FARs are adjusted through the addition of shims, the shims adjust cumulative FARs and do not accommodate for poor tolerances in column length. It is appreciated that other shims, referred to as tolerance shims, may be used in addition to the FAR shims. The tolerance shims may be used to correct for poor tolerances in the length of column elements. As the method 800 maintains the cumulative FAR across all columns within a given storey, it is appreciated that any variations in level in the storey may be attributed to poor tolerances. As modular construction tends to be highly accurate and consistent, the repeatability in length accuracy of column elements across a given storey is expected to be $\leq 0.5\text{mm}$. Survey equipment currently can only reliably detect accuracy within $\pm 2\text{mm}$ such that surveys for tolerance shims are only required at approximately every fifth storey. It is therefore noted that method 800 as described above reduces costs and minimises the risk of introducing human errors as fewer level surveys are required.

[0104] Whilst the method in FIG. 8 is based on the exemplary building of FIG. 1, it is appreciated that the methods and techniques are applicable to other modular building constructions with varying heights, varying storey heights, varying numbers of storeys and varying axial force accumulations down the columns. The methods are applicable provided that dead loads can be accurately estimated in advance, which is a typical feature of modular construction. The estimations provide a representation of the dead loads post-construction. The estimation of the dead loads in advance means that the methods as described above are applicable as dead loads post-construction are predictable and non-changing.

[0105] Referring back to FIGs. 6A and 6B, it is shown that the cumulative FARs of column elements within a given storey can be adjusted to within a specified target range of the average cumulative FAR of the storey. Whilst this is beneficial to minimise the differential axial shortening, the FARs within a given storey are not perfectly equal. By way of example in FIG. 5B, the cumulative FARs of the column elements in the top storey are 700, 904 and 692 respectively. The range of these values is minimised by the method 800 described above but in practice, it is not possible to perfectly

balance these ratios. As such, the adjusted building may experience some differential column shortening, which will hereinafter be referred to as residual column shortening. It is desirable to redistribute the forces arising from the residual column shortening.

[0106] FIG. 9A shows a simplified example of a tie-plate in use with a cluster of column elements, arranged to redistribute the forces arising from residual column shortening. The arrangement 900 in FIG. 9A is comprised of a lower cluster of co-located column elements 902, an upper cluster of co-located column elements 904 and a tie-plate 906 sandwiched between the lower cluster 902 and upper cluster 904. The residual column shortening may arise as a result of variations in the length of at least one column element in the upper cluster 904 and lower cluster 902 of column elements. Alternatively, or additionally, the residual column shortening may arise due to the variation in the load entering at least one of the column elements in the upper 904 and lower cluster 902 of column elements.

[0107] The lower cluster 902 of column elements is comprised of a plurality of column elements that occupy a first storey of a modular building. The upper cluster 904 of column elements is comprised of a plurality of column elements that occupy a second storey of the modular building that is immediately above the first storey. In other words, the upper cluster 904 is stacked on top of the lower cluster 902 such that each of the column elements in the lower 902 and upper 904 clusters are substantially vertically aligned; for example, lower column element 902a is directly below upper column element 904a.

[0108] The column elements within the lower cluster 902 are co-located. The co-location describes column elements that are immediately adjacent to each other. The distance between the column elements may be up to 10cm. The column elements may be spaced apart at substantially regular intervals.

[0109] Whilst four column elements in each cluster are depicted in FIG. 9A, it is appreciated that each cluster of column elements may comprise any number of column elements, provided there are more than two column elements in each cluster. The cluster of column elements may be positioned in any suitable arrangement according to the description above.

[0110] The tie-plate 906 is shown sandwiched between the lower cluster 902 and the upper cluster 904 of columns. The tie-plate is arranged such that, in use, it is in contact with all of the column elements in the respective lower cluster 902 and the upper cluster 904 of columns. The tie-plate 906 has a predetermined length (L). The tie-plate 906 may comprise a sheet of any suitable material such as a fibre composite, steel or any other suitable metal.

[0111] FIG. 9B shows a frontal view of the tie-plate arrangement of FIG. 9A. The tie-plate is configured to offset axial displacements in the upper cluster 904 of columns that arises as a result of the residual column shortening. The tie-plate may be manufactured to be of a specified thickness (t) to offset the deflections.

[0112] The balancing force available at each tie-plate may be described by:

$$Balancing\ Force = \frac{\{Yield\ Stress \times Length \times Thickness^2\}}{\{2 \times Column\ Spacing\}}$$

(7)

[0113] The yield stress, length (L) and thickness of equation (6) are those of the tie-plate; the length and thickness are depicted in FIG. 9B. The column spacing (S) is depicted in FIG. 9B and describes the relative distance between each of the column elements in a given column cluster (e.g. the distance between column elements 902a and 902b).

[0114] In FIG. 9B, the result of the residual column shortening can be seen. Column 908 is formed from column elements 902a and 904a. Neighbouring column 910 is formed from column elements 802b and 804b. Column 908 has shortened more than column 910. The tie-plate is sandwiched between the column elements stacked to form columns 908 and 910 to offset the differences as a result of this residual column shortening, provided that the balancing force of the tie-plate exceeds that of the load of the cluster of the column elements. As this gives little leeway for additional deflections, in practice, a balancing force that exceeds the load of the cluster of column elements by at least 10% is adequate. In preferred examples, the balancing force exceeds the loads of the cluster of column elements by 20%.

[0115] In modular construction, column shortening under load can result in additional challenges. Typically, in modular construction, core elements, alternatively known as fixed structures, which may include walls, stairwells and lift shafts, are constructed first. The modules may be assembled in the correct position relative to these fixed structures.

[0116] As described above, column elements are stacked to form columns. As the column elements are stacked, the load increases such that the column elements undergo shortening under load. This may cause the column elements to move downwards relative to the core element.

[0117] Lateral forces in the plane of the module roof of each of the column elements need to be transferred to the core element. Transferring these forces using a rigid connection is problematic due to the differential vertical movement experienced by the column elements and the core element. Use of such a connection would be likely cause damage to the building as either or both of the column elements moves downwards relative to the wall.

[0118] Mechanical systems such as a bracket with slotted holes or a dowel running in a hole may be employed. However, such systems increase the amount of work required to be undertaken on site as, during installation, they must be carefully aligned. This also increases the risk of human error. Further, such systems may be prone to generating noise as they slide that may be transmitted into the modular building. It is therefore desirable to provide an alternative method for transferring horizontal loads from a column element to a core element.

[0119] An example of a compliant element in use with a core element and a cluster of column elements is shown in FIG. 10. A cluster 1002 of column elements 1002a, 1002b adjacent to a shear wall 1004 is illustrated.

[0120] In FIG. 10, only a single storey of the modular building is shown. Whilst it is not visible in FIG. 10 it is appreciated that column elements 1002a, 1002b may form a part of a stack of different columns. It is appreciated that column elements 1002a, 1002b may be stacked atop lower column elements. Further additional column elements may be stacked above the depicted column elements 1002a, 1002b. Further, whilst only two column elements and one core element are shown, it is appreciated that any suitable number of column elements and core elements can be used to construct a modular building providing it is structurally sound.

[0121] If additional column elements are stacked atop either of column elements 1002a, 1002b, they may move downwards relative to the shear wall 1004. As described above, this differential vertical movement makes it challenging to easily and efficiently transfer lateral forces from the column elements into the core wall.

[0122] FIG. 10 shows compliant elements 1006a and 1006b in use with respective column elements 1002a and 1002b and the core wall 1004. Whilst the compliant elements 1006a and 1006b are depicted as round bars, it is appreciated that the compliant elements may alternatively comprise other sectional profiles or plates. The compliant elements 1006a, 1006b are substantially perpendicular to the plane of differential vertical movement.

[0123] Tie-plate 1008 is positioned atop the cluster 1002 of column elements. Referring specifically to the arrangement of compliant element 1006a for ease of discussion, plate 1010a is affixed to the shear wall 1004. One end of the compliant element 1006a is affixed to the plate 1010a. A substantially opposite end of the compliant element 1006a is attached to the tie-plate 1008. It is noted that compliant element 1006b, column element 1002b and wall plate 1010b are arranged in the same manner with the compliant element 1006b attached to the tie-plate 1008 at a location corresponding to column element 1002b.

[0124] It is appreciated that whilst in the example in FIG. 10 the compliant elements 1006a and 1006b are respectively attached to the wall plates 1010a and 1010b and the tie-plate 1008, the compliant elements 1006a, 1006b may be directly affixed to the column element 1002a and 1002b respectively instead of to the tie-plate 1008. The compliant elements 1006a and 1006b may be directly affixed to the shear wall 1004 instead of to the respective wall plates 1010a and 1010b. It is appreciated that any suitable combination of these affixing arrangements may be adopted.

[0125] Compliant element 1006a is configured to transfer lateral forces applied to the column elements along its length via axial forces. The compliant element 1006a is attached to the wall plate 1010a which is affixed to the core element 1004. The compliant element 1006a therefore provides a direct load path out of the column element 1002a into the core element 1004. The proportions of the compliant element 1006a are selected such that it does not buckle as a result of the axial forces arising in the compliant element 1006a.

[0126] In an example, column elements may be stacked atop column element 1002a. As described above, this may result in column element 1002a moving downwards relative to the shear wall 1004. This differential vertical movement arises due to column shortening under load as the column elements are stacked as the load entering column element 1002a increases. It is therefore a one-time event such that no further differential vertical movement between the core element 1004 and the column element 1002a is expected after the column elements have been stacked and the building has been occupied as no significant further change in load is expected.

[0127] The compliant element 1006a is configured to deform plastically to offset the one-time variable vertical displacement between the core element 1004 and column element 1002a. The variable vertical displacement experienced may typically be up to 30mm. Due to the relative magnitude of this displacement, the compliant element 1006a is configured to yield in vertical bending. The deformation of the compliant element 1006a operates within its plastic range as it is one-time yielding, corresponding to the one-off differential vertical displacement event as a result of stacking column elements.

[0128] The compliant element is configured to deform within its elastic range to offset variable vertical displacements that may occur after the column elements have been stacked. These displacements tend to be much smaller in magnitude than the one-time differential vertical displacements under load and may be up to 5mm. These smaller displacements may be as the result of lateral forces applied to the modular building such as wind. The elastic deformations of the compliant elements are sufficiently small in magnitude so as not to cause premature failure of the connection under the effects of fatigue. As described above, the compliant elements 1006a, 1006b can transfer the lateral forces experienced by the building along its length via axial forces and into the shear wall 1004.

[0129] It is appreciated that the compliant element may be of any suitable size, shape and material provided that its plastic and elastic ranges can withstand the variable vertical displacements that occur during construction and thereafter such that the compliant element is not compromised. The compliant element therefore is not prone to failure or generating

noise.

[0130] Vertical oriented elements other than column elements may also be susceptible to damage as they undergo elastic shortening. As previously described, each module has an uppermost surface, alternatively referred to as a ceiling, a lowermost surface, alternatively referred to as a floor, and vertical surfaces, which may be referred to as walls. Walls typically have internal vertical elements which are attached to floor structure at the bottom and ceiling structure at the top. In some examples of modular construction, the ceiling structure comprises horizontal beams which are supported by the column elements. A rigid connection between the ceiling and the frame means that as the column elements undergo elastic shortening, the ceiling moves downwards into the tops of the walls of the module. This increases the risk of damaging both or either of the ceiling and walls and other vertical elements.

[0131] FIG. 11A illustrates a schematic section through a column element. A floor frame 1104 and ceiling frame 1106 are connected by a column 1102. The column element 1102 is substantially perpendicular to both the floor frame 1104 and the ceiling frame 1106. The column element 1102 provides additional support to ceiling frame 1106. It is appreciated that the ceiling frame 1106 may be further supported by additional walls that are not visible in FIG. 11A.

[0132] The underside of a ceiling board 1114 is in contact with the top of wall 1110 and internal wall 1112. The upper surface of the ceiling board 1114 is in contact with the headed stud 1116 and the ceiling rail 1118. The ceiling board 1114 lies substantially in the horizontal plane. The ceiling board 1114 forms the visible ceiling of the module. The arrangement of the ceiling rail 1118 and the ceiling board 1114 is discussed in greater detail later with respect to FIG. 11B.

[0133] In some examples of modular construction, height tolerances may exist between the floor frame 1104 and the ceiling frame 1106. The difference may result in an effective change in the floor to ceiling dimensions.

[0134] A floor assembly 1108 is supported off the floor frame 1104. The upper surface of the floor assembly 1108 may vary from nominal due to tolerance variation of components used in the floor assembly 1108. This may increase the risk of the wall 1110 and the internal wall 1112 being higher or lower than the nominal position of the wall tops. The poor tolerance of the floor system as depicted by 1104 and 1108 increases the risk of compromising the structure of the wall element via the accumulation of gaps as it allows the distance between the tops of the wall 1110 and internal wall 1112 and the ceiling board 1114 to vary.

[0135] Any shortening of column element 1102 as a result of axial load can further or alternatively vary the distance between the ceiling board 1114 and the wall 1110 and internal wall 1112. Differential deflections of the floor frame 1104 and of the ceiling frame 1106 may also result in a dimensional variation between the ceiling board 1114 and the wall 1110 and the internal wall 1112.

[0136] In order to minimise damage or to prevent gaps forming between the wall 1110, and or the internal wall 1112, and the ceiling board 1114, it is desirable for the ceiling board 1114 of the column element to be able to move independently of the ceiling frame 1106.

[0137] FIG. 11B depicts an enlarged view of a schematic section through the ceiling arrangement of FIG. 11A. As described earlier, the upper surface of ceiling board 1114 is attached to the ceiling frame 1106. Although not visible in FIG. 11B, it is appreciated that the underside of the ceiling board 1114 may be in contact with the tops of walls as depicted in FIG. 11A.

[0138] A ceiling rail 1118 is affixed to the upper surface of the ceiling board 1114. A headed stud 1116 traverses an opening in the ceiling rail 1118 and is attached to the underside of the ceiling frame 1106. The diameter of the opening of the ceiling rail 1118 exceeds that of the shaft of the stud 1116. Additionally, the diameter of the opening of the ceiling rail 1118 is less than that of the head of the stud 1116.

[0139] The ceiling rail 1118 is configured to move independently of the ceiling frame 1106. The ceiling rail 1118 may move vertically along the length of the shaft of the stud 1116 between the head of the stud 1116 and the ceiling frame 1106. This permits the ceiling rail to move only within a distance range dictated by the length of the stud. In a preferred example, the maximum permitted independent movement of the ceiling rail 1118 is 12mm. The independent movement of the ceiling rail is able to accommodate the effects of column axial shortening, structural flexure under in-service loads and cumulative manufacturing tolerances. This is beneficial as it limits excessive sagging of the ceiling board 1114 and limits the ceiling board 1114 either diverging from or pushing into the tops of walls and/or wall boards.

[0140] The ceiling rail 1118 assembly may be able to accommodate up to 12mm of deflections, with 7mm attributable to tolerances. As such, the ceiling rail 1118 is configured to enable the ceiling board 1114 to deflect within a specified threshold. This allows the ceiling board 1114 to remain in contact with the tops of walls and/or wall boards that are different heights, provided the difference in height is within the threshold deflection range of the ceiling board 1114. In a preferred example, the stiffness of the ceiling rail 1118 is selected to enable the ceiling board 1114 to deflect by 10mm under self-weight when the ceiling board 1114 spans 2m. This relative stiffness provides sufficient support to maintain the contact between the ceiling rail 1118 and the ceiling board 1114 whilst enabling the ceiling board 1114 to deflect within an allowable range.

[0141] As described above, the ceiling rail 1118 is affixed to the ceiling board 1114. As a result, the ceiling board 1114 can also move independently of the ceiling frame 1106 along the length of the stud 1116. The ceiling rail 1118 assembly may be able to accommodate up to 12mm of deflections, with 7mm attributable to tolerances.

[0142] The independent movement minimises the risk of gaps forming between the tops of walls, wall boards and the ceiling board 1114 due to factors including but not limited to column shortening, tolerances, and differential frame flexures. Correspondingly, this also reduces the risk of damage to the column element.

[0143] Any reference to 'an' item refers to one or more of those items. The term 'comprising' is used herein to mean including the method blocks or elements identified, but that such blocks or elements do not comprise an exclusive list and an apparatus may contain additional blocks or elements and a method may contain additional operations or elements. Furthermore, the blocks, elements and operations are themselves not impliedly closed.

[0144] The steps of the methods described herein may be carried out in any suitable order, or simultaneously where appropriate. The arrows between boxes in the figures show one example sequence of method steps but are not intended to exclude other sequences or the performance of multiple steps in parallel. Additionally, individual blocks may be deleted from any of the methods without departing from the spirit and scope of the subject matter described herein. Aspects of any of the examples described above may be combined with aspects of any of the other examples described to form further examples without losing the effect sought. Where elements of the figures are shown connected by arrows, it will be appreciated that these arrows show just one example flow of communications (including data and control messages) between elements. The flow between elements may be in either direction or in both directions.

[0145] Where the description has explicitly disclosed in isolation some individual features, any apparent combination of two or more such features is considered also to be disclosed, to the extent that such features or combinations are apparent and capable of being carried out based on the present specification as a whole in the light of the common general knowledge of a person skilled in the art, irrespective of whether such features or combinations of features solve any problems disclosed herein. In view of the foregoing description it will be evident to a person skilled in the art that various modifications may be made within the scope of the invention.

Claims

1. A method for limiting visible damage such as cracking within 3D modules through the control of vertical, flexural and racking deflections wherein the method comprises:

determining an individual axial force for each of a plurality of column elements that are stacked to form a column, wherein:

each of the plurality of column elements links a lower storey to an adjacent upper storey of a modular building such that the column traverses a plurality of storeys of the modular building;

each of the plurality of column elements has a cross-sectional area;

the axial force of a column element in any given storey is the sum of the loads entering the column element from all of the storeys above in that column;

each storey comprises a plurality of column elements of different columns;

determining an individual Force-Area Ratio (FAR) for each of the plurality of column elements based on the determined axial force for each of the plurality of column elements divided by the cross-sectional area of each of the plurality of column elements;

determining a cumulative FAR for each of the plurality of column elements, each cumulative FAR respectively comprising the sum total of each of the determined individual FARs for each of the plurality of column elements summed successively from the column element at the base of the column to the column element at the top of the column; and

adjusting the determined individual FAR of at least one column element to adjust the cumulative FAR of the at least one column element within a specified target range of the cumulative FARs of the other column elements of the storey that the at least one column element occupies.

2. The method of claim 1 wherein adjusting at least one determined individual FAR of at least one column element further comprises adjusting the nominal storey-to-storey height of the modular building by one or more of:

adding a first shim of a specified size to at least one of the plurality of column elements;

adjusting a thickness of at least one tie-plate; and

adjusting a length of at least one of the plurality of column element to adjust the cross-sectional area of the at least one column element.

3. The method as in any preceding claim further comprising adjusting the cumulative FAR of the at least one column element to within a FAR tolerance range of the average cumulative FAR of the storey that the at least one column

element occupies.

5 4. The method as in claim 3 wherein the FAR tolerance range of the average cumulative FAR of the storey that the at least one column occupies is up to 25 per cent of a permitted deformation available to the at least one column element.

10 5. The method as in any preceding claim further comprising adjusting for poor tolerances of length of the plurality of column elements by using a second shim.

15 6. The method of any preceding claim further comprising offsetting deflections experienced in an upper cluster of co-located column elements by sandwiching at least one tie-plate between lower cluster of co-located column elements and the upper cluster of co-located column elements, wherein:

the lower cluster of co-located column elements comprises a plurality of columns elements occupying a first storey;

15 the upper cluster of co-located column elements comprises a plurality of column elements occupying a second storey immediately above the first storey; and

the lower cluster of co-located column elements and the upper cluster of co-located column elements are substantially aligned.

20 7. The method as in any preceding claim further comprising offsetting variable vertical displacements between at least one core element of the modular building and at least one of the plurality of column elements by using a compliant element, wherein:

25 the at least one core element comprises a fixed structure within the modular building; and
the compliant element is arranged substantially perpendicular to the axis of the variable vertical displacements, wherein the compliant element is configured to:

30 adjoin the at least one core element and at least one of the plurality of column elements;
transfer lateral forces that are applied to the modular building along its length via axial forces in the compliant element;

35 deform plastically in flexure to offset variable vertical displacements as a result of a differential vertical movement between the core element and the at least one of the plurality of column elements; and
deform elastically to offset variable vertical displacements as a result of at least one of lateral or vertical forces applied to the building.

40 8. The method of claim 7 wherein the compliant element is further configured to deform elastically within a predetermined range.

45 9. The method of claim 7 or 8 wherein adjoining the at least one core element and at least one of the plurality of column elements further comprises affixing a first end of the compliant element to the one of the at least one tie-plates and affixing a second end of the compliant element to a plate affixed to the at least one core element, wherein the first end and the second end of the compliant element are substantially opposite.

50 10. The method of claims 8 or 9 wherein the compliant element is any of one of a bar, a sectional profile or a plate.

55 11. The method of any of claims 7 to 10 wherein the compliant element is manufactured of metal.

12. The method of any preceding claim further comprising compensating for elastic shortening of at least one column element by attaching at least one headed stud to a structure that moves with the uppermost surface of at least one column element in the at least one column, wherein the headed stud is configured to move within a ceiling rail from a first position to a second position independently of the uppermost surface of the at least one column element by traversing an opening in the ceiling rail.

13. The method of claim 12 wherein the magnitude of the movement of the ceiling rail is within a predetermined range of movement to accommodate the effects of column axial shortening, structural flexure under in-service loads and cumulative manufacturing tolerances.

14. The method of claim 12 or 13 wherein the diameter of the opening of the ceiling rail exceeds that of the shaft of the

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headed stud and is less than that of the diameter of the headed stud.

15. The method of claims 12 to 14 wherein the stiffness of the ceiling rail enables the ceiling rail to deflect within a predetermined threshold level for a specified span of the ceiling rail.

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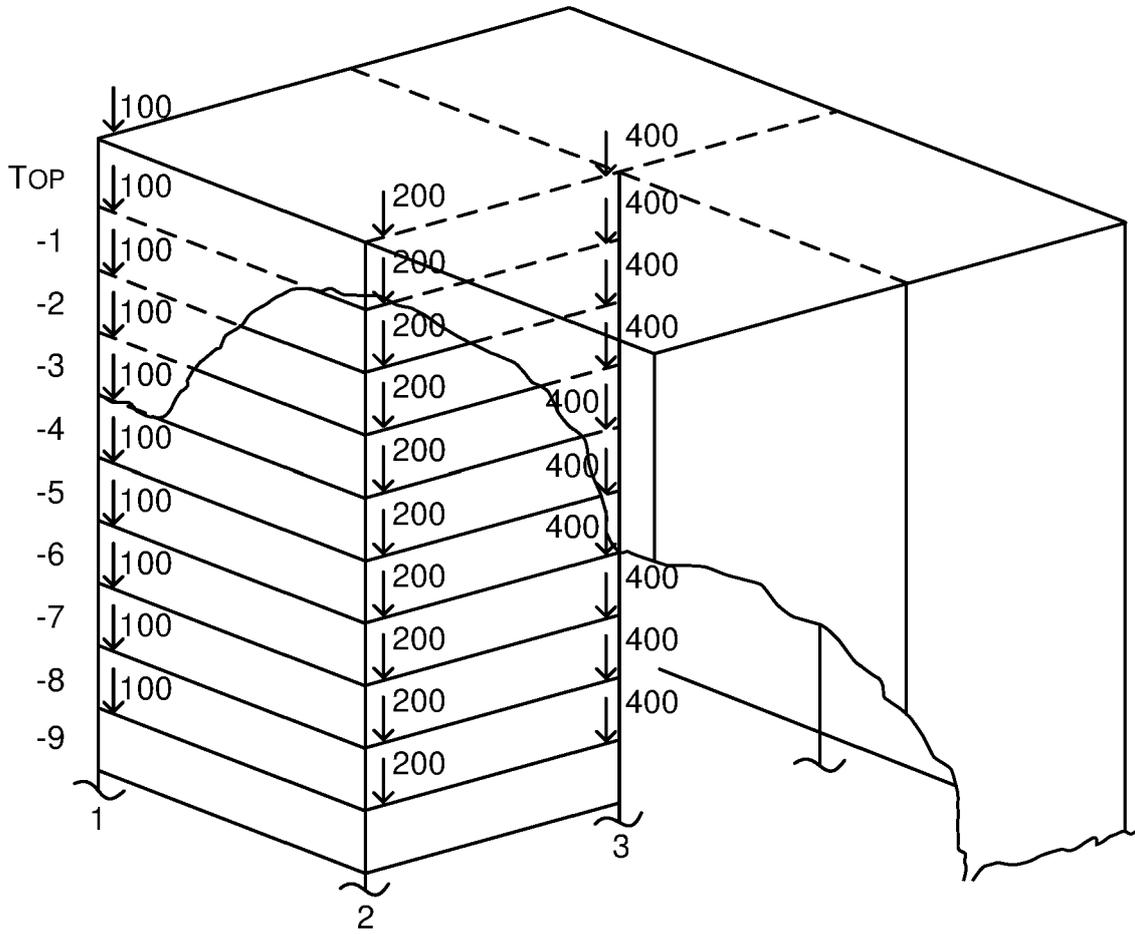


FIG. 1

STOREY	COLUMN 1 CORNER				COLUMN 2 MID-SIDE				COLUMN 3 INTERNAL			
	$\Sigma \downarrow$ LOAD	X- AREA	FAR	$\Sigma \uparrow$ FAR	$\Sigma \downarrow$ LOAD	X- AREA	FAR	$\Sigma \uparrow$ FAR	$\Sigma \downarrow$ LOAD	X- AREA	FAR	$\Sigma \uparrow$ FAR
TOP	100	1	100	1000	200	2	100	1000	400	4	100	1000
-1	200	2	100	900	400	4	100	900	800	8	100	900
-2	300	3	100	800	600	6	100	800	1200	12	100	800
-3	400	4	100	700	800	8	100	700	1600	16	100	700
-4	500	5	100	600	1000	10	100	600	2000	20	100	600
-5	600	6	100	500	1200	12	100	500	2400	24	100	500
-6	700	7	100	400	1400	14	100	400	2800	28	100	400
-7	800	8	100	300	1600	16	100	300	3200	32	100	300
-8	900	9	100	200	1800	18	100	200	3600	36	100	200
-9	1000	10	100	100	2000	20	100	100	4000	40	100	100

FIG. 2

STOREY	COLUMN 1 CORNER				COLUMN 2 MID-SIDE				COLUMN 3 INTERNAL			
	$\Sigma \downarrow$ LOAD	X- AREA	FAR	$\Sigma \uparrow$ FAR	$\Sigma \downarrow$ LOAD	X- AREA	FAR	$\Sigma \uparrow$ FAR	$\Sigma \downarrow$ LOAD	X- AREA	FAR	$\Sigma \uparrow$ FAR
TOP	100	5	20	700	200	5	40	803	400	5	80	890
-1	200	5	40	680	400	5	80	763	800	10	80	810
-2	300	5	60	640	600	10	60	683	1200	15	80	730
-3	400	5	80	580	800	10	80	623	1600	20	80	650
-4	500	5	100	500	1000	10	100	543	2000	20	100	570
-5	600	10	60	400	1200	15	80	443	2400	25	96	470
-6	700	10	70	340	1400	15	93	363	2800	30	93	374
-7	800	10	80	270	1600	20	80	270	3200	35	91	281
-8	900	10	90	190	1800	20	90	190	3600	40	90	190
-9	1000	10	100	100	2000	20	100	100	4000	40	100	100

FIG. 3

STOREY	COLUMN 1 CORNER				COLUMN 2 MID-SIDE				COLUMN 3 INTERNAL			
	$\Sigma \downarrow$ LOAD	X- AREA	FAR	$\Sigma \uparrow$ FAR	$\Sigma \downarrow$ LOAD	X- AREA	FAR	$\Sigma \uparrow$ FAR	$\Sigma \downarrow$ LOAD	X- AREA	FAR	$\Sigma \uparrow$ FAR
TOP	100	5	20	700	200	10	20	700	400	20	20	700
-1	200	5	40	680	400	10	40	680	800	20	40	680
-2	300	5	60	640	600	10	60	640	1200	20	60	640
-3	400	5	80	580	800	10	80	580	1600	20	80	580
-4	500	5	100	500	1000	10	100	500	2000	20	100	500
-5	600	10	60	400	1200	10	60	400	2400	40	60	400
-6	700	10	70	340	1400	15	70	340	2800	40	70	340
-7	800	10	80	270	1600	20	80	270	3200	40	80	270
-8	900	10	90	190	1800	20	90	190	3600	40	90	190
-9	1000	10	100	100	2000	20	100	100	4000	40	100	100

FIG. 4

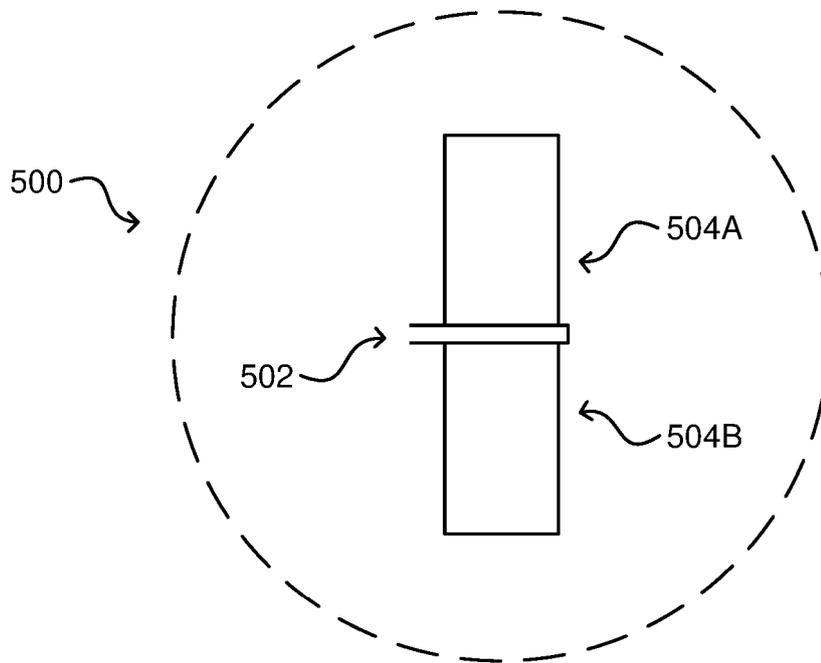
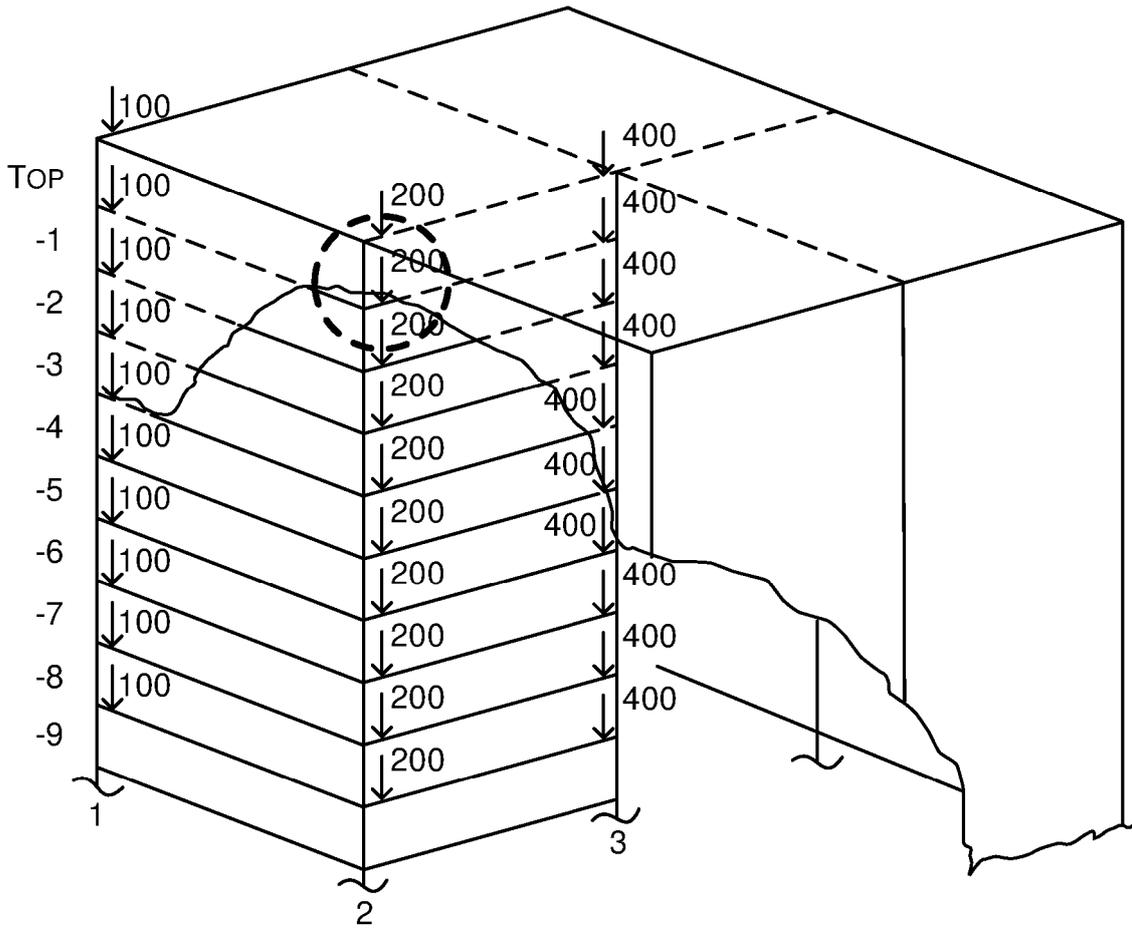


FIG. 5A

STOREY	COLUMN 1 CORNER				COLUMN 2 MID-SIDE				COLUMN 3 INTERNAL			
	$\Sigma \downarrow$ LOAD	X- AREA	FAR	$\Sigma \uparrow$ FAR	$\Sigma \downarrow$ LOAD	X- AREA	FAR	$\Sigma \uparrow$ FAR	$\Sigma \downarrow$ LOAD	X- AREA	FAR	$\Sigma \uparrow$ FAR
TOP	100	5	20	700	200	5	40-33 7	704	400	5	80-66 14	692
-1	200	5	40	680	400	5	80-33 47	697	800	10	80-33 47	678
-2	300	5	60	640	600	10	60	650	1200	15	80-33 47	631
-3	400	5	80	580	800	10	80	590	1600	20	80	584
-4	500	5	100	500	1000	10	100	510	2000	20	100	504
-5	600	10	60	400	1200	15	80	410	2400	25	96-33 63	404
-6	700	10	70	340	1400	15	93-33 60	330	2800	30	93-33 60	341
-7	800	10	80	270	1600	20	80	270	3200	35	91	281
-8	900	10	90	190	1800	20	90	190	3600	40	90	190
-9	1000	10	100	100	2000	20	100	100	4000	40	100	100

FIG. 5B

STOREY	AVERAGE $\sum \uparrow$ FARS ACROSS STOREY	AVERAGE $\sum \uparrow$ FAR – $\sum \uparrow$ FAR		
		COLUMN 1	COLUMN 2	COLUMN 3
TOP	798	98	-5	-92
-1	751	71	-12	-59
-2	684	44	1	-46
-3	618	38	-5	-32
-4	538	38	-5	-32
-5	438	38	-5	-32
-6	359	19	-4	-15
-7	274	4	4	-7
-8	190	0	0	0
-9	100	0	0	0

FIG. 6A

STOREY	AVERAGE $\sum \uparrow$ FARS ACROSS STOREY	AVERAGE $\sum \uparrow$ FAR – $\sum \uparrow$ FAR		
		COLUMN 1	COLUMN 2	COLUMN 3
TOP	699	-1	-5	7
-1	690	10	-7	12
-2	640	0	-10	9
-3	585	5	-5	1
-4	505	5	-5	1
-5	405	5	-5	1
-6	337	-3	7	-4
-7	274	4	4	-7
-8	190	0	0	0
-9	100	0	0	0

FIG. 6B

BUILDING OF FIG:	\sum X-AREA			SUM TOTAL
	CORNER COLUMN	MID-SIDE COLUMN	INTERNAL COLUMN	
2	55	110	220	385
3	75	130	240	445
4	75	150	300	525
5B	75	130	240	445

FIG. 7

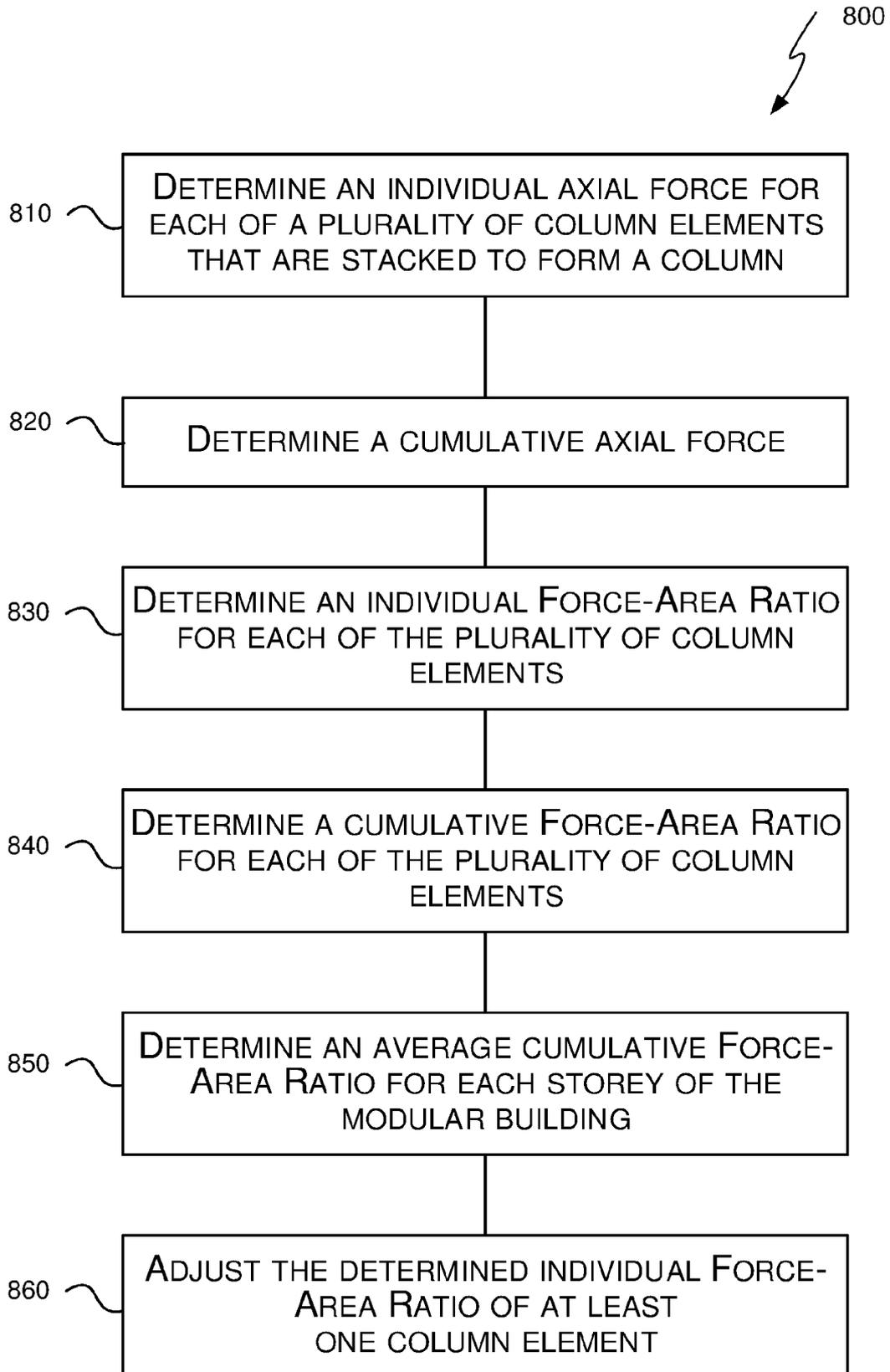


FIG. 8

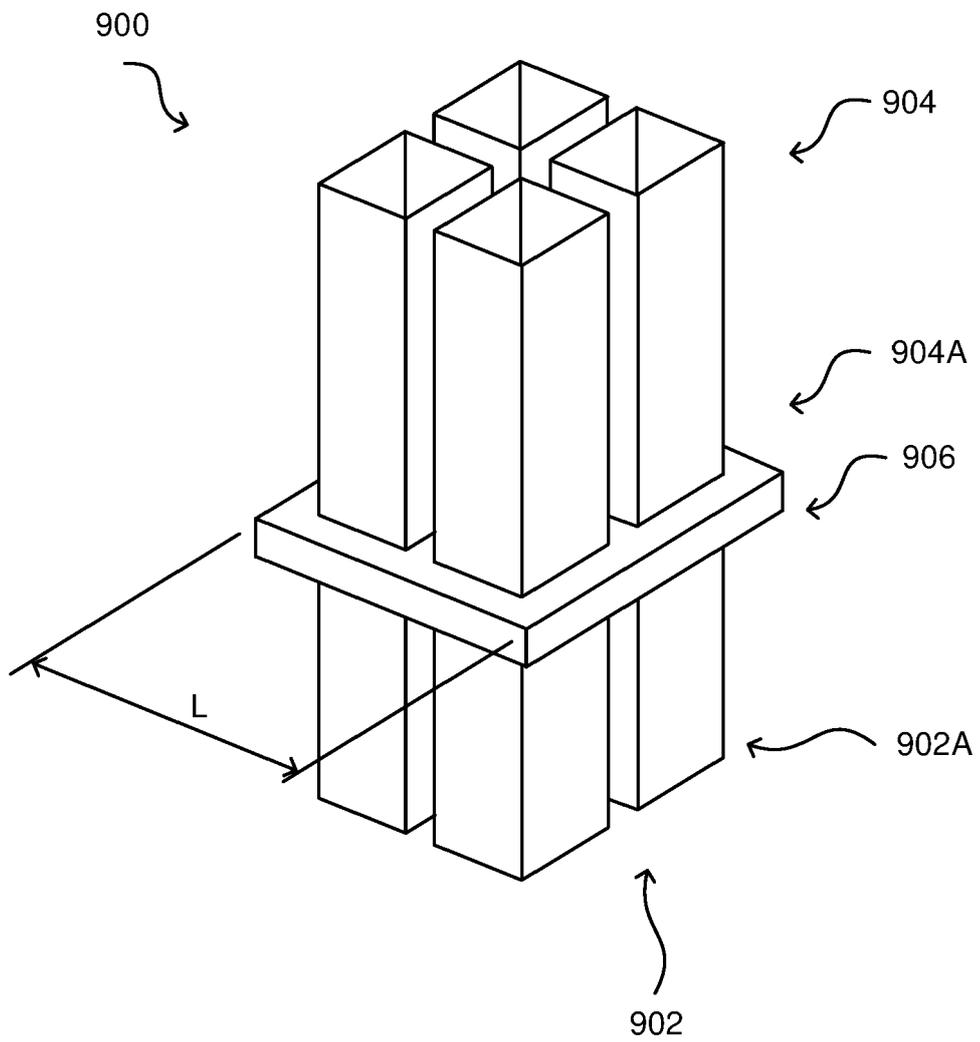


FIG. 9A

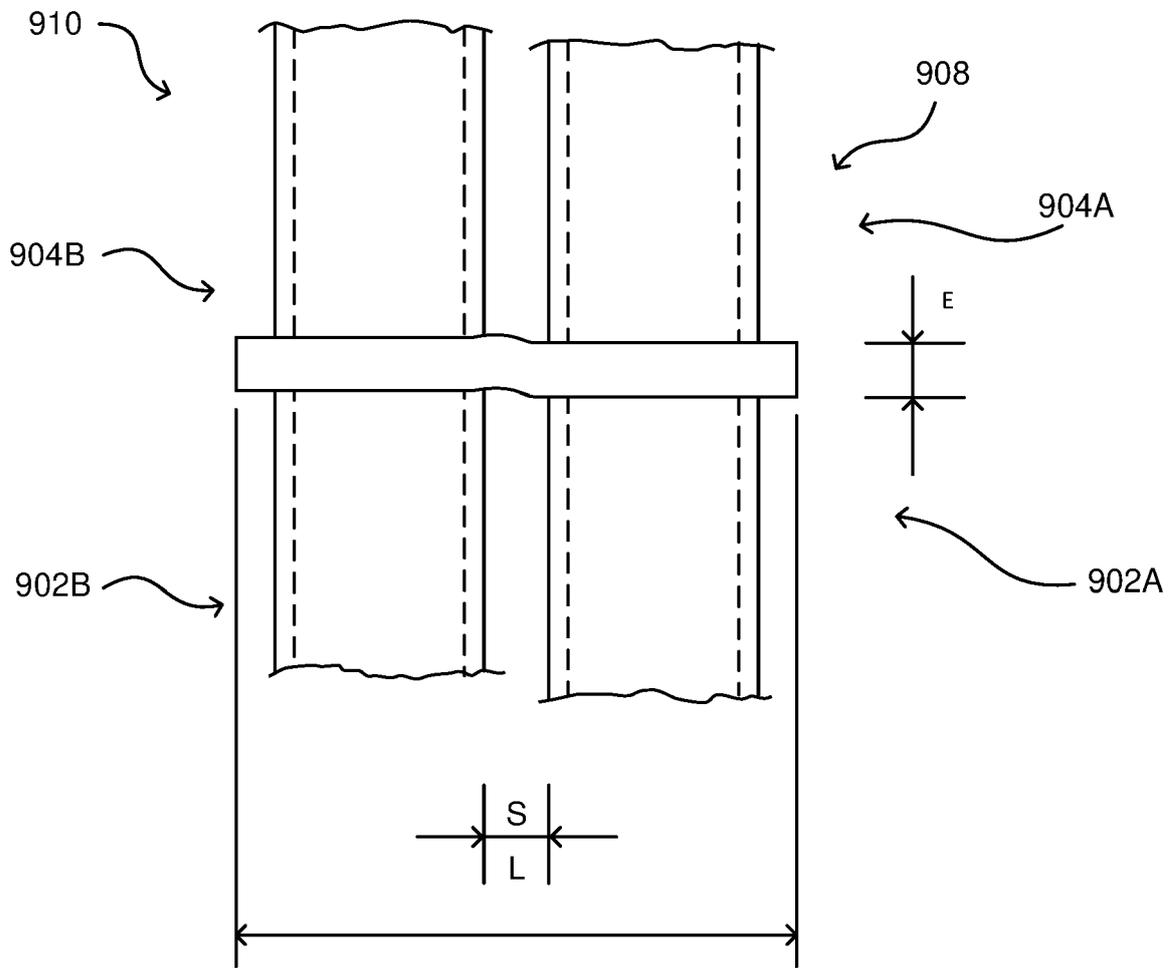


FIG. 9B

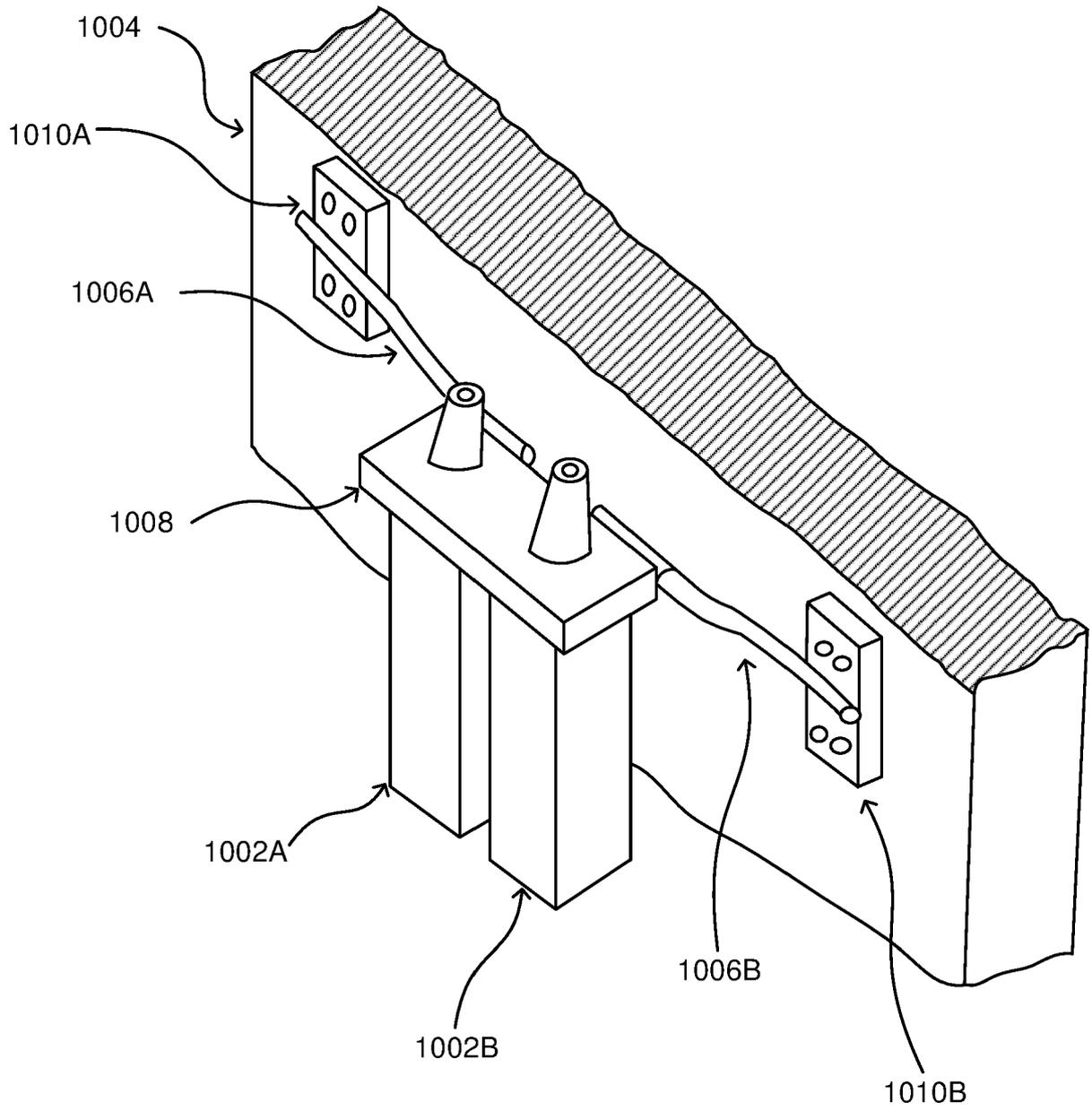


FIG. 10

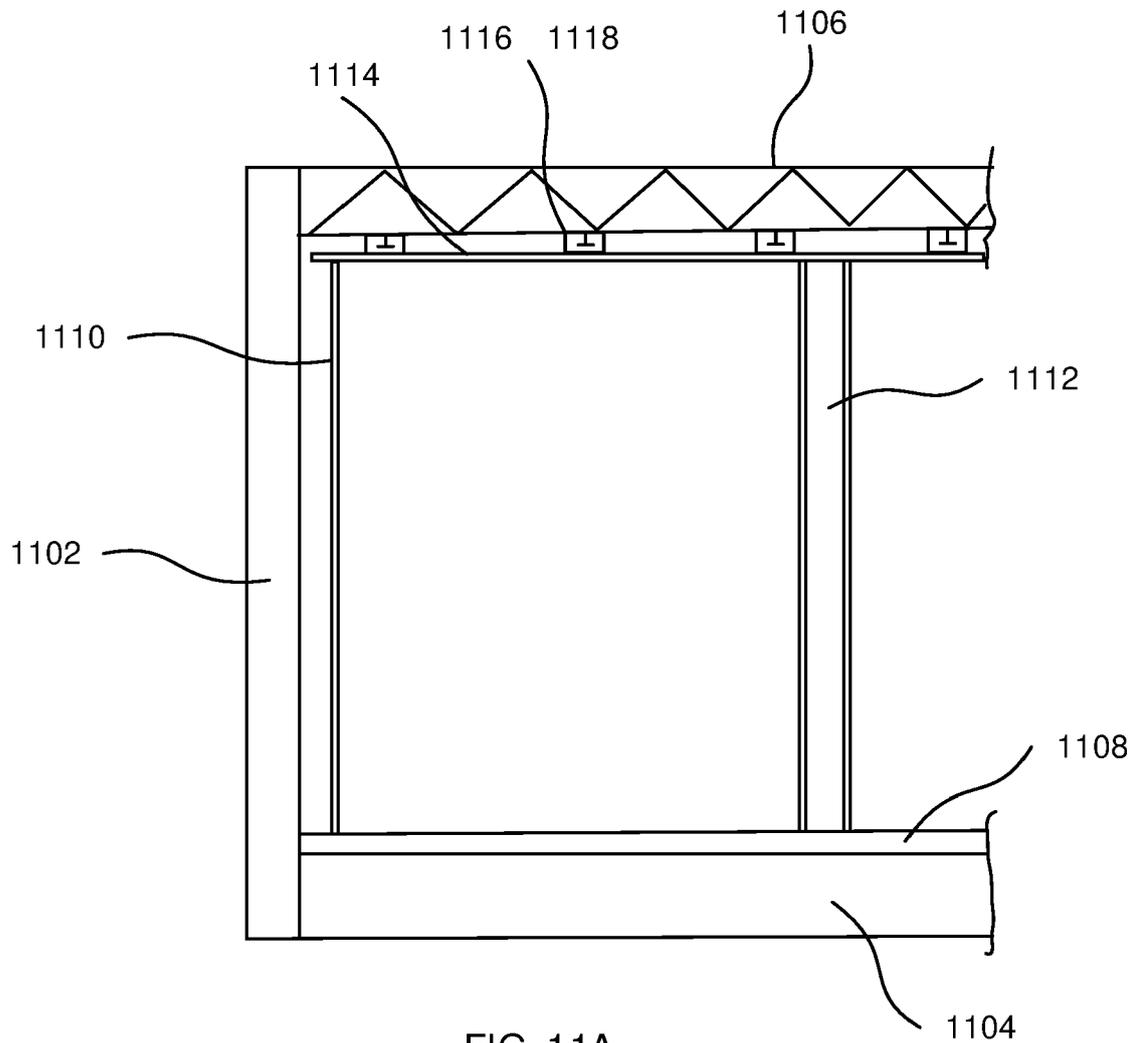


FIG. 11A

FIG. 11A

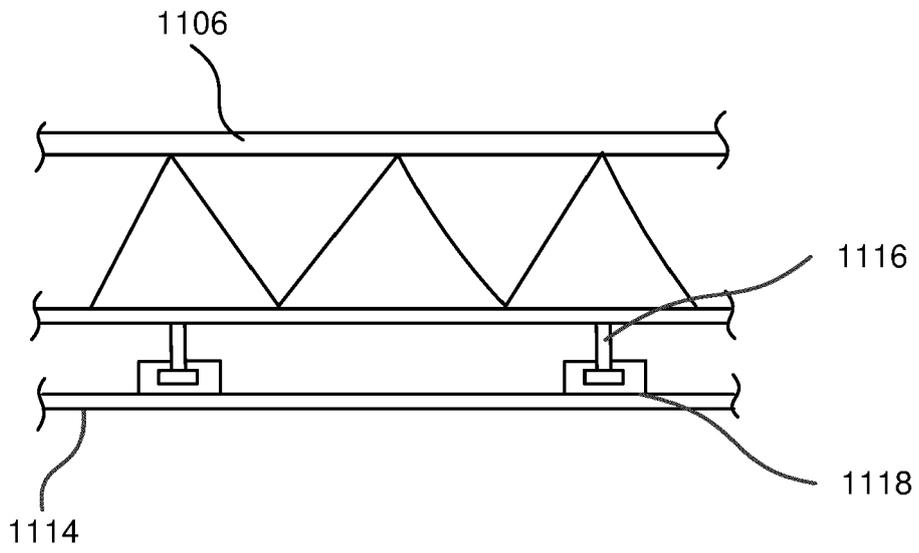


FIG. 11B



EUROPEAN SEARCH REPORT

Application Number

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X	FR 2 842 228 A1 (KNAUFALCOPOR SAS [FR]) 16 January 2004 (2004-01-16) * page 2, line 12 - page 3, line 20; figures 1-3 *	1-15	
			TECHNICAL FIELDS SEARCHED (IPC)
			E04B
1 The present search report has been drawn up for all claims			
Place of search The Hague		Date of completion of the search 9 December 2021	Examiner Melhem, Charbel
CATEGORY OF CITED DOCUMENTS X : particularly relevant if taken alone Y : particularly relevant if combined with another document of the same category A : technological background O : non-written disclosure P : intermediate document		T : theory or principle underlying the invention E : earlier patent document, but published on, or after the filing date D : document cited in the application L : document cited for other reasons & : member of the same patent family, corresponding document	

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