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(54) **DAMPING FOR TALL STRUCTURES**

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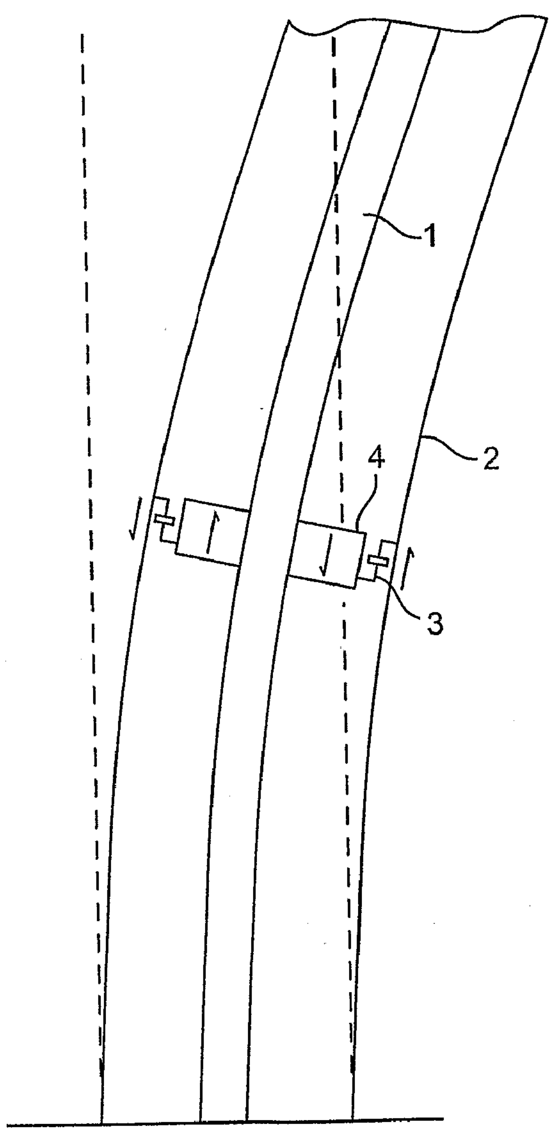
(57) **ABSTRACT**

A tall structure comprising two vertical parts is provided with a vertically orientated damping element, wherein the damping element is arranged to damp relative vertical movement between the two parts.



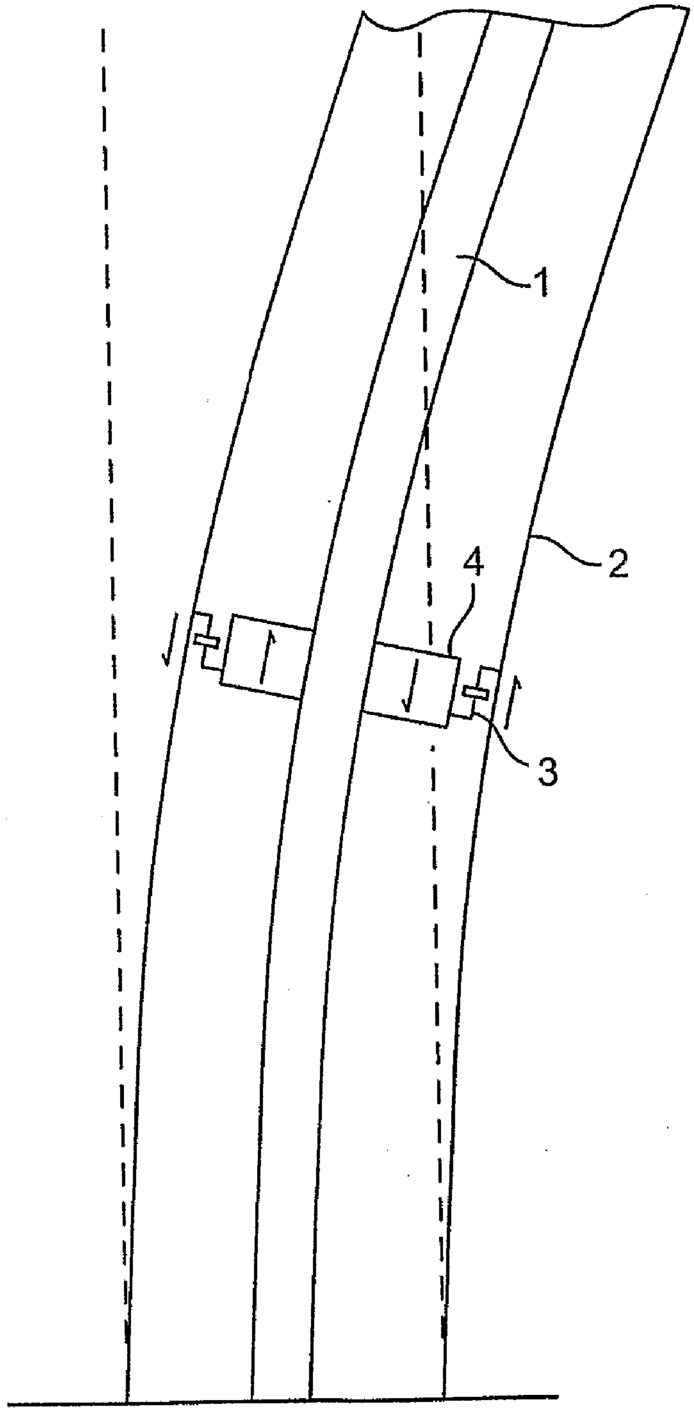


FIG. 1

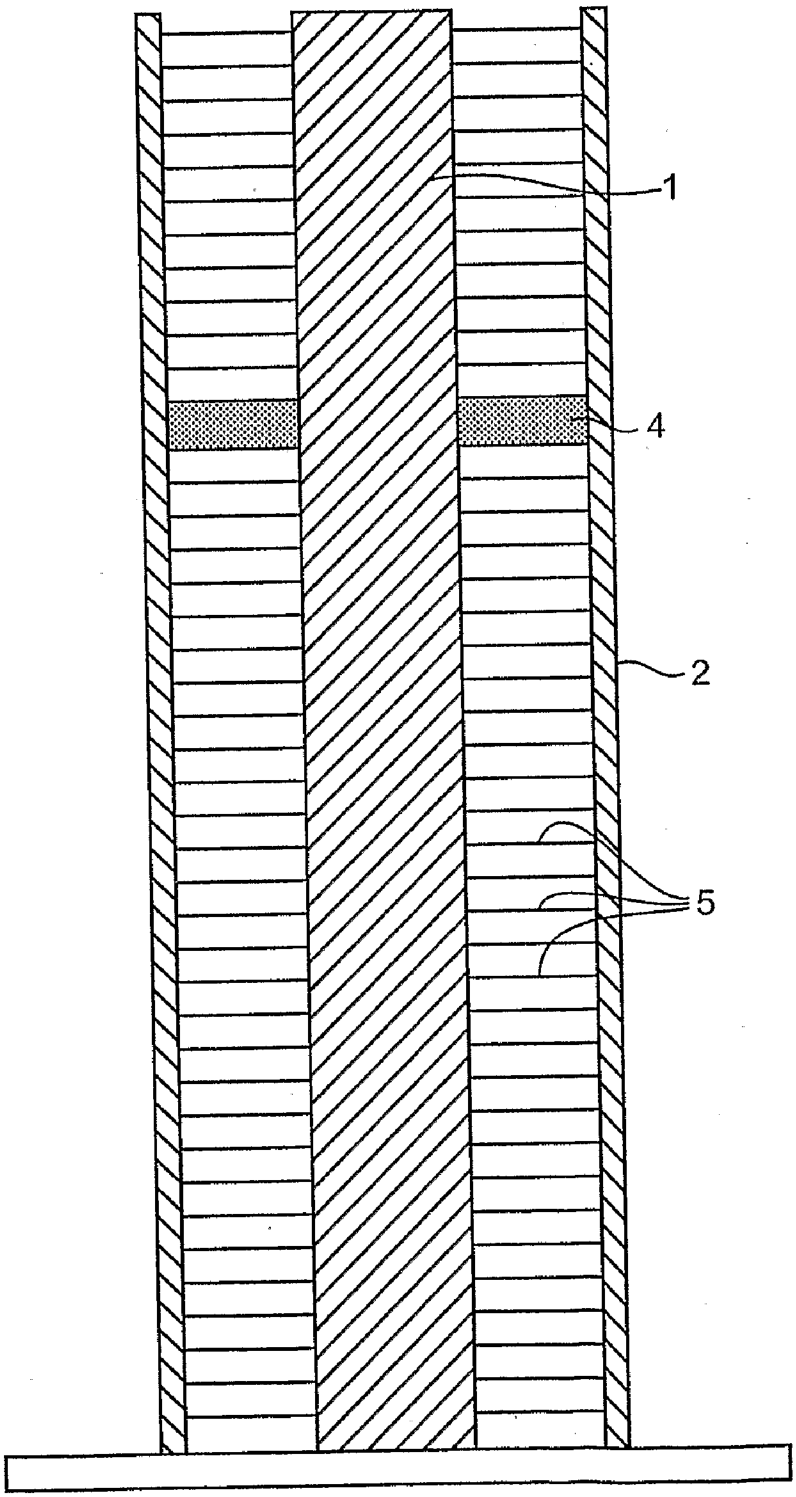


FIG. 2

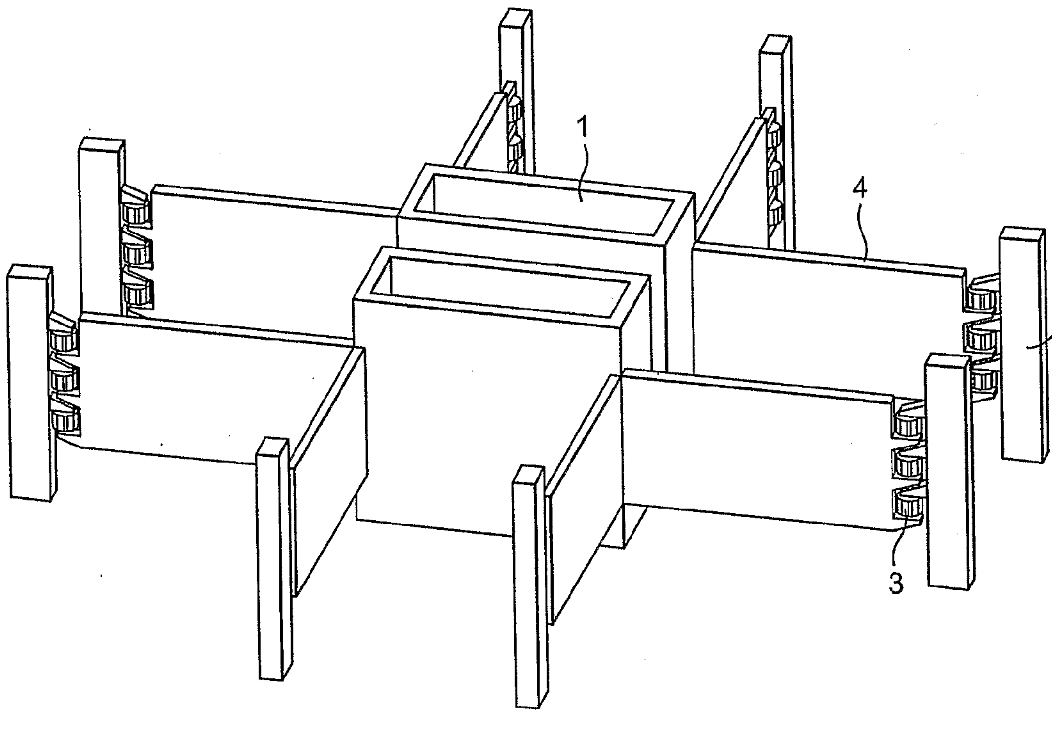


FIG. 3

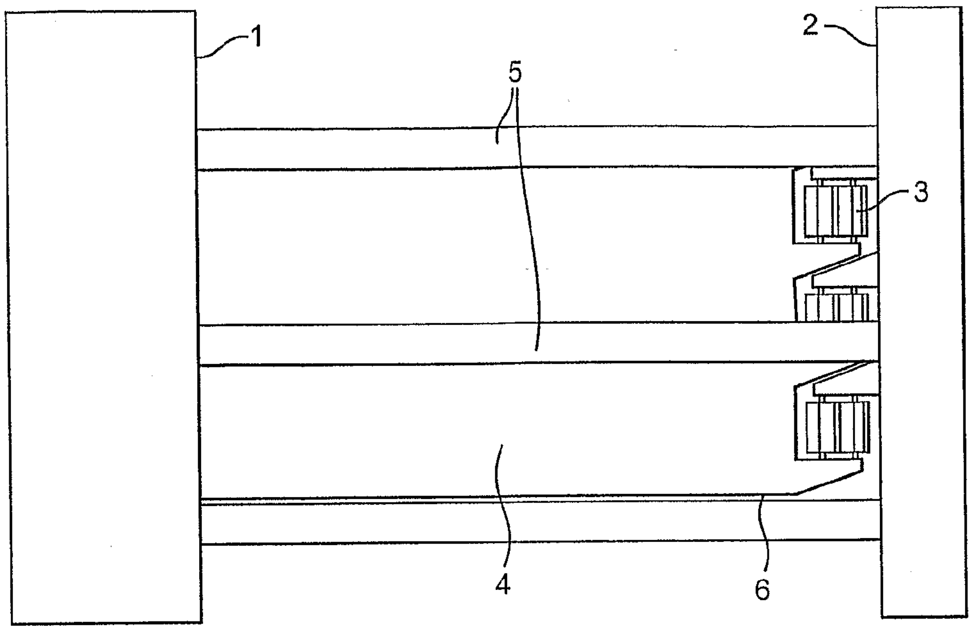


FIG. 4

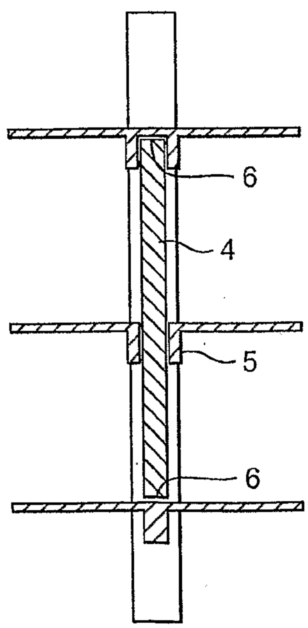


FIG. 5

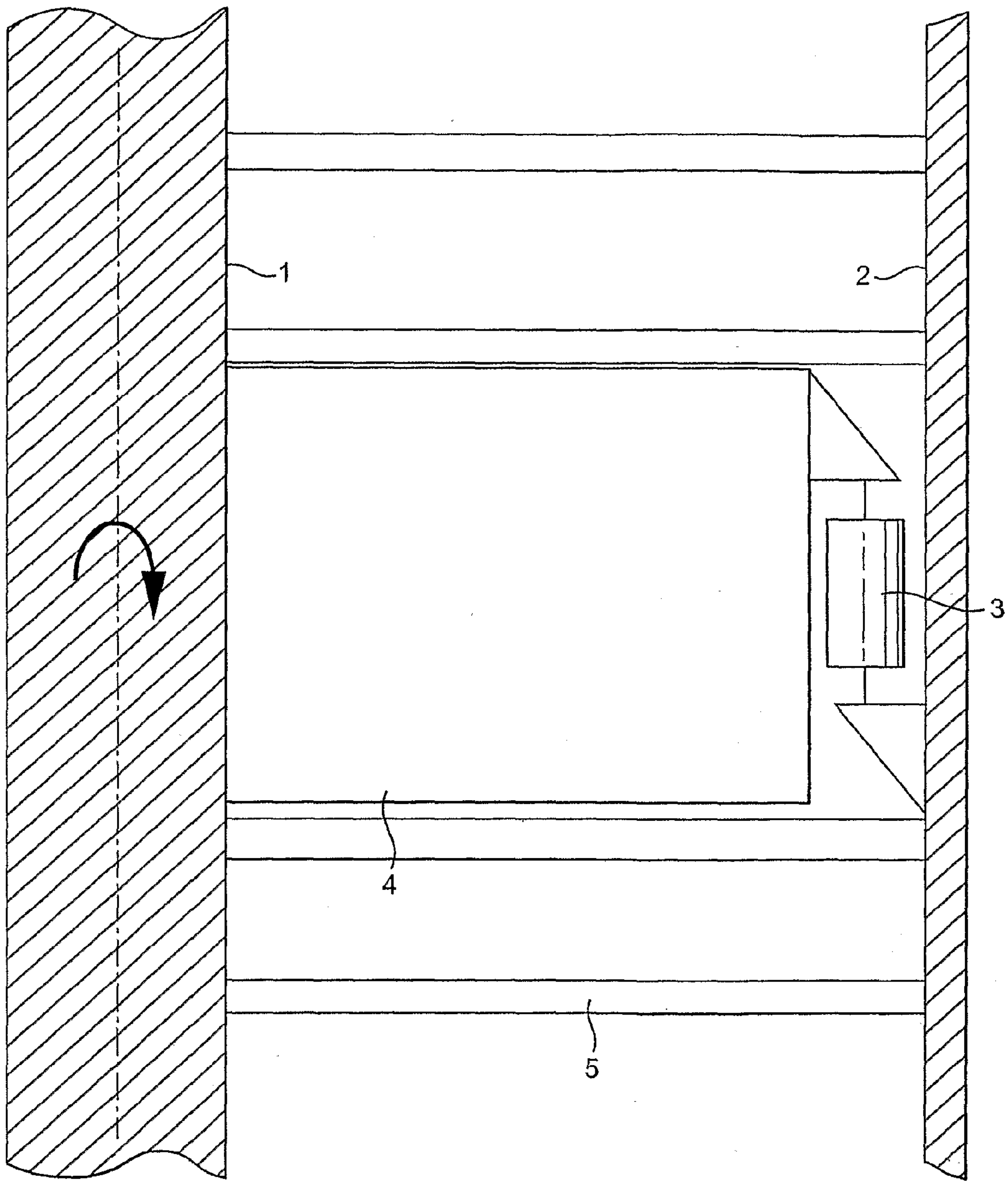


FIG. 6

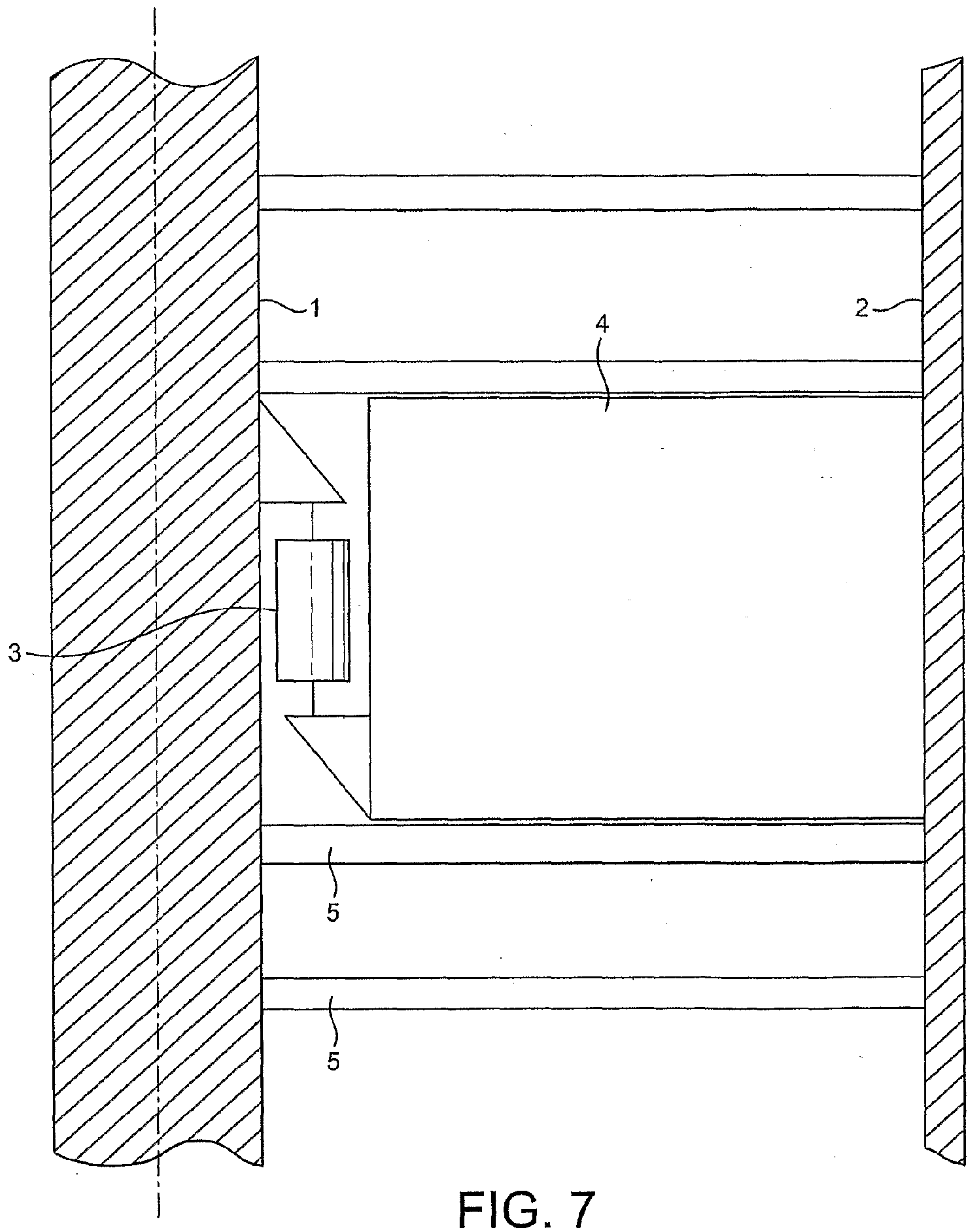


FIG. 7

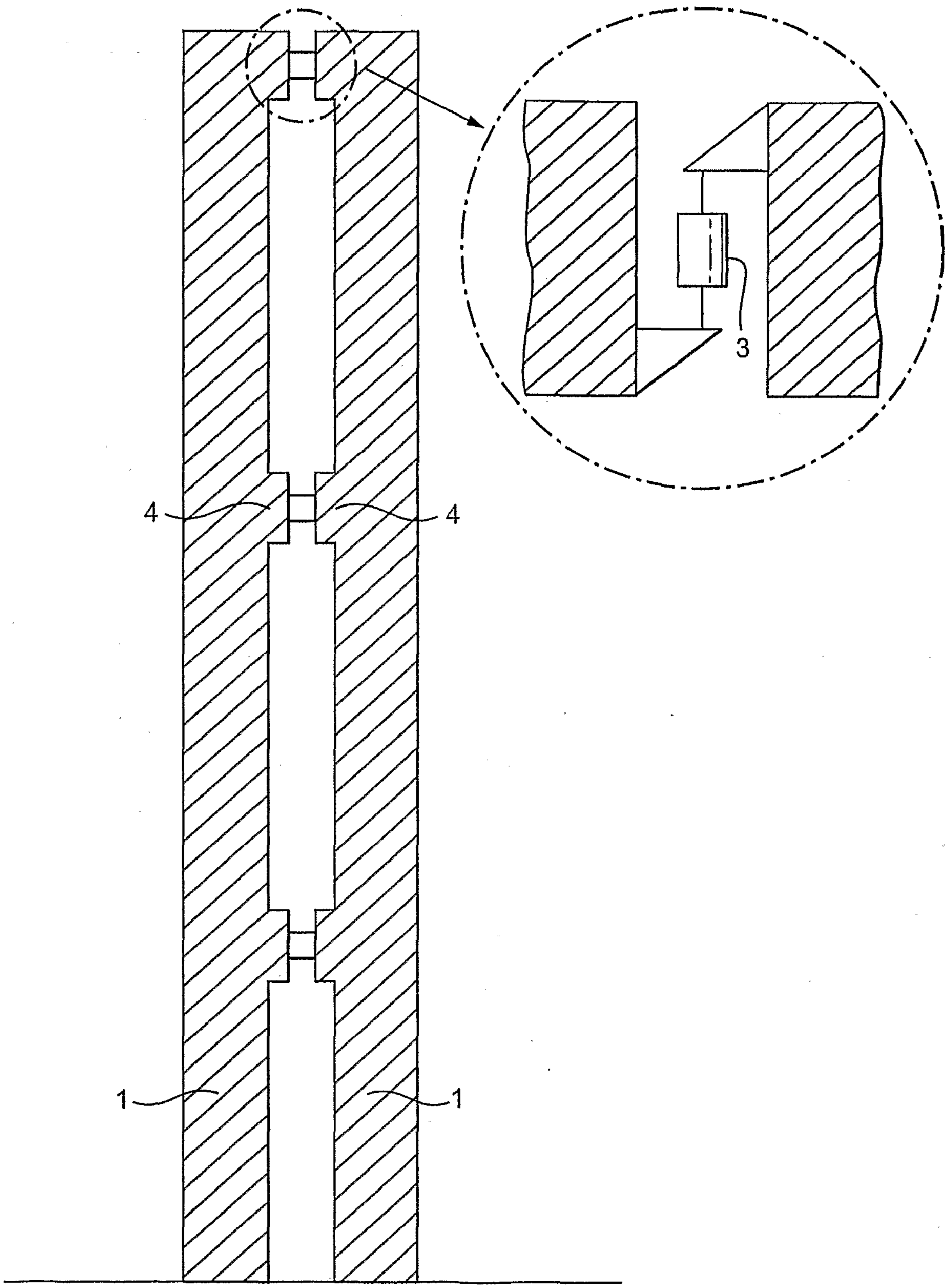


FIG. 8

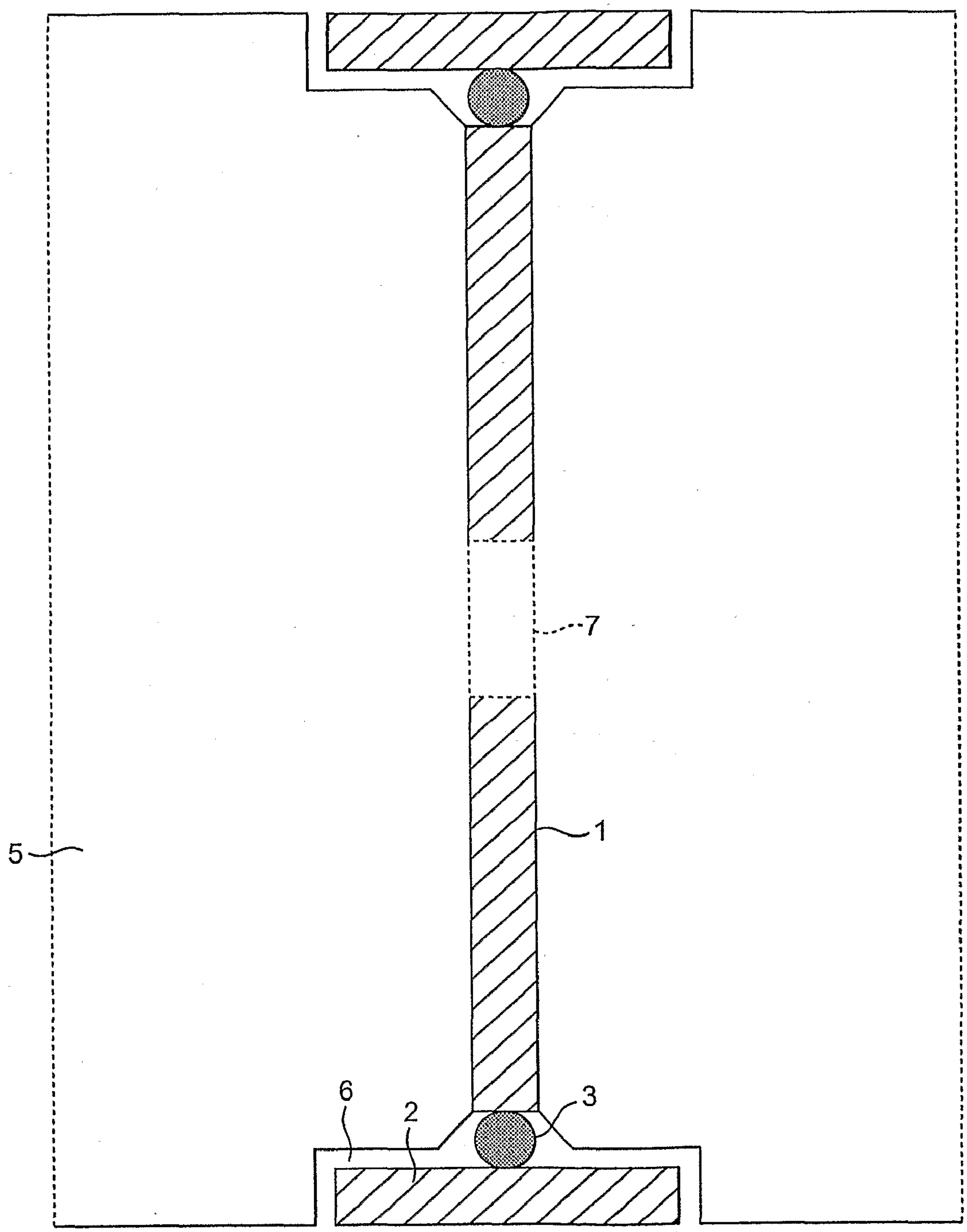


FIG. 9

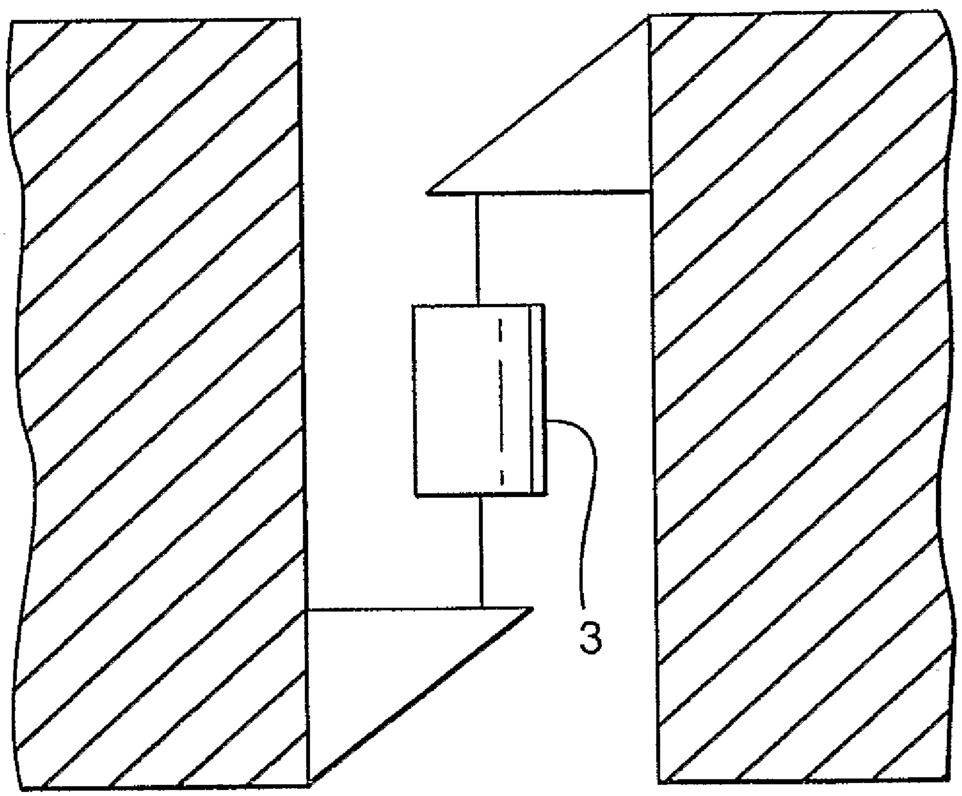


FIG. 10

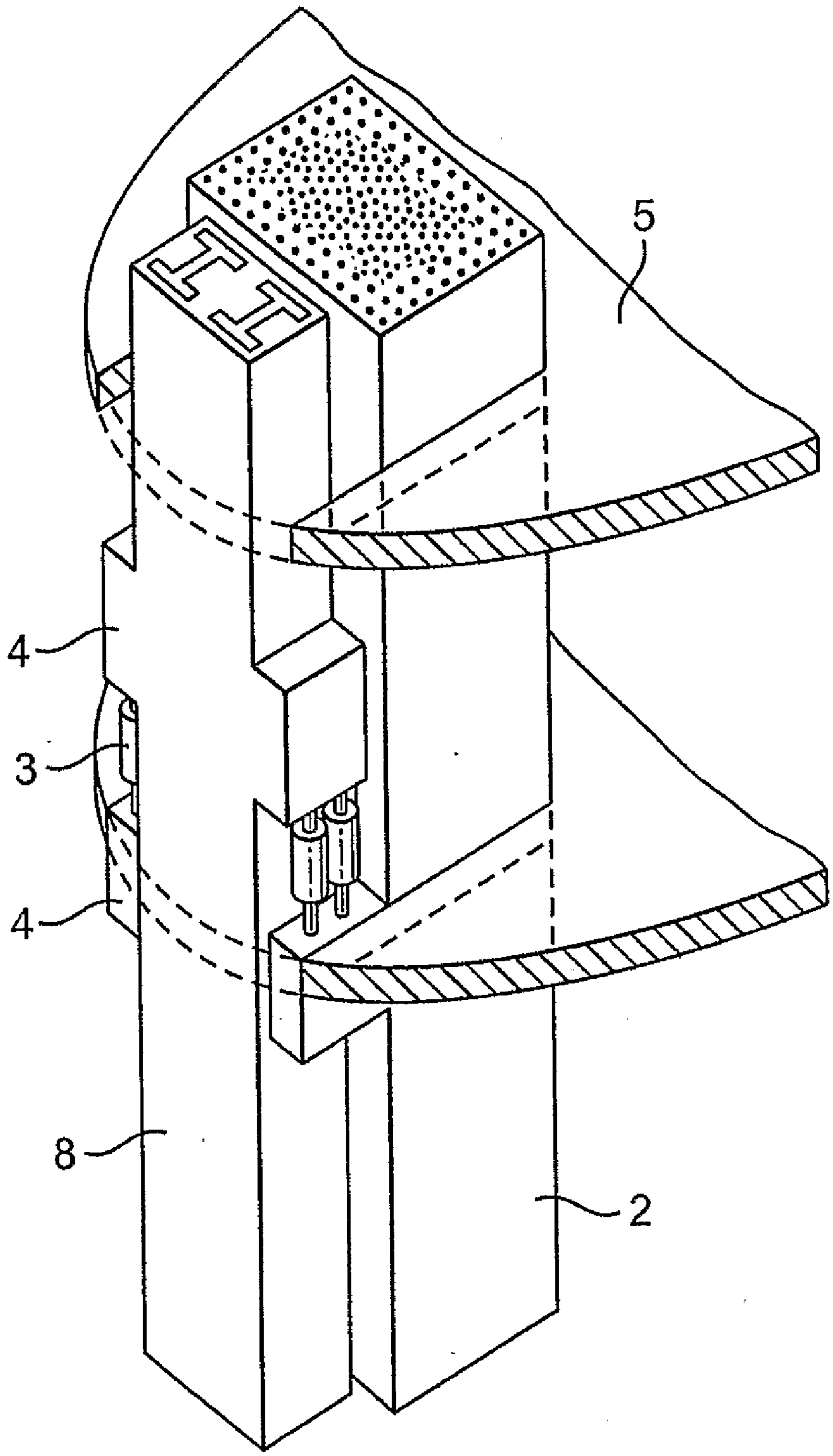


FIG. 11

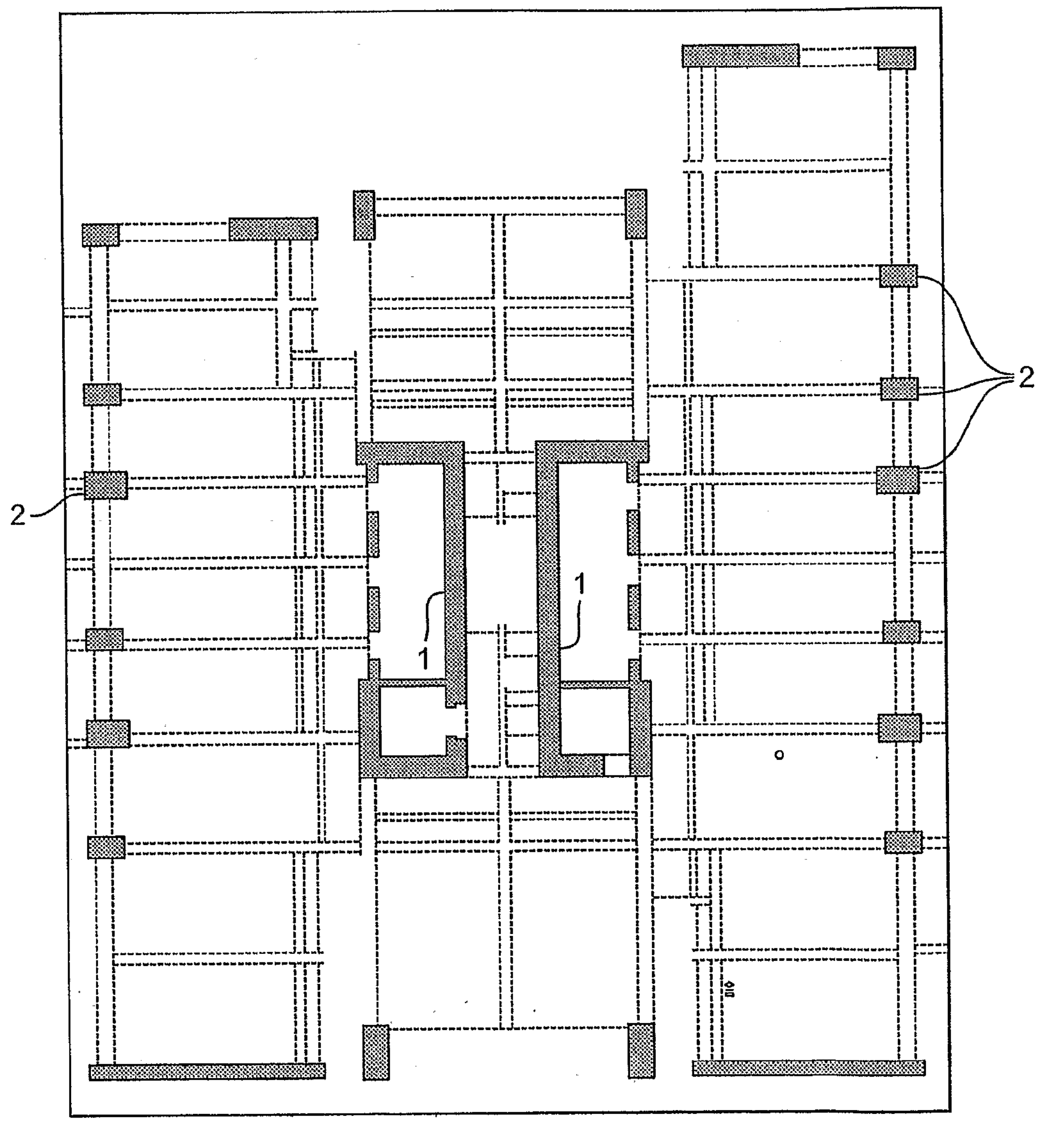


FIG. 12

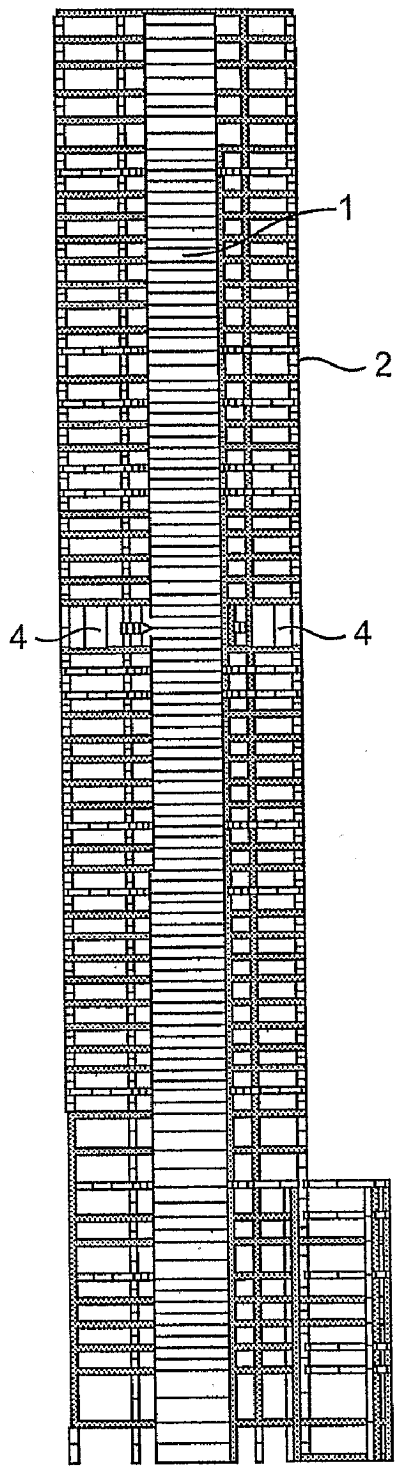


FIG. 13

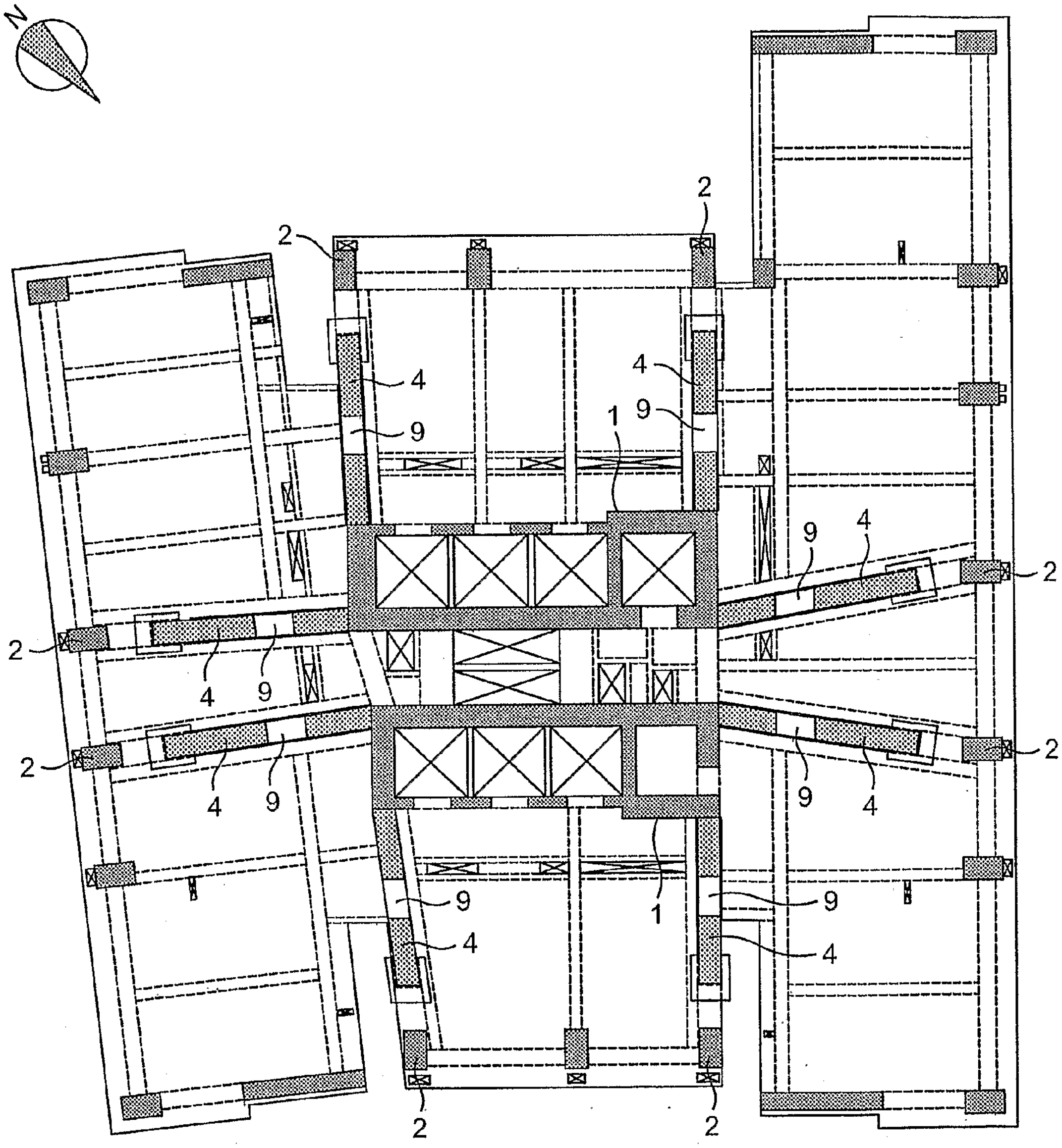


FIG. 14

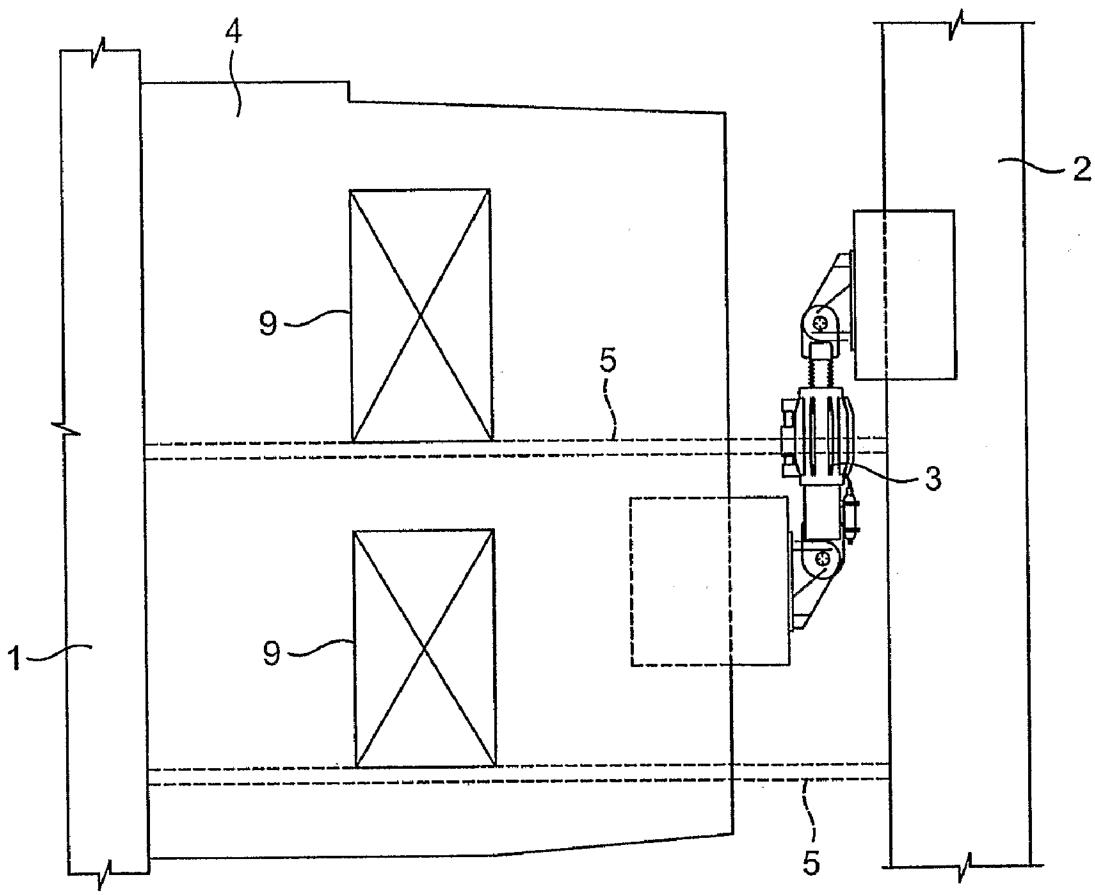


FIG. 15

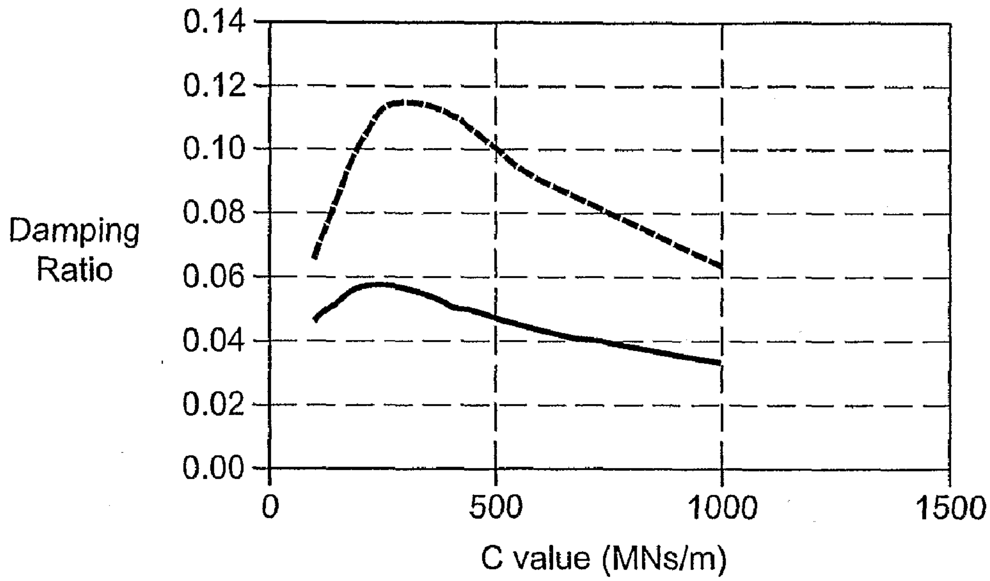

0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
Damping Ratio
0
500
1000
1500
C value (MNs/m)

FIG. 16

DAMPING FOR TALL STRUCTURES

FIELD

[0001] The present invention relates to a system for damping the movement of tall structures, in particular tall buildings.

BACKGROUND

[0002] Tall structures such as high rise buildings are often constructed incorporating several structural systems to provide resistance to lateral forces. Typically there may be 'cores', usually within the body of the building and 'frames' of beams and columns around the external perimeter and sometimes internally too. Each floor is supported vertically by the cores and by external and/or internal columns.

[0003] During the design of tall structures, it is often found that the dynamic resonant response of the structure to incident wind gusts, from vortex shedding and other aerodynamic effects leads to a need for a significant increase in the stiffness and strength in the lateral resisting structure. It is also common for wind-induced sway motion of a building to be perceptible to occupants, and this is a further design consideration that may require the dynamic response to be reduced. In seismic regions, earthquakes also induce strong lateral motions, and reduction of the lateral dynamic response and damage is desirable in this case too. Increasing the stiffness and/or mass of a building by adding structural elements or increasing their sizes may reduce wind induced movement, but also increases the expense of a building and its foundations, and may reduce usable floor area. Adding stiffness does not always improve seismic performance.

[0004] Adding damping (energy dissipation) to a building reduces the dynamic response and thus the loads in the building's structural members and foundation. If sufficient damping is added to the building, structural member sizes and foundations can be reduced and the risk of the motion of a building being noticed and being uncomfortable to occupants can be reduced or eliminated.

[0005] Therefore the incorporation of damping elements into a structure can lead to significant construction cost savings through the reduction of structural element sizes, and superior performance during wind and earthquake loading.

SUMMARY

[0006] The present invention in a first aspect seeks to provide an improved structure that incorporates damping elements.

[0007] Viewed from a first aspect, therefore, the present invention provides a tall structure comprising two vertically extending parts and a vertically orientated damping element, wherein the damping element is arranged to damp relative vertical movement between the two parts.

[0008] By vertically extending it is meant that the two parts have a vertical extent, preferably generally vertical when the structure is at rest. When a swaying motion occurs the parts and the damping element will of course move away from the vertical to some extent as the structure moves. Defined another way, vertically extending could be taken to mean that the parts generally support their own weight and the weight of supported floors, if any, by compression or tension action rather than bending action when the structure is at rest.

[0009] During swaying motion of the structure rotation of the parts and shear movement between the two parts results in relative movement between the parts in the direction along the length of the parts. By providing a damping element to damp this movement, the swaying motion of the structure can be effectively diminished, leading to the advantages discussed above. The use of a vertical damping element also has the additional advantage that it will accommodate the effects of static differential axial shortening between cores or between cores and adjacent frames and the like.

[0010] The damping element may be any energy dissipating element or connection such as a passive viscous, visco-elastic, hysteretic or frictional damper, or an actively controlled damping mechanism.

[0011] The relatively high levels of structural damping provided reduces the lateral forces under wind action for which tall structures have to be designed and permits the use of fewer and/or smaller structural elements and smaller foundations, reducing the construction cost, and reducing the damage sustained by the structure in an earthquake.

[0012] In a preferred embodiment the tall structure is a tall building. As well as the advantages discussed above the additional damping when applied to a building reduces the perceptibility of motion of the building to occupants of the building.

[0013] It is envisaged that the invention will find particular application in buildings over 60 m in height, more particularly over 80 m in height.

[0014] The damping element or elements is or are preferably placed within the upper 75% of the height of the structure.

[0015] The vertically extending parts may be cores, perimeter columns, shear walls, end walls or simply be vertical elements added to the structure for damping purposes. Thus typically, the two parts may be a core and another core, or a core and perimeter columns, or between two sub parts of a column Cores, columns and shear walls are often the primary elements of existing tall structures, and as a result an existing structure may be retro-fitted with damping elements in accordance with the invention.

[0016] In a preferred embodiment the structure may include a horizontal element extending from one of the vertically extending parts, with the damping element damping relative movement between the horizontal element, more particularly the distal end of the horizontal element, and the other vertically extending part. Two horizontal elements may be used, one joined to each vertically extending part with the damping element joined between the horizontal elements.

[0017] By using horizontal elements the rotation of the vertical element in combination with the length of the horizontal element magnifies the relative movement and thus the damping element can act to damp a larger relative movement, which makes the damping more effective. In addition, this arrangement allows damping between vertically extending parts which are spaced some distance apart.

[0018] Preferably the horizontal elements are relatively stiff. This ensures that the forces in the load path between the two vertical parts along the horizontal elements and the damping element do not significantly deform the horizontal element, and thus the maximum displacement is applied to the damping element.

[0019] In a preferred embodiment the vertically extending parts comprise a core and a perimeter column and the horizontal element is a horizontally extending outrigger between the core and the column. The outrigger may be connected to either of the core or the column with the damping element at its free end connected to the other of the core or the column. This arrangement allows the invention to be easily implemented in a core and perimeter column structure of a conventional type.

[0020] This outrigger arrangement is in contrast to known outriggers, which rigidly connect cores and perimeter column structures to stiffen the building. Designs employing the known rigidly connected outriggers can result in larger structural elements and an increased construction cost compared to the present damped arrangement.

[0021] The horizontal element may be relatively thin in width in the horizontal direction perpendicular to the direction of extension of the elements, i.e. it may extend in an elongate fashion from the vertical part when viewed in a floor plan of the structure. Preferably the horizontal element is substantially taller in side view than its width. Where the structure is a tall building the horizontal element may extend in height across more than one storey of the building. This tall thin arrangement provides a horizontal element which is stiff in the vertical direction, but which is light and cheap to construct as it is thin in plan view. The horizontal element also does not disrupt the floor plan of the building as it can be conveniently placed as part of a wall dividing parts of the floor plan. In a particularly preferred embodiment the building is of the order of 60 storeys or 210 m tall, and the horizontal element extends vertically across two full storeys. The horizontal element may have openings forming doorways or passageways for utilities. In particular there may be doorways where the horizontal element intersects a floor level.

[0022] A plurality of damping elements may be arranged at the same height about the vertical parts. The damping elements may join a single core to a plurality of perimeter columns. Where horizontal elements are used there may be elements generally extending in different plan directions from a core. For example there may be horizontal elements extending in opposite horizontal directions from a core, or more preferably there may be elements generally extending at 90° intervals about the core, with each horizontal element having an associated damping element. The arrangement of a plurality of damping elements about the building provides additional damping in all possible directions of sway motion. In a symmetrical structure damping of this type will generally be achieved by a symmetrical damping element arrangement. In a structure with an asymmetrical floor plan an asymmetrical arrangement of dampers may be required. The asymmetry could be achieved, for example, by varying the number or resistance characteristics of the dampers or the size of any horizontal elements. In the case of buildings which have different degrees of susceptibility to dynamic motions in two orthogonal directions e.g. buildings which are rectangular in plan, the damping elements may be arranged to provide more damping for sway motions in the critical direction. This could mean fewer, or lower capacity, or an absence of, damping elements acting to suppress sway motions in the less critical direction of sway.

[0023] There may be several sets of damping elements, the sets being at different heights on the structure. For a given damping ratio, distributing the damping elements across multiple heights can reduce the local damping forces on the structure, the peak forces applied by the damping elements may be a consideration in the design of the structure.

[0024] The vertically extending parts may be two closely spaced cores, or a core and closely spaced end wall or column with the damping element or elements connected between the parts by means of relatively short horizontal elements, corbels or brackets. In this case the relative movement of the vertical parts is a shear movement as the structure sways.

[0025] In a preferred embodiment the vertical parts are a load bearing part and a non-load bearing part provided for damping purposes. By non-load bearing it is meant that the vertical part does not bear any significant load, other than self-weight, when the structure is at rest, i.e. the weight of the floors, cladding and imposed gravity loads structure is carried by other parts. The non-load bearing part mainly carries dynamic loads that arise during swaying movement of the structure. These dynamic loads are passed to the non-load bearing part by the damping element. The additional non-load bearing part may be placed alongside the load bearing part, with damping elements connected between brackets or short horizontal elements such as corbels on the two vertical parts. Using an additional non-load bearing vertical part in this way allows the remainder of the structure to be designed in a conventional fashion to carry the static loads.

[0026] Viewed from a second aspect the present invention provides a method of providing damping for a tall structure, the structure having two vertically extending parts, the method comprising providing a vertically acting damping element which damps relative movement between the two parts.

[0027] The term vertically extending means the same as for the first aspect of the invention. The vertical parts and the damping elements used in the method may incorporate the preferred features described above.

[0028] The method may be used in the construction of a tall structure, preferably a tall building, or alternatively the method may be for retro-fitting damping elements to an existing building.

[0029] In a further aspect, the present invention provides a system for adding significant levels of structural damping to a tall building through the use of stiff 'outrigger' structures extending horizontally between cores or from cores to other vertical elements such as perimeter columns, the system incorporating an energy dissipating connection within the outrigger load path. The energy dissipating connection or damping element may be viscous (i.e. increases with velocity to the power of some exponent), visco-elastic (i.e. provides energy dissipation and stiffness), hysteretic or frictional.

[0030] From a further broad aspect the invention provides a building comprising two parts which may move vertically relative to one another when the building sways, and a damper arranged between the two parts, which is capable of damping that relative vertical movement.

[0031] Preferably the damper is arranged to act generally vertically to damp the movement.

[0032] Preferably the two parts are arranged vertically, so that in a particularly preferred embodiment the damper acts in a direction generally parallel to the parts.

[0033] In another aspect, the invention provides a building comprising two parts which may move relative to one another when the building sways, and a damper arranged so as to act in a direction parallel to the two parts to damp that relative movement.

BRIEF DESCRIPTION OF THE FIGURES

[0034] Some preferred embodiments of the present invention will now be described by way of example only and with reference to the accompanying drawings in which:

[0035] FIG. **1** shows a structure in swaying motion illustrating the placement of damping elements between vertical parts,

[0036] FIG. **2** illustrates a core and perimeter column structure with an outrigger,

[0037] FIG. **3** is a perspective view of an embodiment of a damping element arrangement,

[0038] FIG. **4** shows one of the horizontal element and damping elements of FIG. **3** in side view,

[0039] FIG. **5** shows a cross-sectional view of the parts shown in FIG. **4**,

[0040] FIG. **6** is an embodiment having an outrigger,

[0041] FIG. **7** is an alternative outrigger embodiment,

[0042] FIG. **8** shows damping elements between two shear walls or cores,

[0043] FIG. **9** shows damping elements between shear walls and end walls,

[0044] FIG. **10** is a side view showing detail of a damping element in the embodiment of FIG. **9**,

[0045] FIG. **11** is an embodiment with a load bearing and a non-load bearing column,

[0046] FIG. **12** is a floor plan of a tall building,

[0047] FIG. **13** shows a tall building in side view,

[0048] FIG. **14** is a floor plan at the outrigger level of a tall building,

[0049] FIG. **15** is a side view of an outrigger in FIG. **14**, and

[0050] FIG. **16** is a graph showing how damping varies with damper resistance.

[0051] FIG. **1** illustrates the principle of the present invention.

DETAILED DESCRIPTION

[0052] In FIG. **1** a tall structure is illustrated schematically as having vertical parts in the form of a core **1** and perimeter column **2**. Vertically acting damping elements **3** are placed to damp relative vertical motion between the core **1** and column **2** as the structure sways. The upright or at rest position of the structure is shown by the dashed lines. It will be appreciated that the amount of swaying movement has been exaggerated for illustrative purposes. The damping elements **3** are connected to the core via horizontal elements in the form of relatively stiff outriggers **4**, which are rigidly connected to and extend horizontally from the core **1**.

[0053] FIG. **2** shows a tall building similar in construction to the structure of FIG. **1**. The core **1** and columns **2** support a number of floors **5**. Outriggers **4** are placed at an elevated position and in accordance with an embodiment would be connected to the columns **2** at their outer ends by damping elements which are not shown.

[0054] During sway motion of the tall structure induced by dynamic loading, a core **1** and a perimeter column **2** (or another core) will at one instant in time, at the level of the outriggers **4**, be at some angle, say theta, to the vertical through bending action.

[0055] The outrigger **4** is not connected rigidly to the perimeter columns **2**, but through the relatively flexible vertically acting damping element **3**. As the outrigger **4** is relatively stiff and undergoes little deformation, its outermost end will move vertically by a linear displacement of approximately L multiplied by theta (L.theta), where L is the horizontal length from the centre of the core to the perimeter column. This will cause the damping element **3** to undergo the same displacement (L.theta). As the structure vibrates in its sway modes this relative vertical displacement will continuously vary, and the damping element **3** will change length and develop a force that will oppose the motion, thus converting kinetic energy in the structure to thermal energy in the energy dissipating device.

[0056] FIG. **3** shows a perspective view of an arrangement of horizontal elements **4** and damping elements **3** which can be used in a building of the type shown in FIG. **2**. The horizontal elements **4** are eight outriggers **4** provided in pairs symmetrically about the core **1**. The vertical parts are the core **1** and eight perimeter columns **2**, one for each outrigger **4**. The outriggers **4** take the form of two storey deep reinforced concrete walls and three damping elements **3** (in this case viscous dampers) are provided per outrigger **4** at the connection between the outrigger **4** and the perimeter columns **2**.

[0057] FIG. **4** shows a side view of one outrigger **4** showing the floor beams **5**. A gap **6** is provided between the outrigger **4** and the lowest floor level shown. To accommodate the outrigger **4** and the floor beams **5** and allow vertical movement between the end of the outrigger **4** and the perimeter column **2** it is necessary for the floors **5** to span independently of the outriggers **4**. One method by which this can be achieved is shown in FIG. **5**, in which the outrigger **4** is the height of two floors. In FIG. **5** the gap **6** at the bottom of the outrigger **4** is shown, and another gap **6** is provided between the upper floor level shown and the outrigger. To allow the outrigger **4** to move freely it passes though a slot in the central floor level without touching the floor or floor beams **5**.

[0058] In practice the effectiveness of the system depends on the relative stiffnesses of the various components of the structural system, including the flexibility of the outriggers. The damping may be provided by one or several damping units per outrigger. For simplicity a single damping element **3** is often shown or referred to, but it should be appreciated that this may be replaced by a number of damping elements **3**.

[0059] FIG. **6** shows schematically the connection of a damping element **3** between an outrigger **4** and a column **2**. When swaying causes relative movement of the vertical column **2** and core **1**, and rotation of the core **1** where the outrigger **4** s connected, as shown by the arrow, relative movement along the damping element **3** occurs, and thus the damping element **3** damps motion of the structure.

[0060] FIG. **7** is an alternative arrangement to that shown in FIG. **6**, where the outrigger **4** is joined to the column **2** and the damping element **3** is then installed between the core **1** and the outrigger **4**.

[0061] The damping elements **3** can be installed between two cores or shear walls **1** as shown in FIG. **8**. A number of damping elements **3** are connected to short horizontal elements **4** in the form of corbels, and provide damping between the two core structures **1** over the building height.

[0062] FIG. **9** shows a plan view with damping elements **3** provided between the 'flanges' of building cores or shear walls **1** and end walls or columns **2**. The damping elements **3** can be supported by short horizontal corbels as in the embodiment of FIG. **8**, but can be simply fixed to brackets directly on the vertical parts as shown side view in FIG. **10**. A gap **6** around the floor **5** allows unimpeded relative motion between the walls **1**, **2**, and the two shear walls or cores **1** may be joined by an interconnecting beam **7**.

[0063] In FIG. **11** the damping elements **3** are connected to a load bearing column **2**, and a non-load bearing column **8**. The column **2** provides support for floor parts **5** and other parts of the building, whereas the non-load bearing column **8** is provided for damping purposes in order to carry dynamic loads during movement of the building, but does not carry any significant static loads. The damping elements **3** are joined to short horizontal elements **4** provided on the respective columns **2**, **8**.

[0064] It will be appreciated that in alternative embodiments the column **2** of FIG. **11** could be a core **1** or another vertical part of a building.

[0065] FIGS. **12** to **16** show a damping system installed in a **60** storey 210 m high reinforced concrete building with two central lift-shaft core structures **1** and a number of perimeter walls and columns **2**. FIG. **12** gives a typical floor plan of a building showing cores **1** and perimeter columns **2**. The plan dimensions of the tower are approximately 36 m×39 m. The two cores **1** are connected at each floor level by conventional reinforced concrete coupling beams. The perimeter walls and columns **2** are also connected by floor beams **5** at each floor level.

[0066] FIG. **13** shows a cross section through the height of a tall building. This shows the central cores **1**, the perimeter beams and columns **2** and outrigger wall elements **4** just over halfway up the tower.

[0067] A floor plan at the level of the outriggers **4** is shown in FIG. **14**. The damping elements **3** are placed at the end of the outriggers **4** and connect to perimeter columns **2**. There are four pairs of outriggers **4** extending toward the four sides of the building from the central core **1**. The floor plan also shows doorways **9** formed in the outriggers **4** to allow normal use of the floors at the outrigger level.

[0068] The detailed structure of the outrigger **4** at the upper left of FIG. **14** is shown in a partial sectional view in FIG. **15**. The other outriggers **4** would have a similar structure, but of course the dimensions will be different. In FIG. **15** the outrigger **4** has two doorways **9**, one on the level of each floor **5**. A damping element **3** is joined between the outrigger **4** and the perimeter column **2**.

[0069] The damping obtainable varies as the resistance of the dampers **3** at the ends of the outriggers **4** varies. There is an optimum level of damper resistance for a given structure. This value can be obtained by trial and error through the analysis of a finite element model of the entire structure and damper system. The damping can be obtained by the mathematical procedure known as Complex Modal Analysis, or by a steady state forced response analysis in which the problem is solved by the Direct Method. Normal modal methods are not suitable.

[0070] For this structure using linear viscous dampers FIG. **16** shows how the overall added damping varies with total damper resistance C at each outrigger. The overall damping is expressed as the proportion of critical damping, and C is measured in force per unit relative velocity at each damper, in this case in MN/m/s. The two curves relate to the two orthogonal horizontal sway directions of the building.

[0071] In embodiments which are not shown, damping arrangements of the various types described above can be combined. For example, a building can include outrigger horizontal elements as in FIGS. **2** to **7** between a core and perimeter columns, as well as damping elements between two cores arranged as in FIG. **8**, and/or damping elements arranged as in FIG. **9** or **11**.

1. A tall structure comprising two vertically extending parts and a vertically orientated damping element, wherein the damping element is arranged to damp relative vertical movement between the two parts and the height of the vertically extending parts extends above the damping element.

2-3. (canceled)

4. A structure as claimed in claim **1**, wherein the parts comprise a core and a perimeter column.

5. A structure as claimed in claim **1**, wherein the structure includes a horizontal element extending from one of the parts, with the damping element arranged to damp relative movement between the horizontal element and the other vertical part.

6. (canceled)

7. A structure as claimed in claim **5**, wherein the horizontal element is a horizontally extending outrigger between the vertical parts.

8. A structure as claimed in claim **5**, wherein the horizontal element is relatively thin in width in the horizontal direction perpendicular to the direction of extension of the elements.

9. (canceled)

10. A structure as claimed in claim **8** wherein the structure is a tall building and height of the horizontal element extends across more than one storey of the building.

11. A structure as claimed in claim **5**, wherein the horizontal element forms part of a wall that divides a floor area.

12. (canceled)

13. A structure as claimed in claim **1**, comprising a plurality of damping elements arranged at the same height about the vertical parts.

14. A structure as claimed in claim **13**, wherein the damping elements join a core to a plurality of perimeter columns.

15. A structure as claimed in claim **13**, comprising a plurality of horizontal elements that support at least some of the plurality of damping elements, each of the horizontal elements having an associated damping element.

16-17. (canceled)

18. A structure as claimed in claim **1**, wherein the vertically extending parts are closely spaced.

19. A structure as claimed in claim **18**, wherein the damping element is connected between the vertically extending parts by means of relatively short horizontal elements, or brackets.

20. A structure as claimed in claim **19**, comprising a plurality of damping elements at the same height about the vertically extending parts.

21. (canceled)

22. A structure as claimed in claim **18**, wherein the vertical parts comprise a load bearing part and a non-load bearing part, the non-load bearing part being provided for damping purposes.

23. (canceled)

24. A structure as claimed in claim **1** comprising several sets of damping elements, the sets being at different heights on the structure.

25. (canceled)

26. A structure as claimed in claim **1**, wherein the structure is a building over 60 m in height, preferably over 80 m in height.

27. (canceled)

28. A method of providing damping for a tall structure, the structure having two vertically extending parts, the method comprising providing a vertically acting damping element which damps relative movement between the two parts, wherein the height of the vertically extending parts extends above the damping element.

29-56. (canceled)

57. A building comprising two parts which may move vertically relative to one another when the building sways, and a damper arranged between the two parts, which is capable of damping that relative vertical movement, wherein the height of the vertically extending parts extends above the damping element.

58-60. (canceled)

61. A structure as claimed in claim **1**, wherein the damping element is located in a mid-height section of the structure.

62. A tall structure comprising two vertically extending parts and a vertically orientated damping element, wherein the damping element is arranged to damp relative vertical movement between the two parts and the damping elements are located part way up the height of the structure.

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