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ProtaStructure Design Guide

3D Sway Effects of multi storey building

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3D Sway Effects of multi storey building

Many structures will undergo a natural sway under purely vertical (gravity) loads. These sways can sometimes introduce significant changes to the expected moment diagrams in beams. The axial force & moment of the columns and walls can also be significantly changed due to sway. .

In such cases it is important to ensure that checks are made for combinations where notional load cases are applied in sympathy with the natural sway of the structure.

In such situations where you might like to check for differences exposed by a 3D analysis of a floor in isolation, the topic Analysis and Design using FE introduces this option.

In more extreme cases buildings stabilized by shear and core walls will sway significantly under purely vertical load.

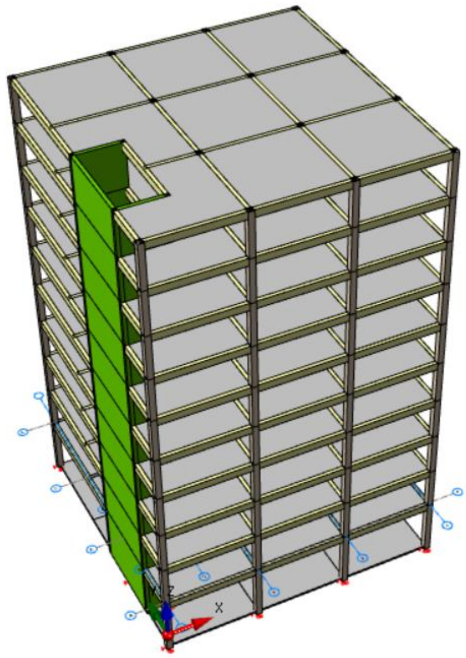
Sway Effects Under Gravity Load

Most models will sway to a small degree when subjected to purely vertical loads. For most models/structures this effect is likely to be quite insignificant. For some models it could be more significant.

In this section, we will show that:

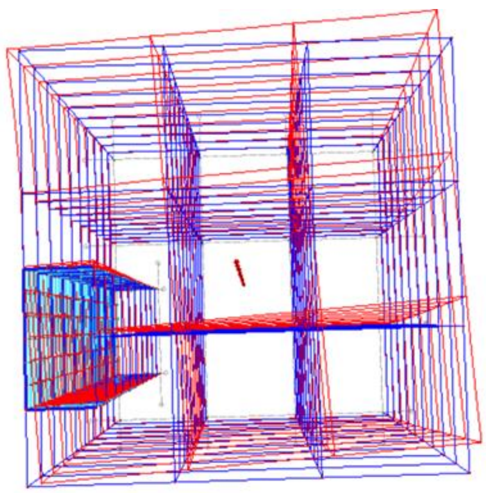
1. This effect relates to differential axial compression within the lateral load resisting elements of the structure, primarily shear and core walls.
2. This effect is always exposed by any analysis of a fully framed structure.
3. This effect can be exposed in Flat Slab models which are stabilized by core walls.
4. There are many reasons why this effect will generally be insignificant in terms of design.

Fully Framed Structures



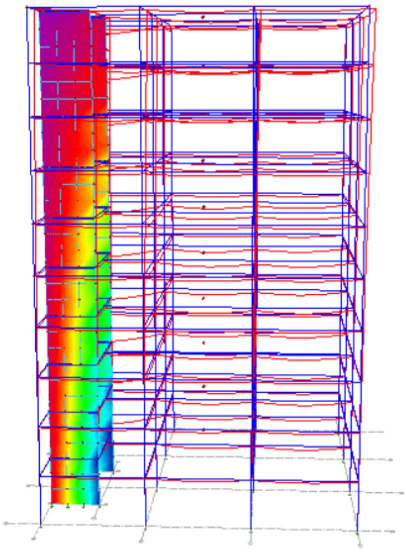
The structure above is a very simple 10 storey model with a single C-Shape core which is completely offset to one side of the building. For the purposes of this example only, all the beams have been pinned at both ends thus eliminating any frame action which would provide sway stiffness. The structure is therefore completely reliant on the core walls for stability.

The first point to note is that this is an extreme example. The view below shows how the building sways and twists under the action of notional loads.



The twisting effect is considerable and the maximum deflection at the top floor exceeds 100mm. A real structure cannot be acceptably stabilized by such an eccentric C-Shape core.

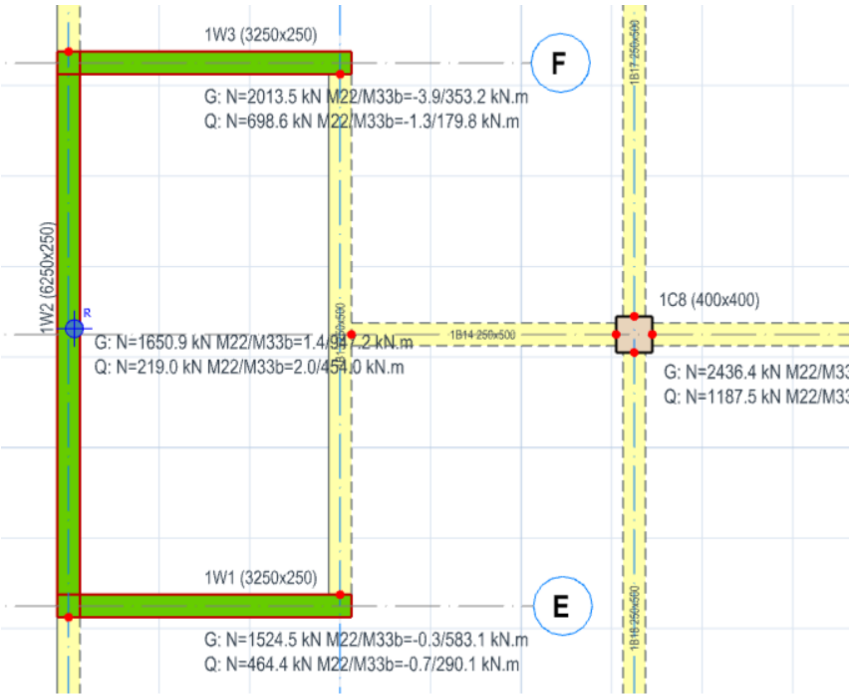
When we consider the dead load case (where only vertical loads are applied) lateral sway is also evident as shown below.



Why does this sway happen?

In the view above the vertical stress contours are also shown in the core walls – the variation of stress along the length of the flanges of the C-shape core is evident.

The design forces in the wall panels at first floor level are shown below. Note that the loads in the flanges 1W3 are higher than in the web 1W2. The average load per meter in these shorter flanges is therefore a lot higher.

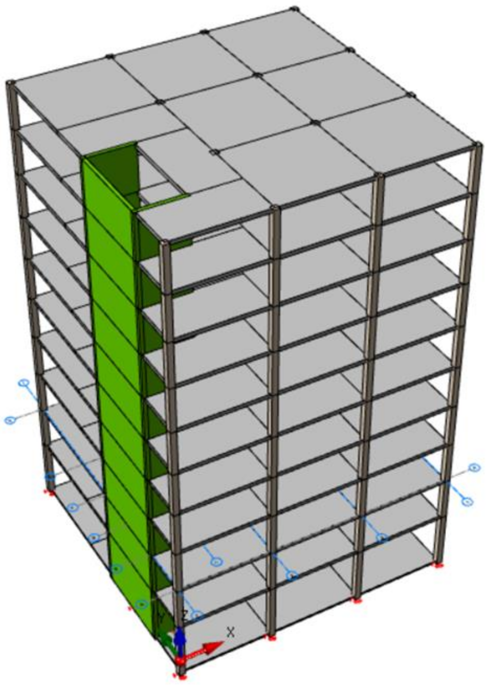


Looking at this view it is possible to imagine how the effective centre of loading applied to the C-shape core is offset to the right and above its centroid (which will be quite close to the centre of rigidity shown in the view above). The eccentric load causes an non-resisted curvature in the core and hence sway develops at the upper floors.

The same effects are evident regardless of whether meshed or mid-pier idealizations are used.

Before moving on to look at a similar model but using flat slabs it is worth noting that the total Imposed Load in the three panels of the above core wall is 698.6 + 219 + 464.4 = 1382kN.

Structures Incorporating Flat Slab Areas

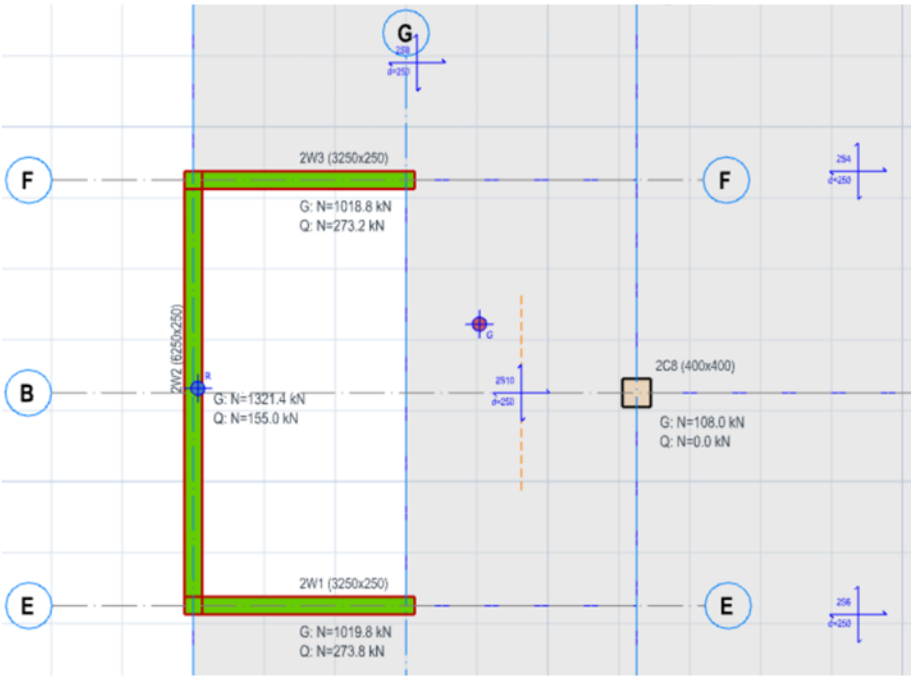


As is noted above the sway effect arises because of the eccentric application of load to a core wall. The magnitude of the sway is related to the magnitude and point of application of the axial load.

Slab Loads – Yield Line Decomposition

If this building is analyzed using yield line decomposition of slab loads, then a message is displayed to indicate that the building analysis has not captured all the applied loads.

At this stage, the analysis results displayed on plan will show no loads in columns and some loads in walls.

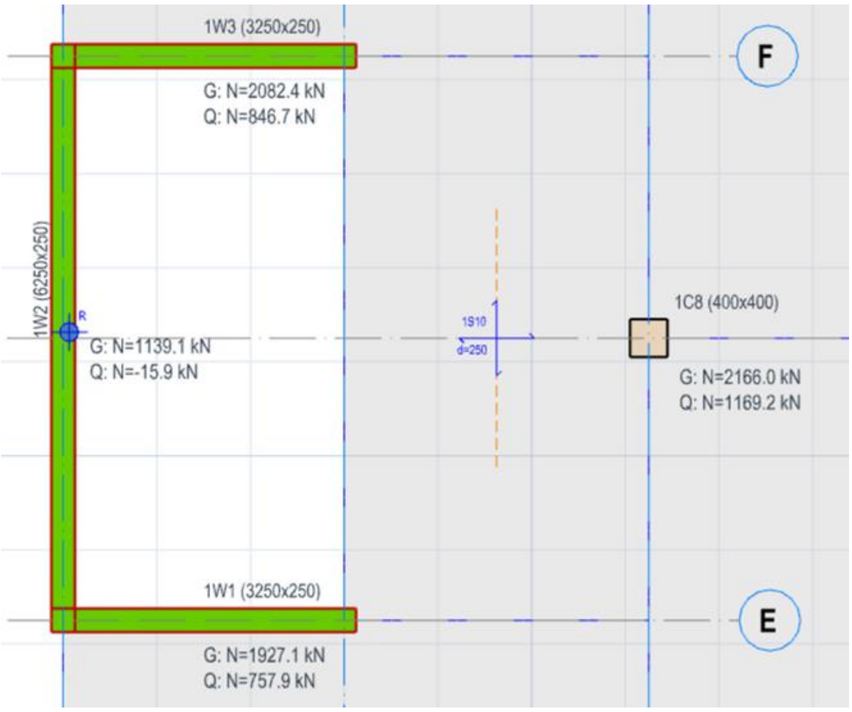


The amount of load in the walls will be incorrect, it could be too high or too low, in this case the total Imposed Load in the three panels of the above core wall is 273.2 + 155 + 273.8 = 702kN – a lot less than was derived in the model where pinned beams were included.

Basically, as is well documented elsewhere, this building analysis is of no value as regards the dead and imposed load cases. For a flat slab model, the design cases for the dead and imposed loads would usually come from the merged results of an FE chase down.

Slab Loads – FE Decomposition

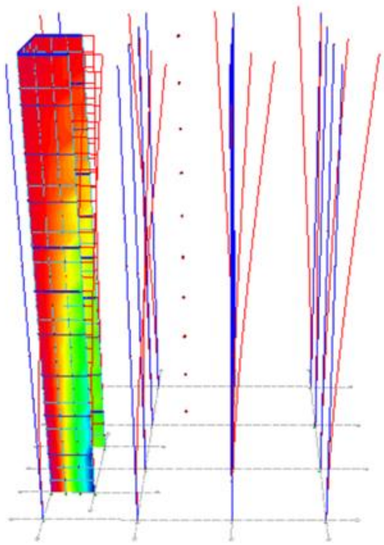
However, the loading applied to the walls (not the columns) can be corrected by using the FE load decomposition option (refer to the section Yield Line and FE Load Decomposition with Example for more information on this option). After making this change the loads in the walls change as shown below.



The total Imposed Load in the three panels of the above core wall is now 846.8 - 15.9 + 757.9 = 1588.8 kN. As a total this is not too dissimilar to the 1382 kN total given for the model that included the pinned beams, slab continuity effects in the FE analysis mean that more load is attracted to the core in this case. This load is also more eccentric with the result that tension develops in the web (for this extreme example).

Once again, the sway of the structure for the gravity load case is evident in the analysis postprocessor view and the variation of stress along the length of the flanges of the C-shape core is also evident.

In this example the maximum sway that is developing is 46 mm, the discussion below should put this in some context.



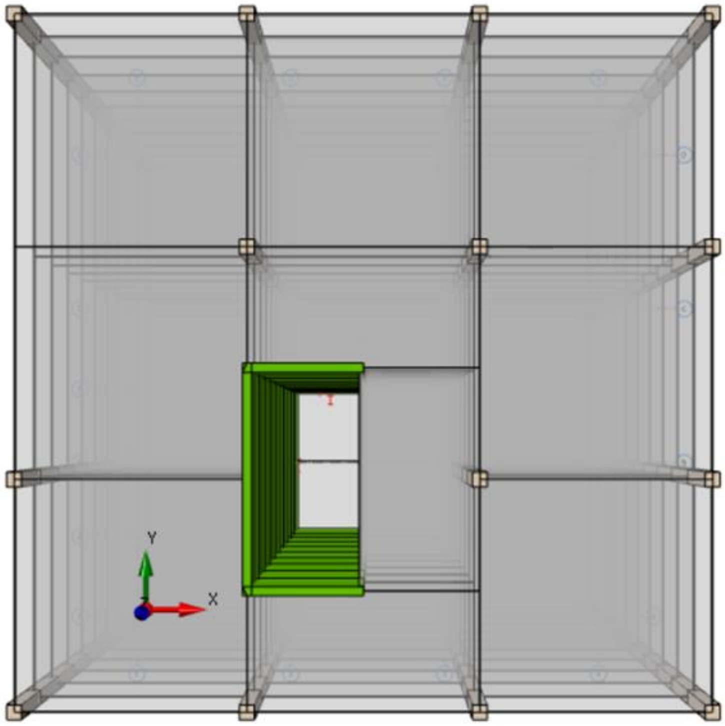
Please note that for flat slab models, you can also choose to mesh the slabs of the storey in building analysis. Refer to this article : https://support.protasoftware.com/portal/en/kb/articles/model-options#Slab_Model

Discussion

Load Eccentricity

As noted at the outset, the model used above is an extreme example. To generate the most extreme offset loading within the C-shape core it is positioned along on edge of the model. In this position this single core cannot stabilize the structure effectively. The sway under notional load cases exceeds 100 mm. This structure is not something that would be built.

Where structures are stabilized by a single core, the core is normally positioned more centrally and will tend to attract more uniform loading.



If the example is adjusted as shown above so that the core attracts load from all sides than the sway under gravity load only drops from 46 to 40 mm (everything else being equal). Even so this structure still undergoes significant sway due to notional loads and would again probably not be something that would be constructed. (The open C-Shape of the core is very susceptible to twist.)

Construction and Creep Effects

In the event that sway induced by gravity loads seems significant and some estimation of the actual displacement is required then some thought should be given to the sequence of construction and to subsequent creep effects.

The sway is occurring because of differential axial deformation within the walls. This axial deformation is a combination of immediate deformations each time a new floor is supported and ongoing creep deformations. Both effects are time dependent. When a floor load is added the concrete in the walls that support the floor will be younger in the floor immediately below and progressively older at lower floors. The younger concrete will see a greater immediate deformation and a greater long term creep deformation because of any applied load. A detailed discussion of this is beyond the current article, but it is worth noting that there would be a good deal of common background with the discussion of flat slab deflections accessed via the topic on Flat Slab Models.

A very sophisticated assessment of this effect would take account of construction sequencing and time dependent effects. In such circumstances the result needs to be assessed for sensitivity to variations in the assumptions on which they are based. To be fully accurate this analysis would need to take account of the fact that some of the deflection would be constructed out as the walls are constructed as vertical as is practical during construction.

In fact, the result achieved by any such complex analysis will lie somewhere between two extremes that might be predicted more readily be a simple linear static analysis using different E (Young's Modulus) values for the concrete.

A short-term E value might be used to estimate a minimum value for the total deflection.

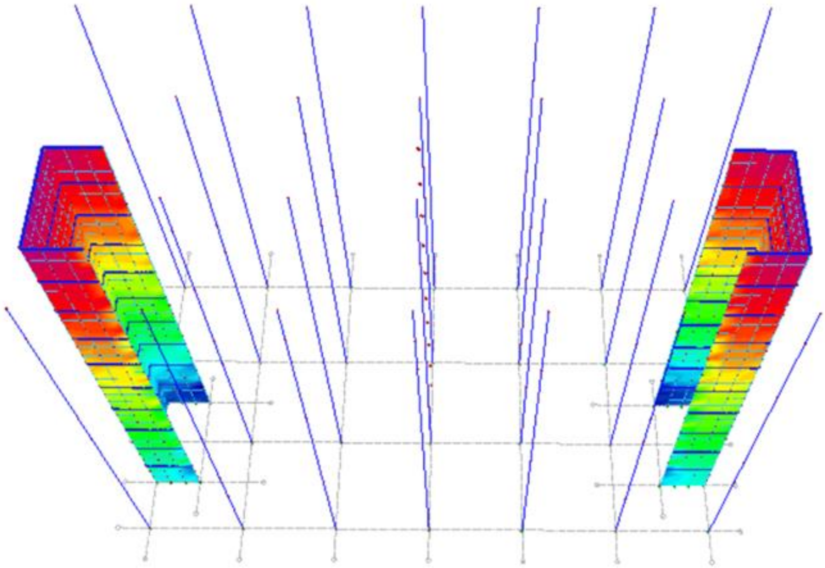
In the case of walls cracking effects can probably be discounted so only additional creep effects need to be considered. It is likely that the net effect of creep will be something less than a doubling of instantaneous deflection. Hence the value determined above could be doubled, or another analysis could be made with E set to half of the short-term value.

Notes :

Where flat slab models are being considered it is common practice to use long term values of E set at around ¼ of the short-term value. When this has been done deflection estimates of sway arising from the building analysis are likely to be too high, perhaps by a factor of 2 based on the suggestions above.

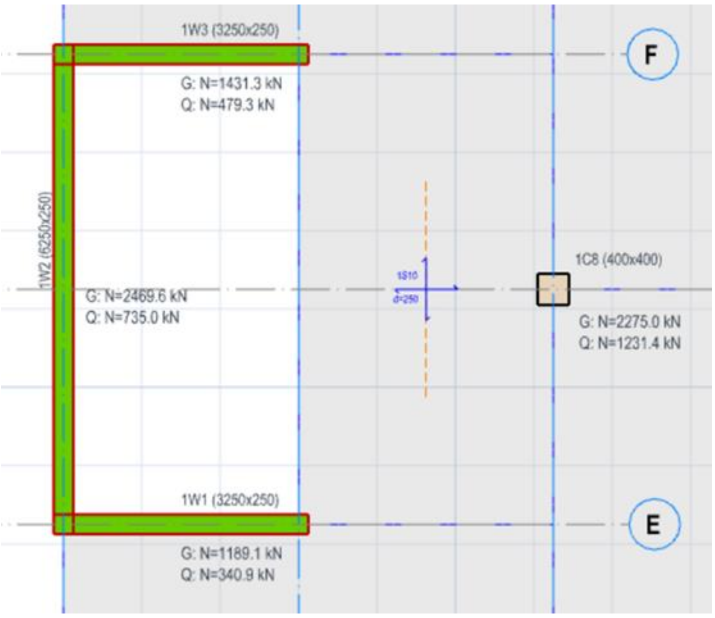
Discrete Cores

Where structures have discrete cores or numerous discrete walls providing stability the effects will often counteract each other.



In the above view the model is mirrored so that there are two C-shape cores. This model does not sway at all in the X direction under gravity load and the vertical load contours indicate relatively uniform stresses within the cores.

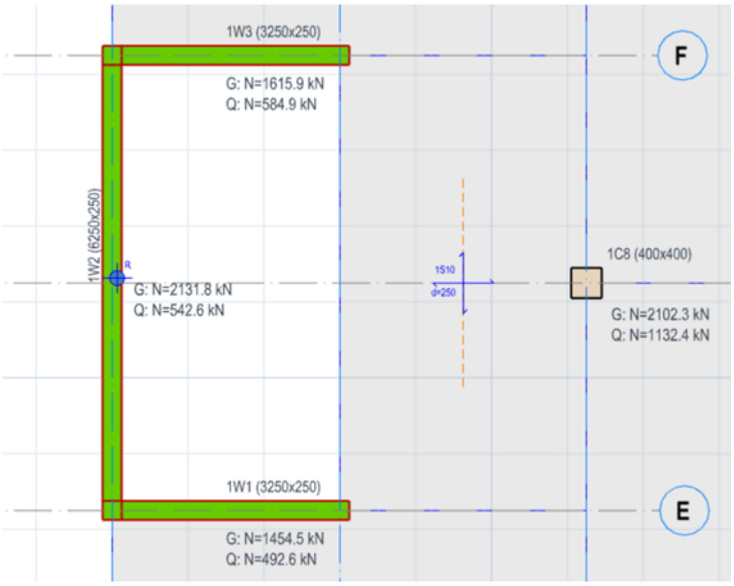
In this case the two cores lean against each other, the diaphragms at each floor stop any curvature from developing. The axial loads in the wall panels at first floor level are much more uniform as shown below.



The total Imposed Load in the three panels of the above core wall is now 479.3 + 735 + 340.9 = 1555.2 kN. On a panel-by-panel basis these are quite different forces than were given by the un-mirrored model, but the total for the 3 panels is similar to 1588.8 kN given previously. Note that the major axis moments in the wall panels are also much reduced.

Results based on an FE Chase Down

For most models, engineers will be happy to use the panel design forces merged from an FE analysis chase down. In this case the results for this core wall would then be as shown below:



Once again, the distribution of forces in the 3 wall panels is different, but the total Imposed Load is similar at 584.9 + 542.6 + 492.6 = 1620.1 kN. The FE Chase down method does not deal with sway introduced by differential axial compression in the core walls over the full height of the building. It does however introduce more minor axis bending effects where the walls interact with the slabs.

For many walls supporting flat slab floors, the minor axis bending can be more significant in the panel design than variations in axial load and major axis moment that may be introduced by sway effects.

For this simple 10 storey example building, despite the fact that the sway effects have been forced to be unrealistically extreme, the walls only require nominal reinforcement regardless of which set of design forces their design is based on.

It is suggested that for flat slab models it is important to have always designed the walls for the loads generated based on an FE chase down. You then have the option of cross checking these designs for the results generated by a building analysis where wall loading has been determined using FE decomposition at each floor.

Closing Summary

In this section we have been discussing Sway Effects Under Gravity Loads, it is important to emphasize that this relates entirely to sway that is generated in the presence of purely vertical applied loads.

The possibility of sway developing due to differential axial shortening is something that would have been routinely ignored in hand calculations by most engineers looking at most structures.

This has nothing to do with notional loads which are applied separately and will always be designed for provided you have included them in your design combinations.

For framed models in ProtaStructure the effect is always included / exposed by the 3D analysis.

For flat slab models the effect will not be exposed by an FE chase down but can be exposed if desired. It is emphasized however that we recommend walls are designed for the loads from an FE chase down and then a subsequent check design can be made for building sway effects if desired. For many reasons noted within the text of this section it is anticipated that this check will only produce more critical design in tall buildings and/or quite extreme examples.

Note : For differential axial shortening effects, please refer to this article : https://support.protasoftware.com/portal/en/kb/articles/protastructure-differential-axial-deformation-effect

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