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ProtaStructure Design Guide

3D Effects in a Building with Transfer Beam Supporting Discontinuous Column

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Introduction

Traditionally, transfer beams are analyzed and designed in isolation using simplified methods :

- The tributary area method estimates the transfer column load and accumulates for each storey.
- Yet another method is to analyze each story as a 2D subframe with beams and columns.
- Transfer column reactions are then accumulated and applied as a point load in the analysis of the storey below.
- Reactions are accumulated this way until the transfer story subframe is reached.
- The simplified method above means the stiffness & framing of all the floor above the transfer beam does not affect the resultant forces of the transfer beam, as each floor is analyzed in isolation.

In a 3D analysis program such as ProtaStructure, the analysis method is different :

- The entire 3D model from top to bottom story is analyzed and solved simultaneously as a single indeterminate structure.
- All members act together from top to bottom story in unison to support the transfer column, i.e., transfer column load will be affected by the framing above the transfer level.
- Hence, all the connected members of the floor above the transfer beam, impact the resultant forces of the transfer beam, as they are analyzed together & must satisfy deflection compatibility.

We will use a simple 3-story model with transfer beams at the 1st story to demonstrate some of the 3D effects of the transfer beam structure.

For detailed information on how to model a transfer beam, refer to this article: https://support.protasoftware.com/portal/en/kb/articles/how-to-model-a-transfer-beam

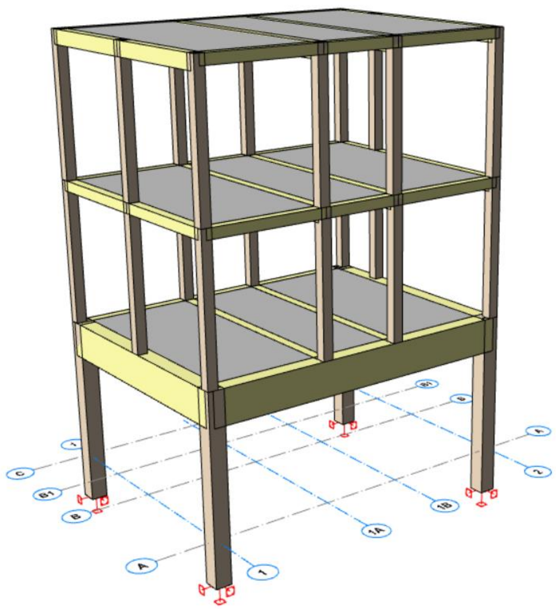


Figure 1: 3D physical view of the model

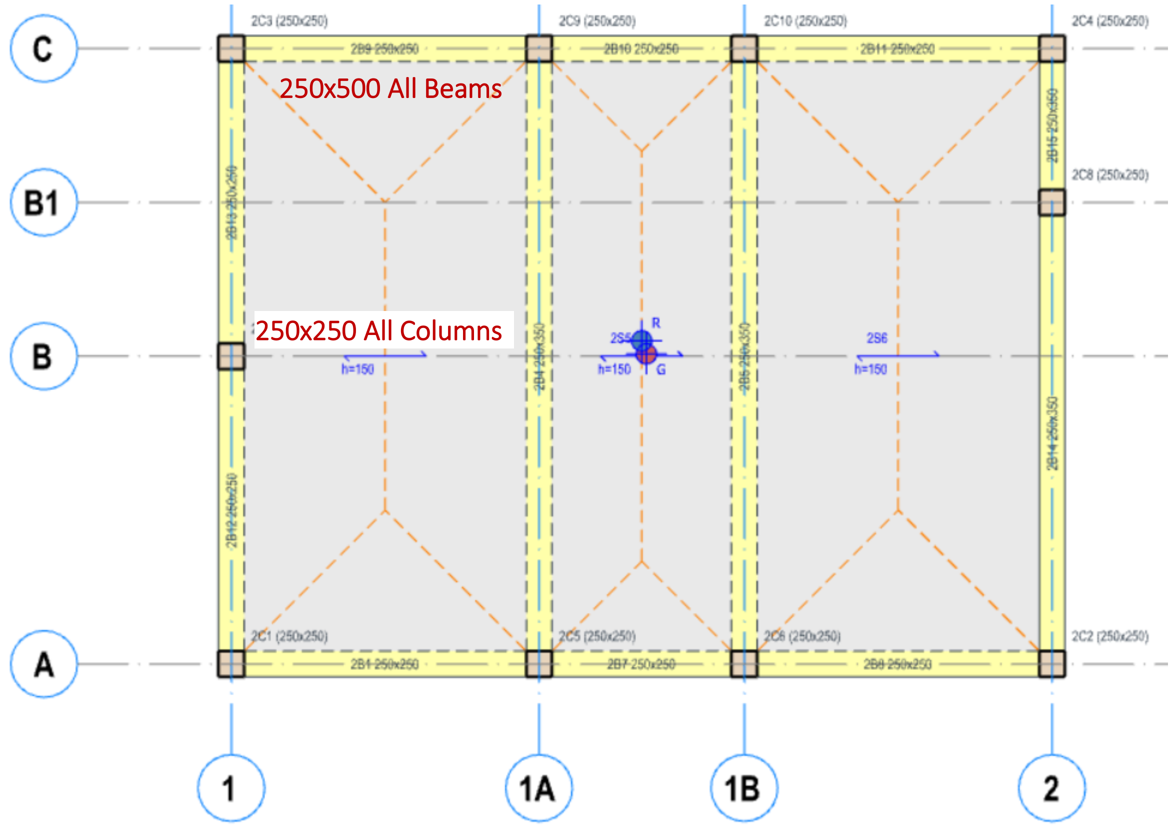


Figure 2: Plan View of ST02 (similar to ST03)

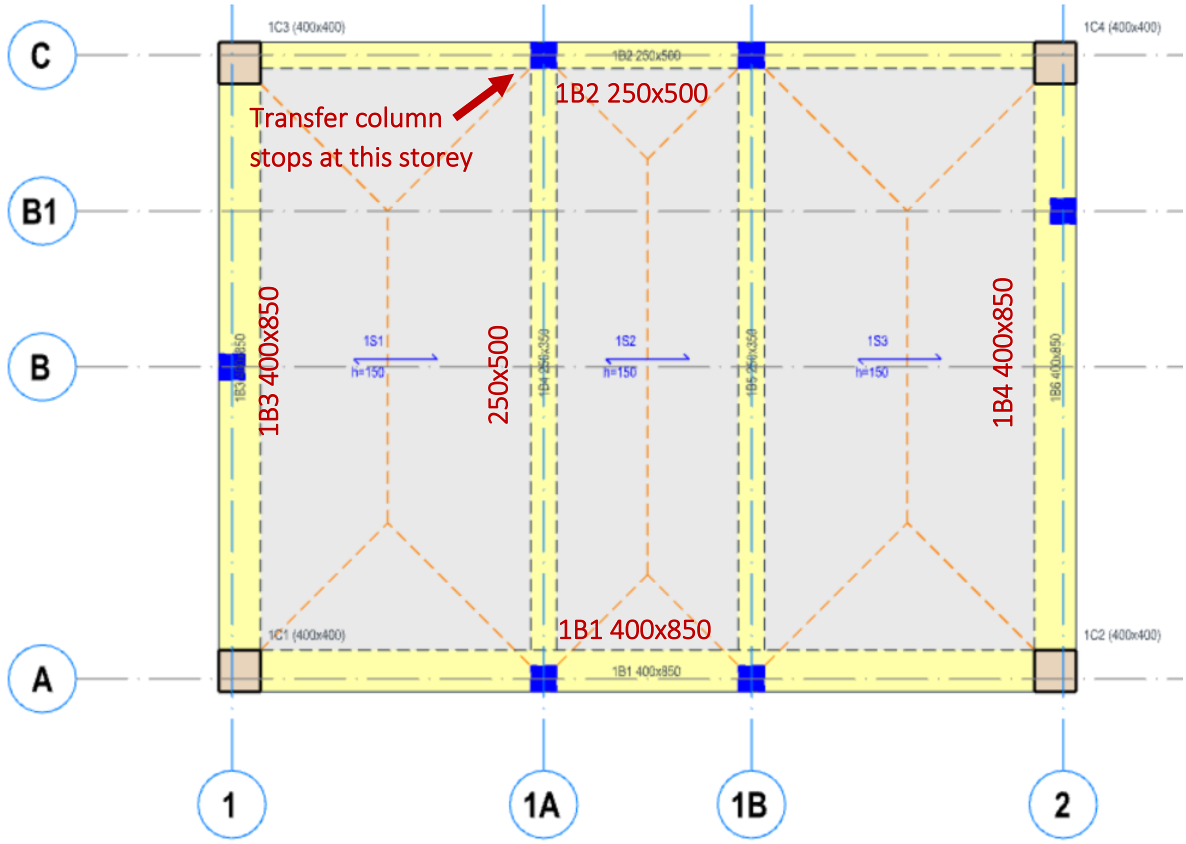


Figure 3: Plan view of ST01 (transfer story)

Concerning the figures above, the member sizes and loads are as follow :

- All slabs in the model are 150 mm thick, with service dead load = 1.2 kN/m^2 & live load = 5 kN/m^2.
- For ST02 & ST03, all the beams are 250x500 mm, while all the columns are 250x250 mm.
- ST01 is the transfer level, with transfer beams supporting discontinuous columns at various locations. The transfer beams 1B1 and 1B3 have a dimension of 400x850 mm, while 1B2 is 250x500 mm.
- The concrete grade is C35/45 for all members.

Axial Loads of Columns after Building Analysis

Building analysis is performed using the Singapore Eurocode template with default load cases and load combinations generated for gravity load cases only (Dead & Live). No Rigid Zone is considered.

The axial loads (1.35G + 1.5Q) developed in the columns and walls on the second floor (ST02) are shown below (by activating the appropriate option in Visual Interrogation). Note that ST02 & ST03 have the exact layout.

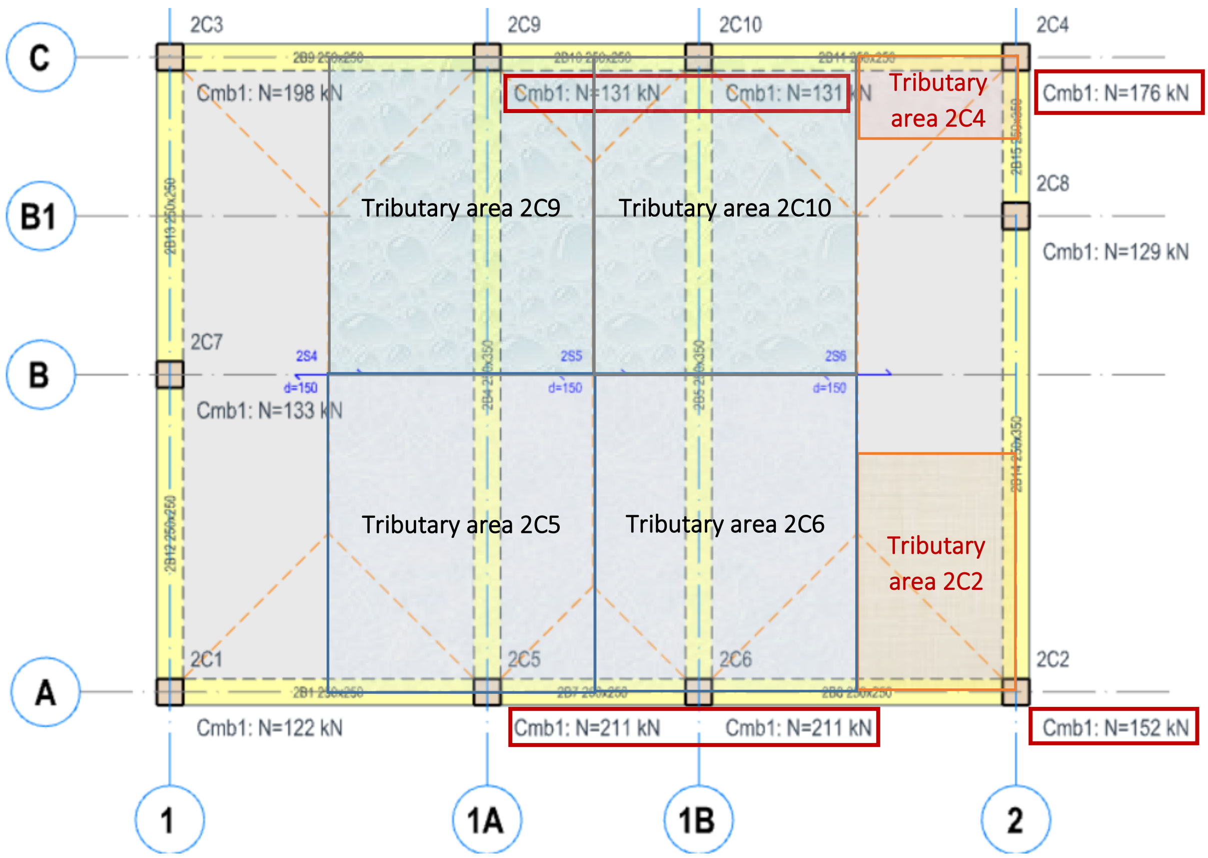


Figure 4: Axial load of columns in ST02 (1.35G + 1.5Q)

Firstly, let's look at internal columns **2C5** and **2C6** along grid **A.** Notice that the axial **211 kN** is only 30% higher than that of corner column **2C2** (**152 kN**), despite the fact this internal column supports double (200%) loading by traditional tributary area load calculation.

Next, look at internal columns **2C9** and **2C10** located on grid **C.** The axial load of **131 kN** is unexpectedly less than that of the corner column 2C4 (**174 kN**). This is even more difficult to understand as the 2C4 tributary area load is much smaller than 2C9 & 2C10.

Is the analysis result wrong? We will explain these unexpected results in the following sections.

Building Analysis Results

The analytical wireframe and results can be reviewed graphically via the **Analytical Model** view. Firstly, let us look at the model displacement due to the 1.35G + 1.5Q load combination.

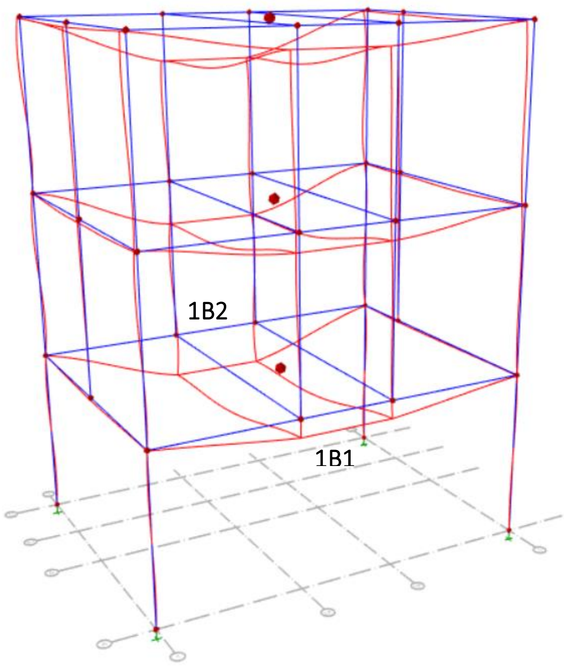


Figure 5 : 3D Displacement

It is immediately noticeable that the rear transfer beam (1B2 @ Grid C) deflects more than the front transfer beam (1B1 @ Grid A). The key reason is the sizes of these transfer beams are different. 1B1 is while 1B2 is 250x500 mm. This is expected in the context of 3D stiffness analysis as a larger transfer beam is stiffer; hence deflection will be smaller.

Front Transfer Beam Frame @ Grid A

Let us focus on the front transfer beam 1B1 for now. We can display the result of this beam in isolation by selecting this beam, right-click, select ***Analysis Results Diagram***.

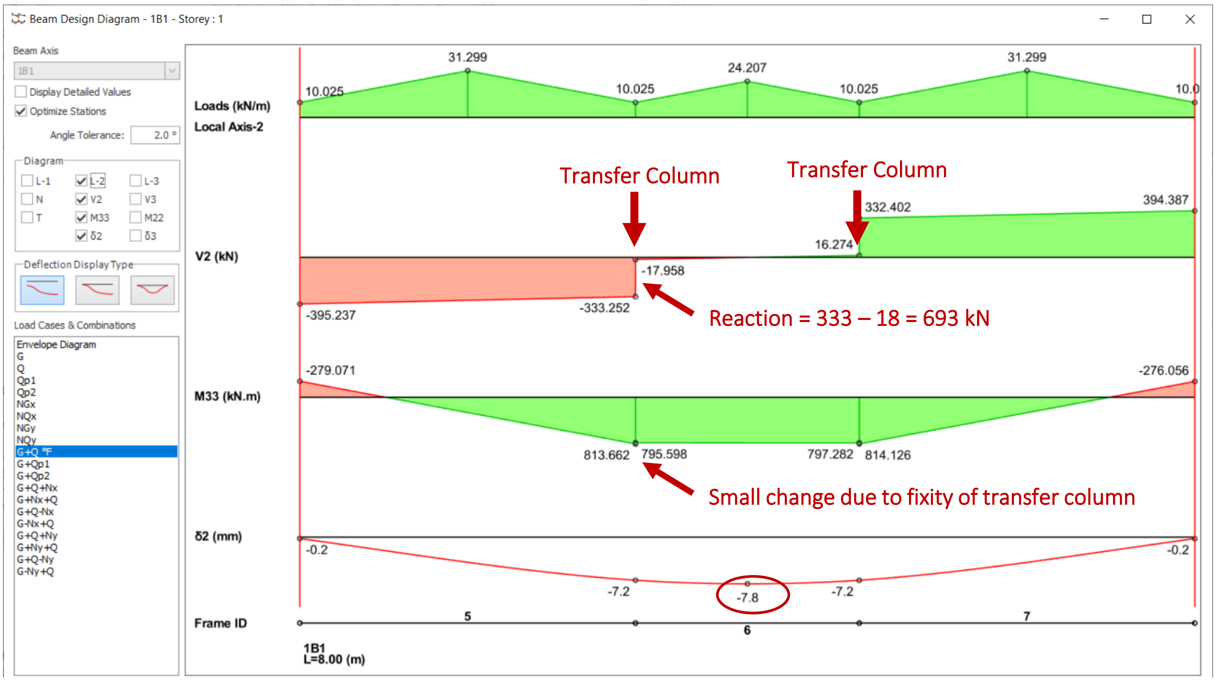


Figure 6: Beam Analysis Diagram – 1B1

It all looks very reasonable – a peak sagging moment of 813 kN.m and end shears of up to 395 kN.

The maximum deflection of the transfer beam is 7.8 mm, nothing surprising here.

The "Loads" diagram only shows the auto-calculated slab loads and any manually inserted beam loads. It will not show transfer column loads as they are "internal" & not "external" forces. The transfer columns are part of the analysis model, so the loads they transfer can only be seen in the steps / change in the shear force diagram, which are visible. The change in shear force value is the axial load/reaction of the transfer column.

Notice the small steps in the bending moment diagram under the supported column positions:

- These are small indications of the frame action developed in the columns.
- The transfer column is by default assumed to be fixed jointed to the transfer beam.
- Due to the deformation of the transfer beam, the transfer column being fixed jointed, will attempt to resist the rotation. Hence small moments will develop at the transfer column base.

Now consider the moment diagrams for the continuous beamline at the second floor level (ST02) above the front transfer beam.

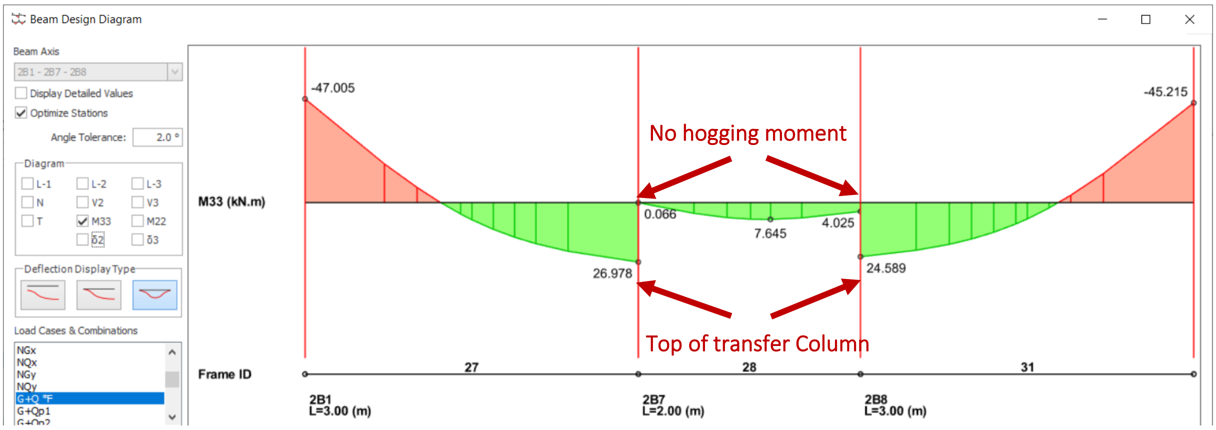
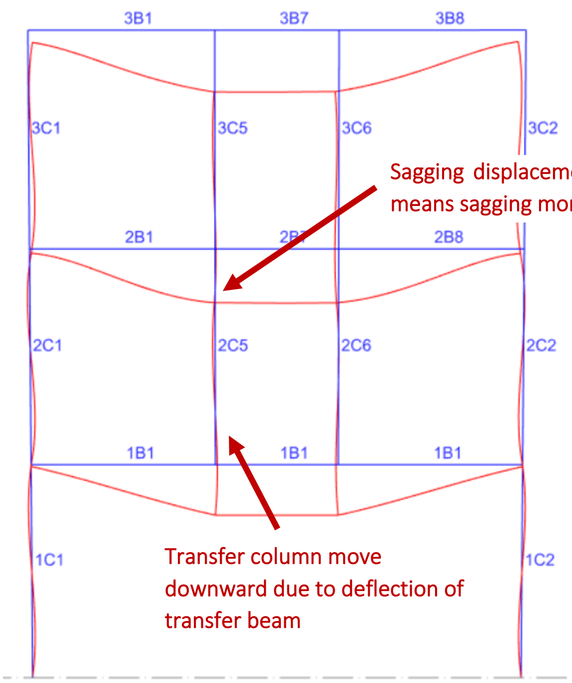


Figure 7: Beam Bending Moment Diagram: 2B1-2B7-2B8

Perhaps not what some might initially expect – there is no hogging across the transfer column positions:

- This is a logical result of any complete 3D analysis (i.e., all stories considered together); the transfer beam below deflects. Hence the supported columns deflect too, which affects the beams above.
- This means that at ST02 and ST03, the supporting columns are moving downwards (support settlement), pulling the hogging moment down to a sagging moment.
- In essence, the loads are shared with the beams at all levels above (3D frame load shedding).

This effect makes more sense when the deflections & bending moment for the frame are viewed filtered side by side, to show only the frame along the grid A, as shown below.



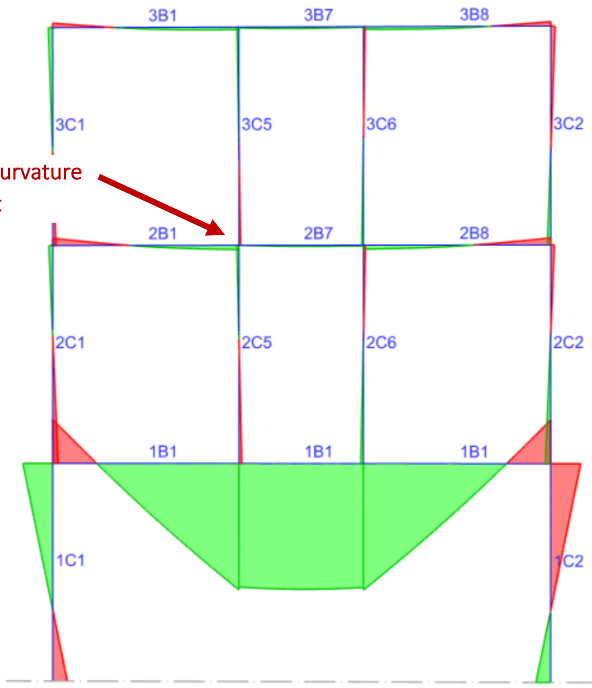


Figure 8: Displacement of frame @ Grid A

Figure 9: Bending moment diagram of frame @ Grid A

It is much easier to explain forces by examining the displacement, as the displaced shape & curvature are a direct reflection of the bending moment in the member. Animate the displacement & increase the scale for better visualization in the Analytical Model view.

This also explains the low axial loads noted in the transfer columns at the start of this section:

- Transfer beam 1B1 is 250x800, much larger than the standard beam above 250x500.
- However, some loads are still being shared with all beams.

This result is correct in the context of 3D stiffness analysis (which is verifiable with any other general 3D analysis program). It is not the same result derived by traditional hand calculation methods. An engineer carrying out hand calculations would probably consider each floor independently & assume the columns provide a rigid (unmoveable) support. This will produce a moment diagram similar to as shown below.

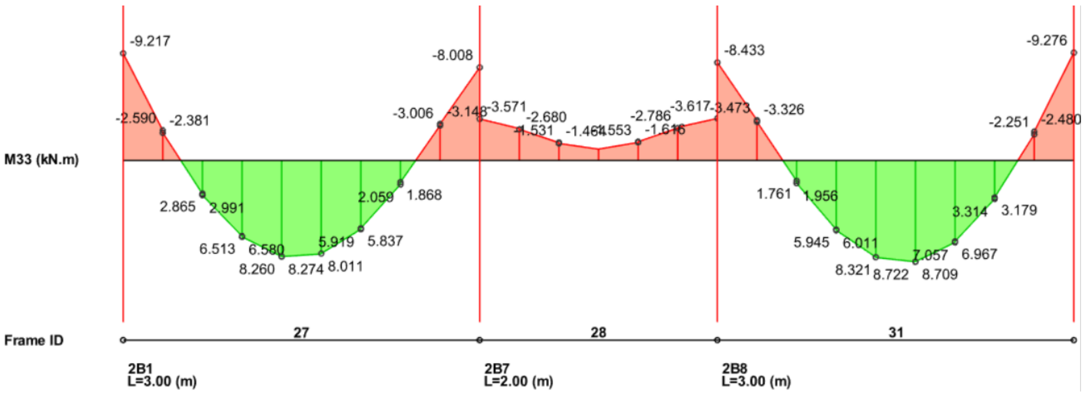


Figure 10: Beam Bending Moment Diagram when supporting columns are immovable: 2B1-2B7-2B8

This may align with traditional expectations, ignoring the vertical deflection of columns supported by transfer beams or slabs at a lower level. A 3D analysis inherently considers this effect.

Is there a correct answer – what is it? Since the answer is related to deflection, it relates to stiffness assumptions. This can become an extremely complex subject as we attempt to approximate a transfer structure's “real” behavior. A very sophisticated assessment 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 it is based. The result achieved by any such complex analysis will lie somewhere between the two extremes shown above. A more straightforward approach to satisfying these extremes is to ensure that your design covers both possibilities. This can be achieved in ProtaStructure in one of two ways.

1. Carry out a building analysis on the basis described above and design all members.
2. EITHER:

Edit the properties of the transfer beam and artificially increase its stiffness (by increasing both the inertia and the shear area), essentially eliminating transfer beam deflection. Reanalyse and examine results to see that this has had the desired effect, then run a design check on all members in the structure – if any member fails, investigate and increase reinforcement accordingly.

3. OR, as an alternative to 2. above:

In ProtaStructure, it is possible to force the entire vertical load to be carried by the transfer beam by using FE Floor Analysis Chasedown, followed by a design check on all members. In essence, this emulates the traditional hand calculation approach. This will be discussed in later sections.

For FE Floor Analysis Chasedown, refer to this article: Difference between Building Analysis and FE Floor Analysis.
The FE Floor Analysis Chasedown method cannot be used for transfer beam supporting transfer walls. Please use Building Analysis with Finite Element Shell for shearwall in this case.

Rear Transfer Beam Frame @ Grid C

Let us focus on the rear transfer beam 1B2 @ Grid C. We can display the result of this beam in isolation by selecting this beam, right-click, and selecting ***Analysis Results Diagram***.

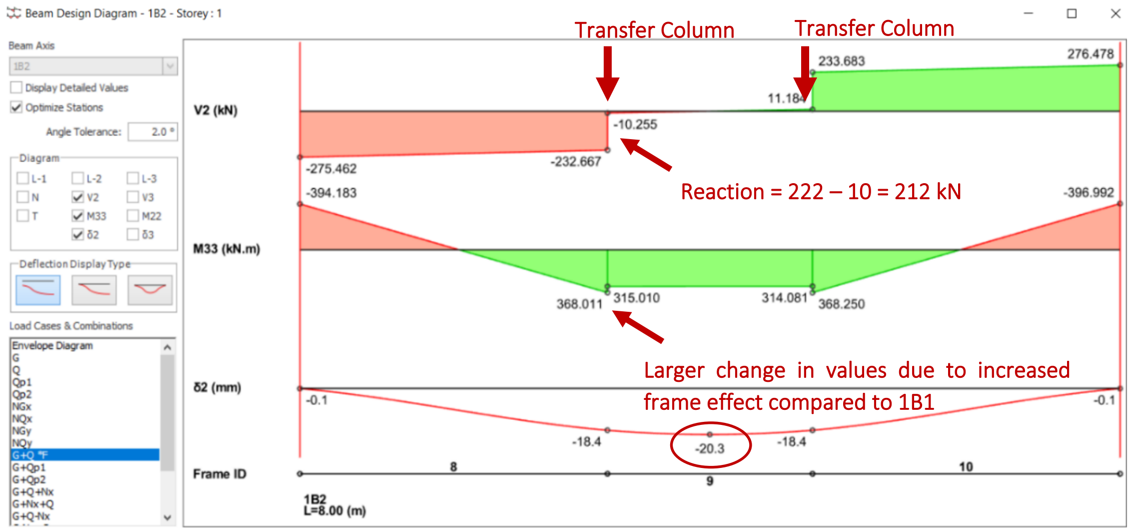


Figure 11: Analysis Results Diagram 1B2

This transfer beam 1B2 has been purposely sized smaller, 250x500 mm, the same size as all the beams above @ Grid B. In contrast, the transfer beam 1B1 is 250x800 mm. Due to the difference in sizing and stiffness, there is a significant difference in the analysis as summarized below :

- The transfer columns 2C9 & 2C10 axial force is 212 kN, which is much smaller than that of 1B1 693kN (change in shear value at the position of transfer)
- Hence the maximum bending moment of 368 kNm is smaller, compared to that of 1B1, 814 kNm
- Due to its smaller size, the max deflection of 1B2 is 20.3mm, much higher than 7.8 mm of 1B1

This effect can be explained by examining the deflections & bending moment for the analytical model, filtered to show only the frame along the grid C, as shown below.

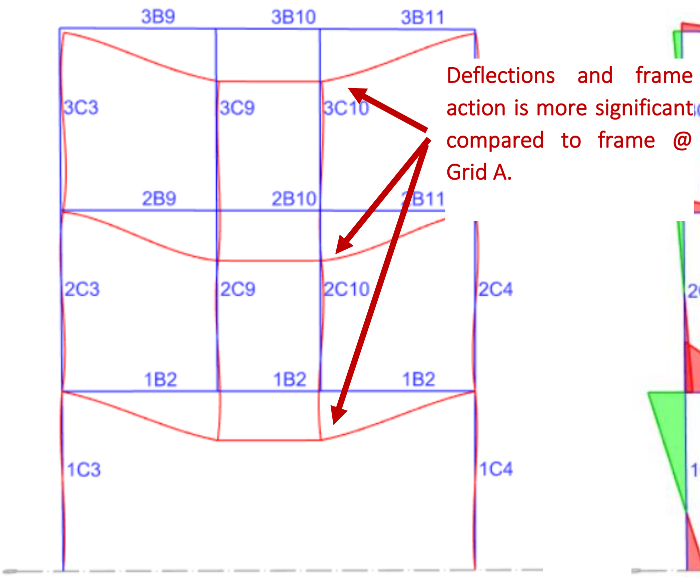


Figure 12: Displacement of frame @ Grid C

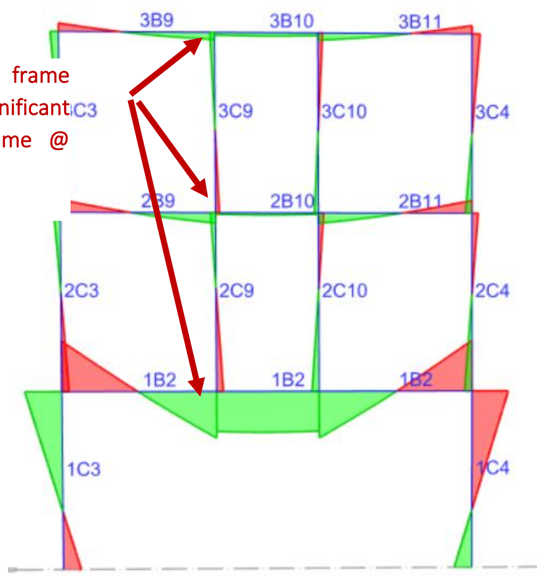


Figure 13: Bending moment diagram of frame @ Grid C

The diagrams below compare axial forces & bending moment diagrams for frame @ Grid A & C.

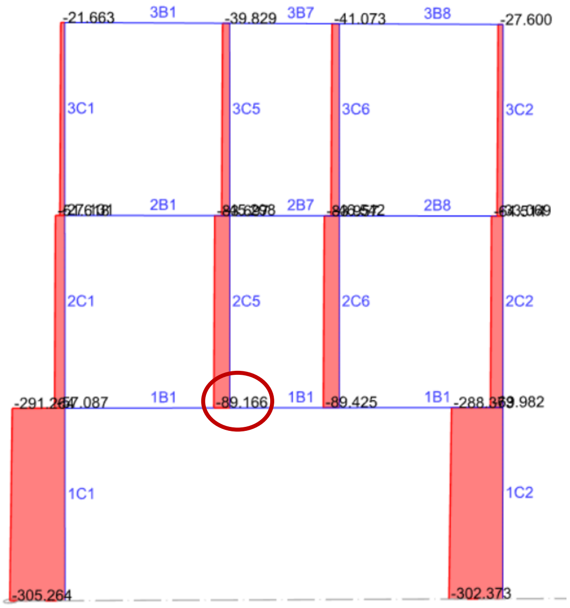


Figure 14: Axial forces of column @ Grid A

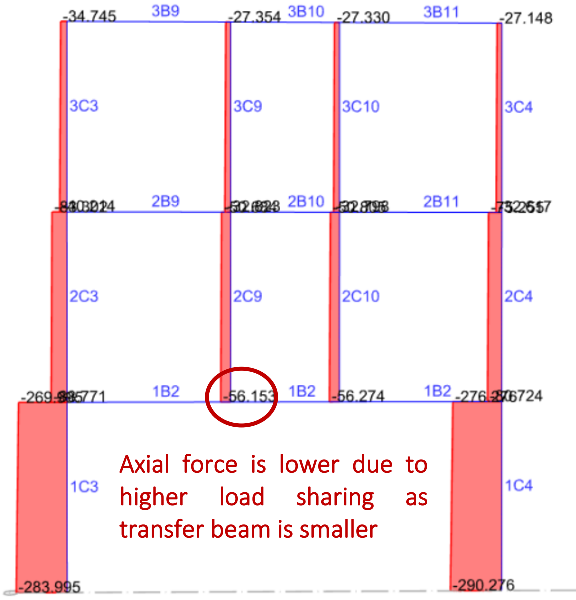


Figure 15: Axial forces of column @ Grid C

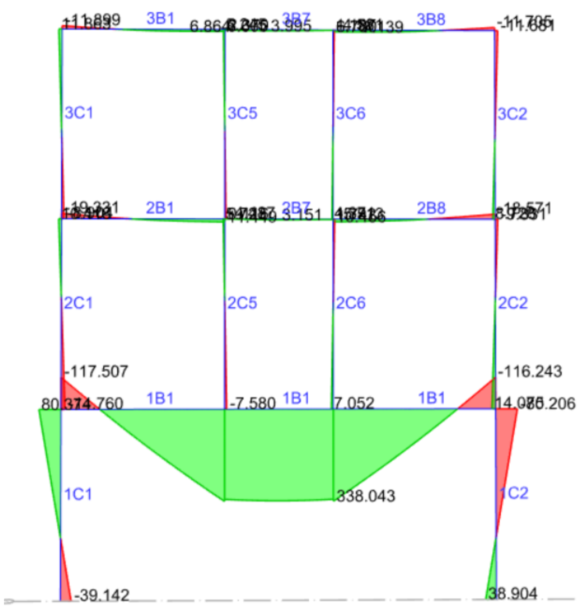


Figure 16: BMD of frame @ Grid A

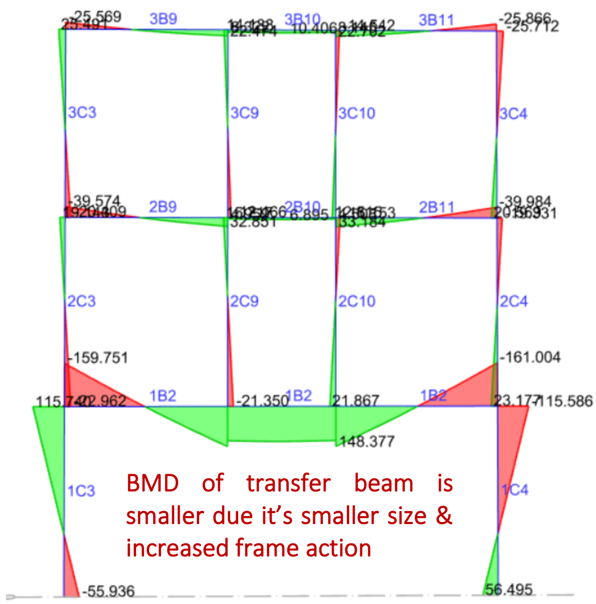


Figure 17: BMD of frame @ Grid C

As shown in the diagrams above, the frame effect is more significant compared to frame @ Grid A :

- Because transfer beam 1B2 is smaller, there is more load sharing with the frame on the upper floors.
- This means that beams 2B9-10-11 & 3B9-10-11 are helping to support some of the transfer column loads of C9 & C10, shifting some loads to the external columns.
- This is evident by observing the larger change in the bending moments at joints of the beams & discontinuous columns C9 & C10 at all storeys.
- As a result, the bending moment of the discontinuous column C9 & C10 is also higher than @ Grid A, as the larger change in the bending moments must be transferred to these columns for equilibrium.

Transfer Beam Frame @ Grid C

Let us now look at the transfer frame along with Grids 1 & 2. The difference is the position of the transfer column. Along Grid 1, transfer column 2C7 is right in the midspan of transfer beam 1B3. Along Grid 2, transfer column 2C8 is at the quarter point of transfer beam 1B6.

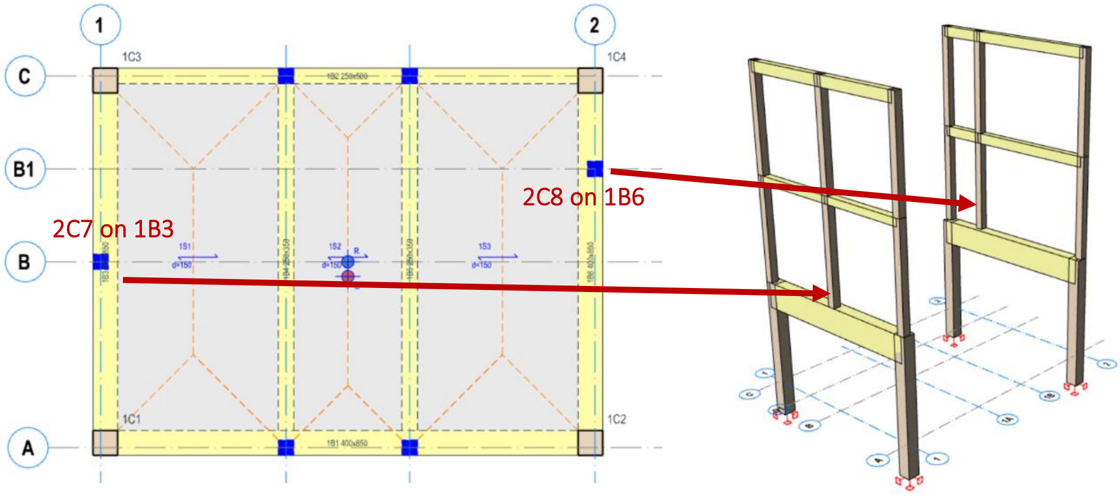


Figure 18 : ST01 plan view showing discontinuous column (hatched blue)

Figure 19: 3D view showing only frame @ Grid 1 & 3

Let's compare the deflection of the two frames due to load combination 1 (factored).

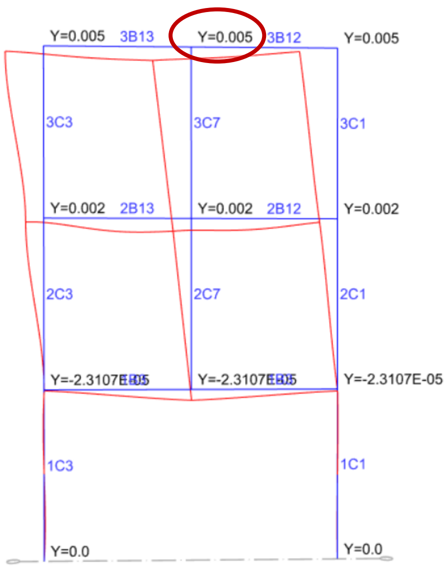


Figure 20 : Deflection of frame @ Grid 1

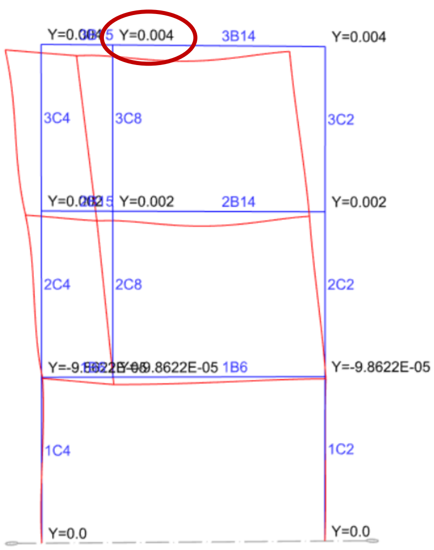
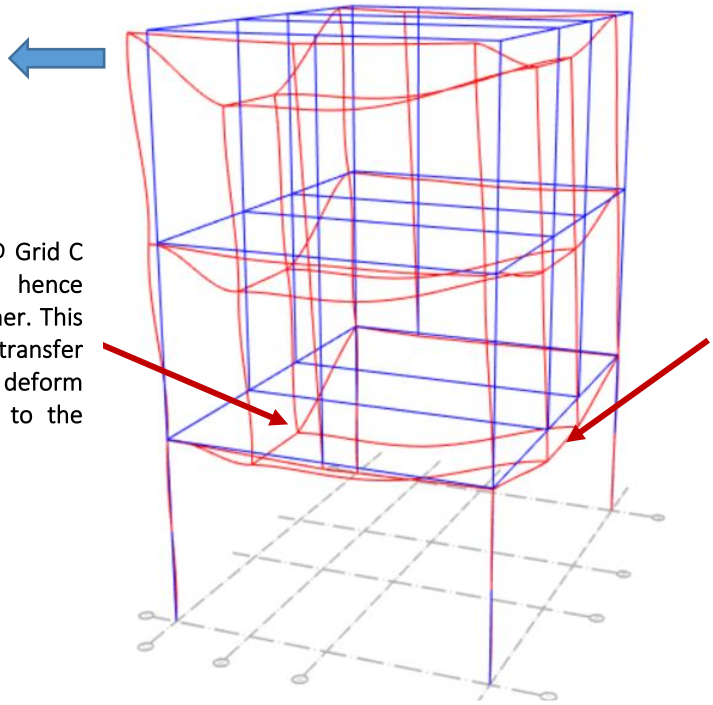


Figure 21 : Deflection of frame @ Grid 2

Surprisingly, even under gravity load, the two frames swayed slightly to the left (global Y direction) by 4mm to 5mm. Recall all the frames are interconnected in the 3D analytical wireframe. Hence this must be explained in the context of 3D analysis by observing the behavior of the entire 3D frame.

Whenever in doubt, the first approach is to turn on & examine the displacement, as displacement is a direct reflection of the forces in the members. Turn on "Animation" to better visualize the deformation of the structure.

Transfer beam @ Grid C is smaller and hence deflection is higher. This causes the transfer columns here to deform more and sway to the left.



Transfer beam @ Grid A is bigger and hence deflection is lower.

Figure 22 : 3D deflection of entire model

As explained in the diagram above, the sway is due to inherent 3D behavior, precisely due to the difference in sizing & hence deflection of the transfer beams, which in turn affected the lateral deflection of the orthogonal frame along Grid 1 & 3.

Let us now compare the bending moment diagram of the beams & columns @ Gride 1 & 2

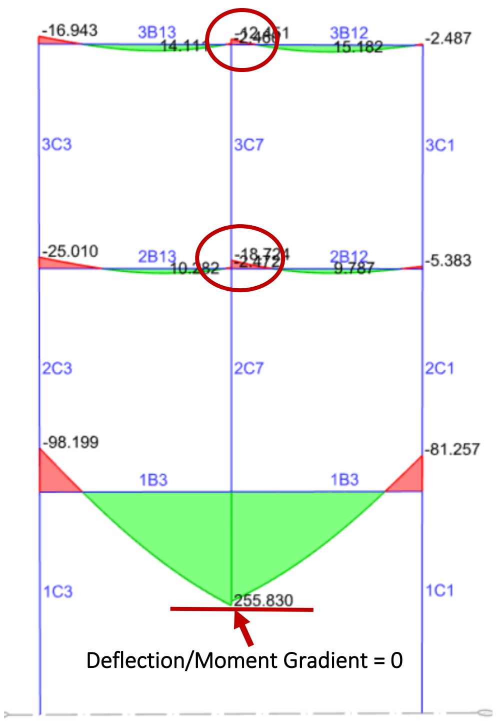


Figure 23 : BMD of beams @ Grid 1

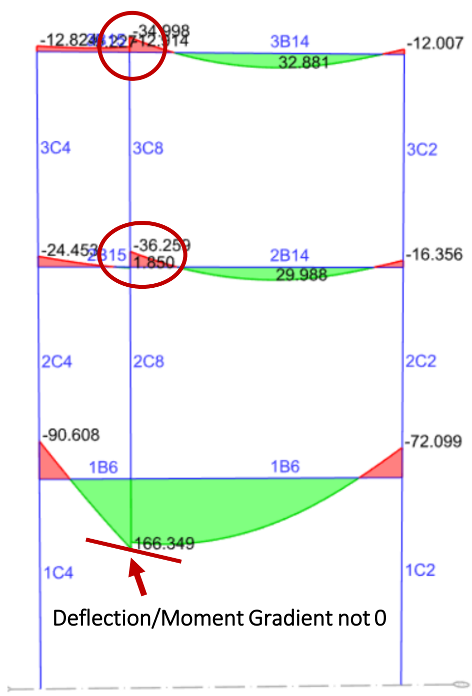


Figure 24 : BMD of beams @ Grid 2

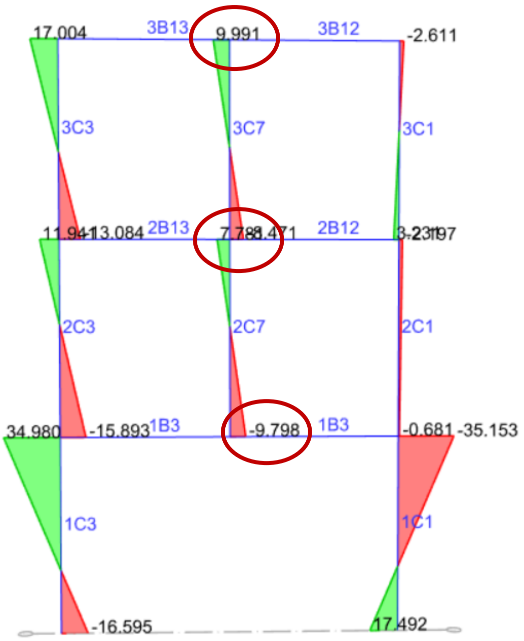


Figure 25 : BMD of columns @ Grid 1

Figure 26 : BMD of columns @ Grid 2

Discussion of Results

Along grid 1, the transfer column moment at the bottom of 2C7 is small, as the transfer column is located at the mid-span of transfer beam 1B3. The transfer beam deflection/moment gradient is zero at the midspan; hence beam-column joint does not rotate. The small moment is due to the sway of the frame to the left, as explained above. Hence to resist this movement, all joints will rotate slightly, giving rise to a small moment.

Along grid 2, the transfer column moment at the bottom of 2C8 is larger, as the transfer column is located near the beam's support. The deflection gradient is not zero at this point, so there will be a rotation of the beam-column joints. The transfer column will resist this rotation, giving rise to a counter moment.

For the above floors along grid 2, there is a larger change in the bending moment of the beams due to the unequal span and unequal loading. The unbalanced moment must be distributed to the columns.

To summarize, the transfer column or wall located further away from the mid-span of the supporting transfer beam will experience a higher moment. Although you can hinge to the bottom of the transfer column to release the moment, this will reduce the model's overall stiffness.

Only the shearwall with the Mid-Pier assumption can be hinged. FE Shell wall cannot be hinged as shells are automatically fixed analytically.

Conclusion & Summary

The resultant axial force and moments may be significantly different from traditional area tributary calculation, depending on the 3D structural framing.

In a 3D stiffness analysis of the transfer beam, supporting transfer columns are affected by the transfer beam's size and the frame above the transfer level. If the transfer beam is size appropriately larger than the beams above it, more loads are attracted to the transfer beam & hence there will be a higher bending moment diagram as expected. However, there will still be some load sharing with the beams above it, depending on the framing system.

Conversely, suppose the transfer beam is unreasonably small compared to the beams above it. In this case, there may be significant load sharing with the beams above it, resulting in a smaller bending moment diagram than expected.

Thus, it is not surprising if distortion or unexpected bending moments or shear forces are observed in the beams connected to the discontinuous columns above the transfer level. The deflection of the transfer beam directly influences this. More deflection means more downward displacement of the column; the net effect is support settlement for beams above. Expect a decrease in the hogging moment in beams support above. If support settlement is significant, it may even result in a sagging moment at the beam supports.

The fixity and location of connectivity with the transfer beam also affect how forces, e.g. moment develops in discontinuous columns. Discontinuous columns connected to the transfer beam's mid-span will have less developed moments, than when they are supported further away from the mid-span.

The behavior may be impacted by 3D sway even under gravity loading. Any sway will inherently be resisted by the 3D frame, generating shear and moments in members that are not captured in the traditional 2D analysis, which ignores 3D lateral sway under vertial loads.