ProtaStructure Design Guide

Vertical Earthquake Effects

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Publisher

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Vertical Earthquake Analysis

ProtaStructure can reflect the effects of vertical earthquake action in the design by providing two methods.

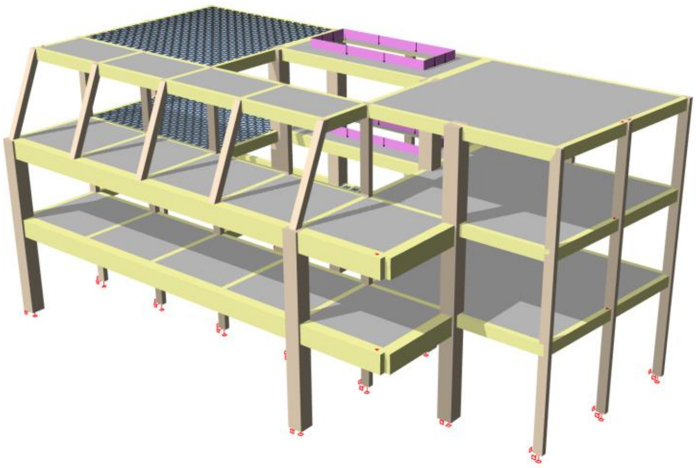
1. Approximate Static Approach
2. Modal Spectrum Analysis Method

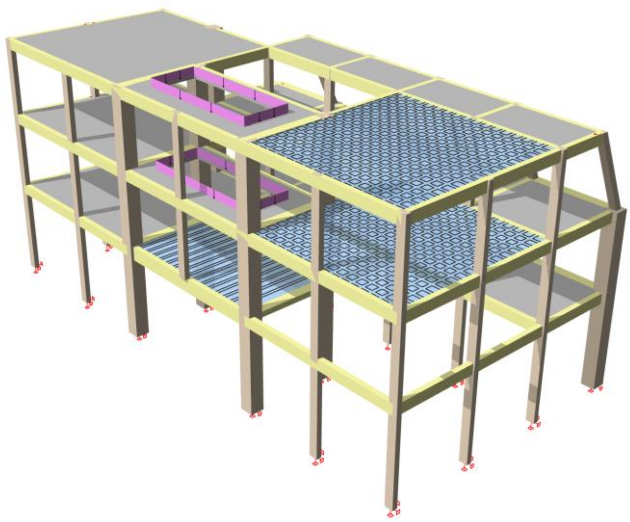
Approximate Static Approach

In the static approach, the result from gravity load case is multiplied with a fraction of horizontal spectral acceleration such as $0.2S_{DS}$. Vertical vibration modes and a dedicated vertical spectrum is not considered in this approach.

Static vertical earthquake calculation may not be sufficient (or may not be allowable by the code) especially for the buildings with transfer columns, beams or slabs covering large spans, long cantilevers, or slanting columns.

Certain seismic codes require modal vertical earthquake analysis in these scenarios. For example, Eurocode only allows the use of modal vertical earthquake analysis.



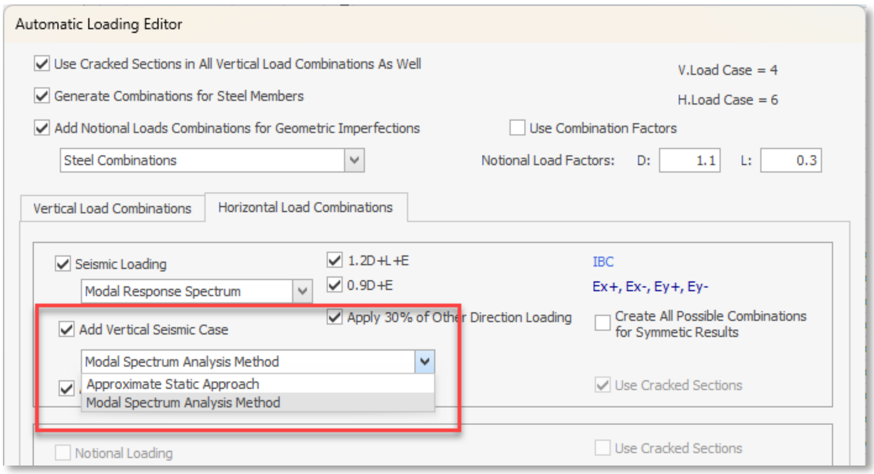


Modal Spectrum Analysis Method

In modal spectrum method, vertical vibration modes of the structure are considered together with a vertical acceleration spectrum.

To activate the modal vertical earthquake analysis:

1. Open **Automatic Loading Editor**
2. Select **Modal Spectrum Analysis Method**
3. Click **OK**. The load combinations including the vertical earthquake load cases will be generated automatically.



Combining Vertical Earthquake Cases with Other Actions

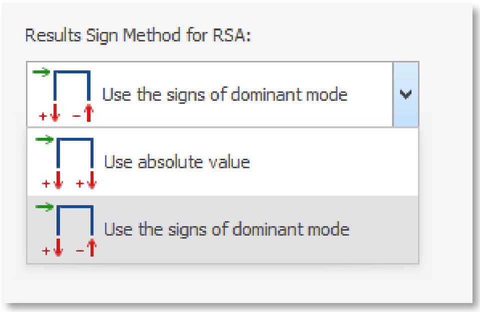
Approximate Static Approach

Static Vertical Earthquake load cases will be combined with a positive sign in G + Q + E combinations, whereas they will be combined with a negative sign in 0.9G + E combinations.

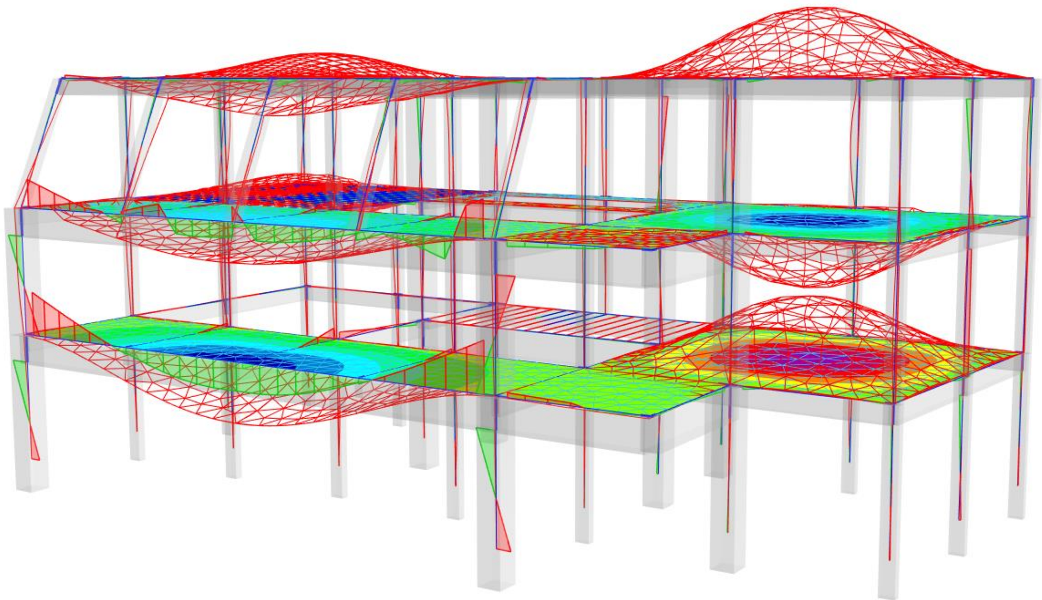
ID	Label	LL Red	VOM	T...	Load Combinations
2	D+L	☑	☑		1.2D + 1.6L
4	D+Lp1	☑	☑		1.2D + 1.6Lp1
6	D+Lp2	☑	☑		1.2D + 1.6Lp2
11	Dc+Lc+Ez+Ex+	☐	☐		1.2D + L + 0.3Ez + Ex+ + 0.3Ey-
12	Dc+Lc+Ez-Ex+	☐	☐		1.2D + L + 0.3Ez - Ex+ - 0.3Ey-
13	Dc+Lc+Ez+Ex-	☐	☐		1.2D + L + 0.3Ez + Ex- + 0.3Ey+
14	Dc+Lc+Ez-Ex-	☐	☐		1.2D + L + 0.3Ez - Ex- - 0.3Ey+
15	Dc+Lc+Ez+Ey+	☐	☐		1.2D + L + 0.3Ez + 0.3Ex- + Ey+
16	Dc+Lc+Ez-Ey+	☐	☐		1.2D + L + 0.3Ez - 0.3Ex- - Ey+
17	Dc+Lc+Ez+Ey-	☐	☐		1.2D + L + 0.3Ez + 0.3Ex+ + Ey-
18	Dc+Lc+Ez-Ey-	☐	☐		1.2D + L + 0.3Ez - 0.3Ex+ - Ey-
19	Dc+Ez+Ex+	☐	☐		0.9D - 0.3Ez + Ex+ + 0.3Ey-
20	Dc+Ez-Ex+	☐	☐		0.9D - 0.3Ez - Ex+ - 0.3Ey-
21	Dc+Ez+Ex-	☐	☐		0.9D - 0.3Ez + Ex- + 0.3Ey+
22	Dc+Ez-Ex-	☐	☐		0.9D - 0.3Ez - Ex- - 0.3Ey+
23	Dc+Ez+Ey+	☐	☐		0.9D - 0.3Ez + 0.3Ex- + Ey+
24	Dc+Ez-Ey+	☐	☐		0.9D - 0.3Ez - 0.3Ex- - Ey+
25	Dc+Ez+Ey-	☐	☐		0.9D - 0.3Ez + 0.3Ex+ + Ey-
26	Dc+Ez-Ey-	☐	☐		0.9D - 0.3Ez - 0.3Ex+ - Ey-

Modal Spectrum Analysis Method

When a **Modal Vertical Earthquake Analysis** is performed, the result signs are lost because of CQC modal combination. Depending on the **Results Sign Method** option set by the user on **Seismic Parameters > Settings**, the resulting values will be positive or will have the sign of the dominant vertical mode.



In the modal vertical earthquake analysis, results will reflect the combined effect of building's vertical vibration modes. You can see it clearly from the displaced shape in analysis post-processor. You can review the vertical vibration modes in the analysis post processor.



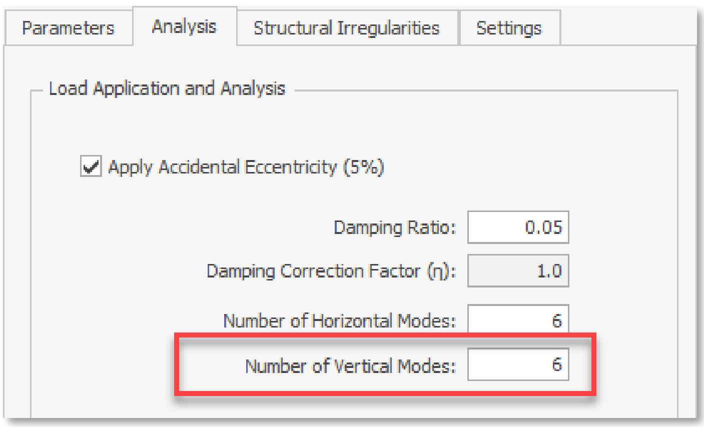
Hence, to capture the critical effects, the modal vertical earthquake load cases will be combined with dead and live load cases using both positive and negative signs. So, the number of seismic combinations will be doubled.

ID	Label	LL Red	VOM	T...	Load Combinations
2	D+L	☑	☑		1.2D + 1.6L
4	D+Lp1	☑	☑		1.2D + 1.6Lp1
6	D+Lp2	☑	☑		1.2D + 1.6Lp2
11	Dc+Lc+Ez+Ex+	☐	☐		1.2D + L + 0.3Ez + Ex+ + 0.3Ey-
13	Dc+Lc-Ez+Ex+	☐	☐		1.2D + L - 0.3Ez + Ex+ + 0.3Ey-
14	Dc+Lc+Ez-Ex+	☐	☐		1.2D + L + 0.3Ez - Ex+ - 0.3Ey-
16	Dc+Lc-Ez-Ex+	☐	☐		1.2D + L - 0.3Ez - Ex+ - 0.3Ey-
17	Dc+Lc+Ez+Ex-	☐	☐		1.2D + L + 0.3Ez + Ex- + 0.3Ey+
19	Dc+Lc-Ez+Ex-	☐	☐		1.2D + L - 0.3Ez + Ex- + 0.3Ey+
20	Dc+Lc+Ez-Ex-	☐	☐		1.2D + L + 0.3Ez - Ex- - 0.3Ey+
22	Dc+Lc-Ez-Ex-	☐	☐		1.2D + L - 0.3Ez - Ex- - 0.3Ey+
23	Dc+Lc+Ez+Ey+	☐	☐		1.2D + L + 0.3Ez + 0.3Ex- + Ey+
25	Dc+Lc-Ez+Ey+	☐	☐		1.2D + L - 0.3Ez + 0.3Ex- + Ey+
26	Dc+Lc+Ez-Ey+	☐	☐		1.2D + L + 0.3Ez - 0.3Ex- - Ey+
28	Dc+Lc-Ez-Ey+	☐	☐		1.2D + L - 0.3Ez - 0.3Ex- - Ey+
29	Dc+Lc+Ez+Ey-	☐	☐		1.2D + L + 0.3Ez + 0.3Ex+ + Ey-
31	Dc+Lc-Ez+Ey-	☐	☐		1.2D + L - 0.3Ez + 0.3Ex+ + Ey-
32	Dc+Lc+Ez-Ey-	☐	☐		1.2D + L + 0.3Ez - 0.3Ex+ - Ey-
34	Dc+Lc-Ez-Ey-	☐	☐		1.2D + L - 0.3Ez - 0.3Ex+ - Ey-
35	Dc+Ez+Ex+	☐	☐		0.9D + 0.3Ez + Ex+ + 0.3Ey-
37	Dc-Ez+Ex+	☐	☐		0.9D - 0.3Ez + Ex+ + 0.3Ey-
38	Dc+Ez-Ex+	☐	☐		0.9D + 0.3Ez - Ex+ - 0.3Ey-
40	Dc-Ez-Ex+	☐	☐		0.9D - 0.3Ez - Ex+ - 0.3Ey-
41	Dc+Ez+Ex-	☐	☐		0.9D + 0.3Ez + Ex- + 0.3Ey+
43	Dc-Ez+Ex-	☐	☐		0.9D - 0.3Ez + Ex- + 0.3Ey+
44	Dc+Ez-Ex-	☐	☐		0.9D + 0.3Ez - Ex- - 0.3Ey+
46	Dc-Ez-Ex-	☐	☐		0.9D - 0.3Ez - Ex- - 0.3Ey+
47	Dc+Ez+Ey+	☐	☐		0.9D + 0.3Ez + 0.3Ex- + Ey+
49	Dc-Ez+Ey+	☐	☐		0.9D - 0.3Ez + 0.3Ex- + Ey+
50	Dc+Ez-Ey+	☐	☐		0.9D + 0.3Ez - 0.3Ex- - Ey+
52	Dc-Ez-Ey+	☐	☐		0.9D - 0.3Ez - 0.3Ex- - Ey+
53	Dc+Ez+Ey-	☐	☐		0.9D + 0.3Ez + 0.3Ex+ + Ey-
55	Dc-Ez+Ey-	☐	☐		0.9D - 0.3Ez + 0.3Ex+ + Ey-
56	Dc+Ez-Ey-	☐	☐		0.9D + 0.3Ez - 0.3Ex+ - Ey-
58	Dc-Ez-Ey-	☐	☐		0.9D - 0.3Ez - 0.3Ex+ - Ey-

Number of Vertical Modes

ProtaStructure will perform an eigenvalue analysis in vertical direction considering the vertical mass matrix and stiffness of the structure. This will identify the local vibration modes of the structure due to long span beams/slabs, large cantilevers, slanting columns, transfer beams and slabs supporting vertical members etc. These modes are used in the mode-superposition analysis done in vertical direction.

You can specify the number of vertical modes in **Seismic Parameters > Analysis > Number of Vertical Modes.**



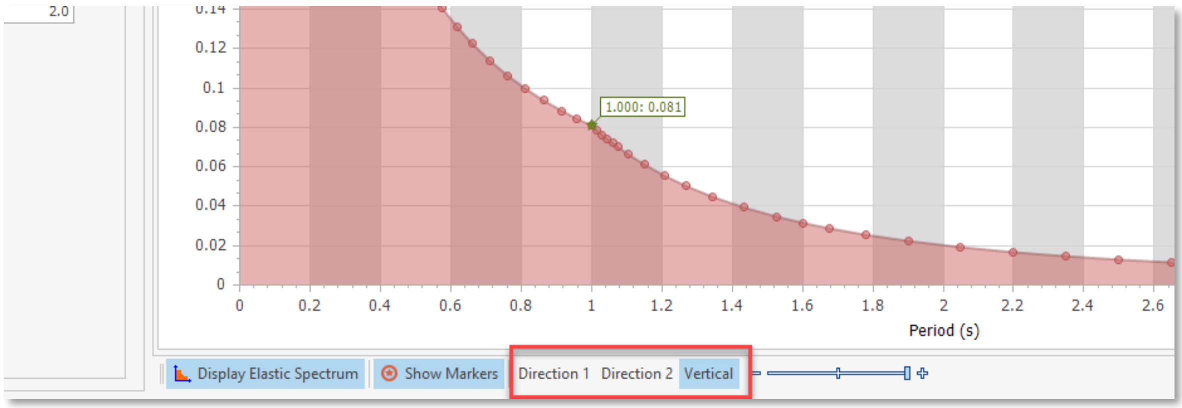
Calculated modal values can be reviewed in **Eigenvalue Analysis Report** after the analysis.

Definition of Vertical Acceleration Spectrum

To perform a modal vertical earthquake analysis, a vertical spectrum definition is necessary. For this purpose, we introduced the vertical acceleration spectrum in ProtaStructure, which is accessible from the **Seismic Parameters** window.

1. Click the **Vertical** button underneath the spectrum graph to switch to the vertical spectrum view.

Vertical spectrum is also tabulated and graphically presented in **Pre-Analysis Checks** Report.



Code-Specified Vertical Spectrum

Some of seismic codes explicitly specify the shape of the vertical spectrum. Among those codes are ASCE07, Eurocode 8, TBDY2018, NTE030, DPT1302 and SNI1726. ProtaStructure will automatically calculate the vertical spectrum for these seismic codes.

Constant Acceleration or Fraction of Horizontal Spectrum

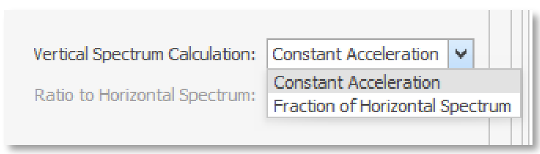
For the codes that do not specify an explicit vertical spectrum, two options are provided.

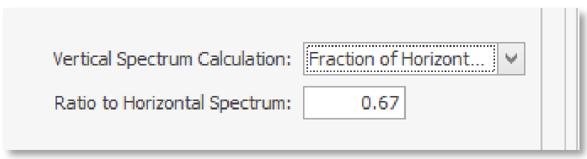
1. Fraction of Horizontal Spectrum
2. Constant Acceleration

In the **Fraction of Horizontal Spectrum Method**, the vertical spectrum is calculated by multiplying the horizontal design spectrum with a user-defined factor with a default value of 2/3.

The **Constant Acceleration Method** provides an alternative where you want to use the same response for all vertical modes. The response value is the same as the one used in static approach.

You can access these two options from **Seismic Parameters > Analysis** window.





Constant Acceleration and Fraction of Horizontal Spectrum options are not available for ASCE07-16, SNI1726-2019, TBDY2018, EN1998-1:2004 and NTE030. Because these codes directly specify a vertical acceleration spectrum.

The table below summarizes the codes and adopted approaches in ProtaStructure.

Code	Static Approach	Modal Approach	Constant Acceleration	Fraction of Horizontal Design Spectrum
ASCE07-16	$0.2S_{DS}$	Vertical Spectrum Cl.11.9	N/A	N/A
SNI1726-2019	$0.2S_{DS}$	Vertical Spectrum Cl.6.11	N/A	N/A
TBDY2018	$\frac{2}{3}S_{DS,DD2}$	Vertical Spectrum Cl.2.3.5	N/A	N/A
EN1998-1:2004	N/A	Vertical Spectrum Calculated Cl.3.2.2.3	N/A	N/A
NTE030	$\frac{2ZUS}{3}$ Cl. 4.5.6	Vertical Spectrum Cl. 4.6.2	N/A	N/A
IS1893-2016	$\frac{\left(\frac{2}{3}\frac{Z}{2}\right)2.5}{\left(\frac{R}{I}\right)}$ Cl. 6.4.6	No vertical spectrum specified by the code	$\frac{\left(\frac{2}{3}\frac{Z}{2}\right)2.5}{\left(\frac{R}{I}\right)}$	Default value is 2/3
UBC97	$0.5C_aI$ Cl. 1630.11	No vertical spectrum specified by the code	$0.5C_aI$	Default value is 2/3
NSCP2015	Same as UBC97			
NSR10A	$\frac{2}{3} \times A_aF_aI$	No vertical spectrum specified by the code	$\frac{2}{3} \times A_aF_aI$	Default value is 2/3

Mass Calculation and Mass Matrix

To capture an accurate structural behavior in modal vertical earthquake analysis, the vectoral mass distribution (in Z direction) must be accurately calculated. Depending on the selected analytical options, mass distribution may change significantly.

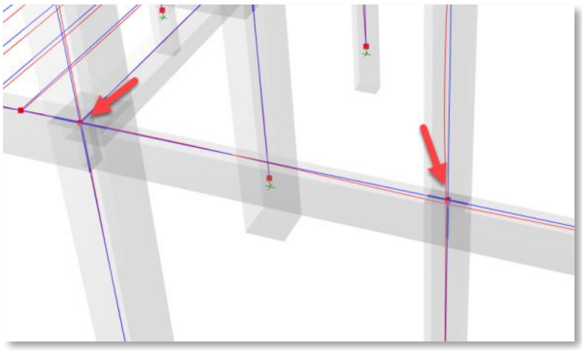
In vectoral terms, active masses in Z direction (m_Z) must not be confused with the active lateral masses in translational X (m_X) and Y (m_Y) direction and mass moment of inertia around Z axis. Mass moment of inertia (m_{RZ}) is only assigned to diaphragm master joints if a diaphragm constraint is used. Translation X and Y masses can be lumped into diaphragm master joints (if a diaphragm constraint is used) or distributed to all relevant nodes (if diaphragm constraint is not used).

Vertical mass has nothing to do with diaphragm assumption. ProtaStructure will still calculate and assign vertical masses (m_Z) even if diaphragm constraints are used.

ProtaStructure will automatically calculate the vertical mass distribution. However, certain points must be considered for obtaining a more accurate behavior.

Beams Not Supporting Any Slabs

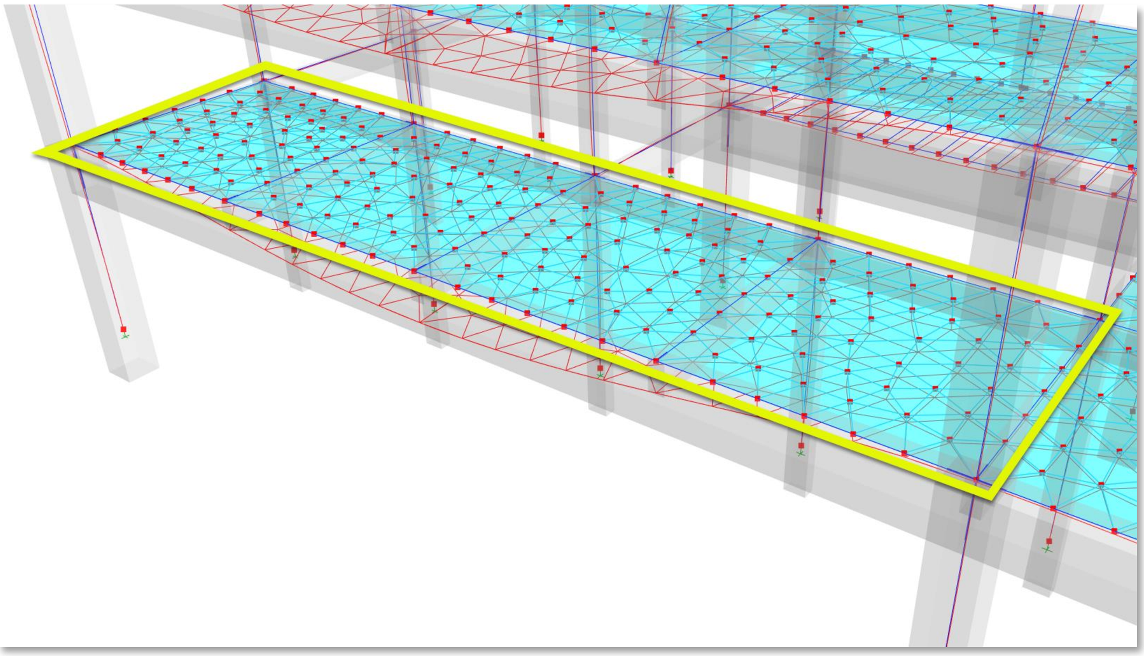
The masses are calculated only at the start and end nodes of such beams. If you need to capture the vertical earthquake effects on these beams more accurately, we recommend inserting them in multiple adjacent pieces. Usually, long span beams will be affected more.



Masses are lumped at the ends of the beam.

Beams Supporting Ordinary Slabs

To capture the vertical earthquake effects more accurately, the slabs and beam must be meshed. In this way, the masses will be calculated in the intermediate points on the beam.

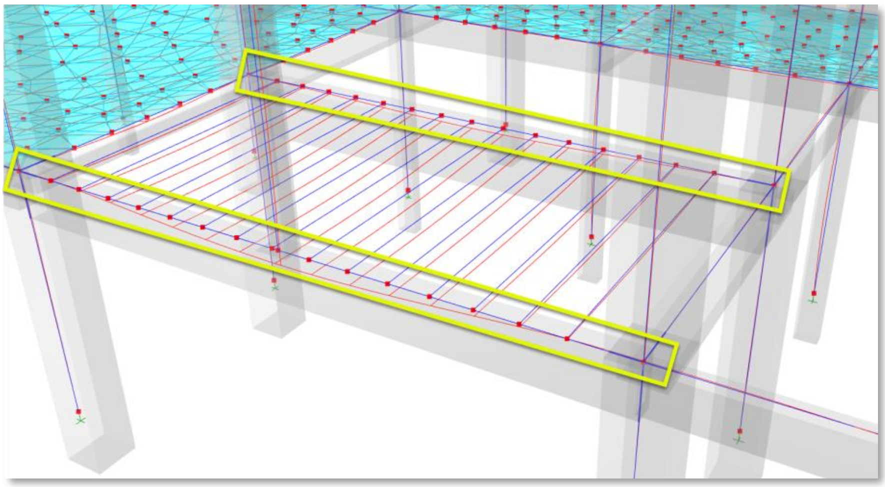


For meshed slabs, masses are calculated at each meshed node and the nodes on the beam.

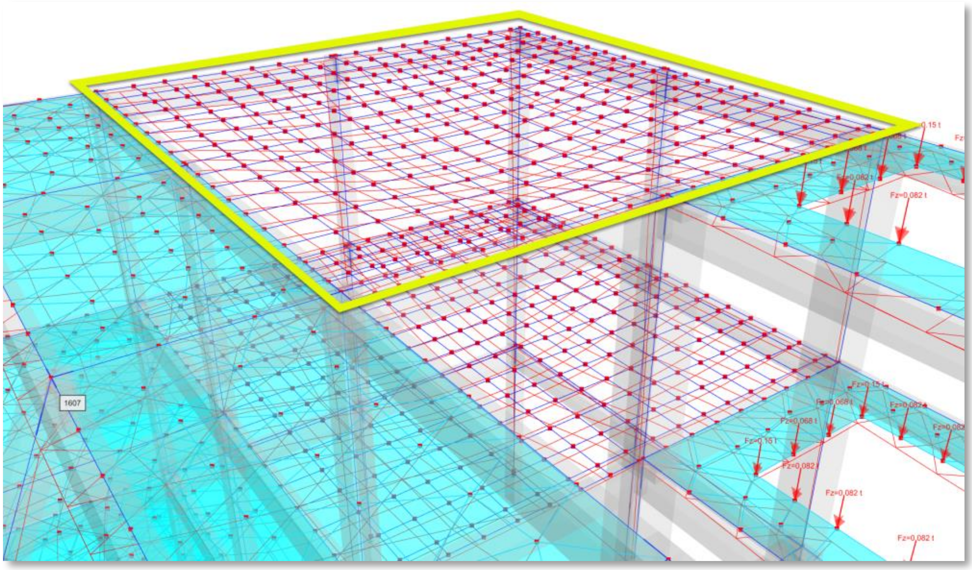
Beams Supporting Ribbed and Waffle Slabs

Rib and waffle beams are automatically considered as a part of the analytical model in building analysis. That means, the rib/waffle beams are chopped automatically with each other and the primary beam. Vertical masses are automatically assigned at these intersections.

Unlike waffle slabs, one-way rib beams are assigned vertical mass only at their start and end joints since there are no other direction beams crossing them.



Masses are lumped at the ends of the rib beams.



Masses are lumped at the intersections and at the ends of the waffle beams.

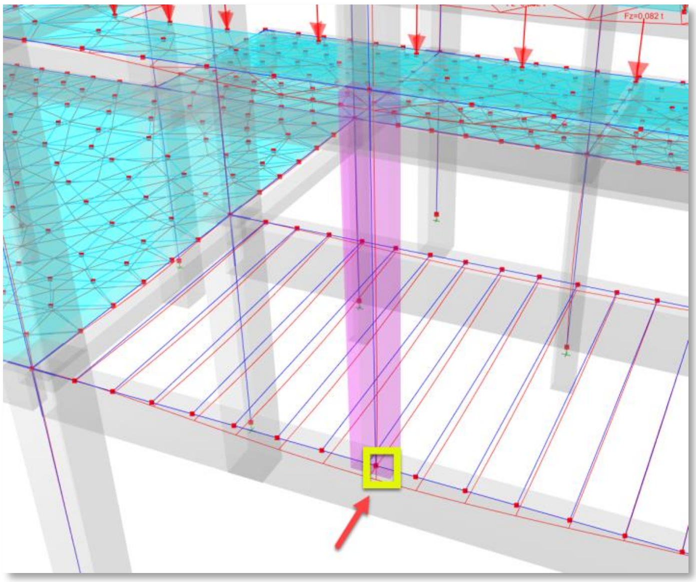
Beams Supporting Composite Slabs

Like rib slabs, vertical masses are assigned to start and end points of the secondary composite beams.

Transfer Beams or Slabs Supporting Stub Columns

When a beam or a slab is modelled to support a stub column, the beam and the slab are meshed compatibly with the column ends so that the stiffness and the load transfers are taking place correctly.

In this case, masses will be lumped at both ends of the discontinuous/stub column. In fact, masses will be lumped at the ends of all columns regardless of their continuity condition.



Vertical or Slanting Columns

Masses will be lumped at the ends of all vertical or slanting columns.

Members Intersecting Each Other

ProtaStructure will automatically understand and connect the members intersecting at 3D space, be it a column, shearwall, beam and so on. The masses will be automatically calculated and assigned to the intersecting nodes. For example, if a beam frames into a column at its mid-height, an additional node will be created at the intersection and the column will be represented by two analytical frames. The three nodes on the column will be assigned a mass.

Steel Purlins, Girts, Planar Trusses, Space Trusses, Domes, Brace

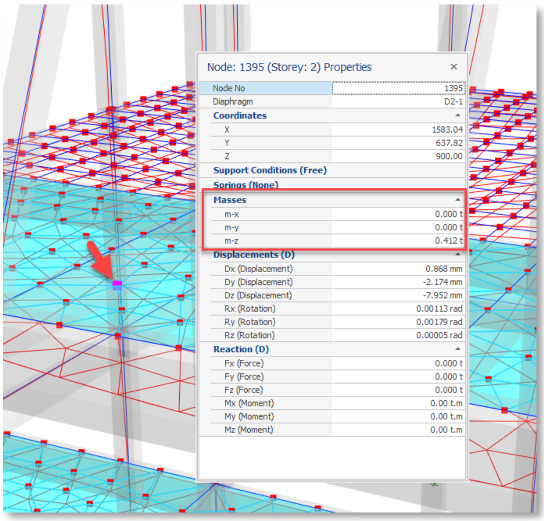
Like other members, the mass values will be automatically calculated at intersection points.

Mass Distribution

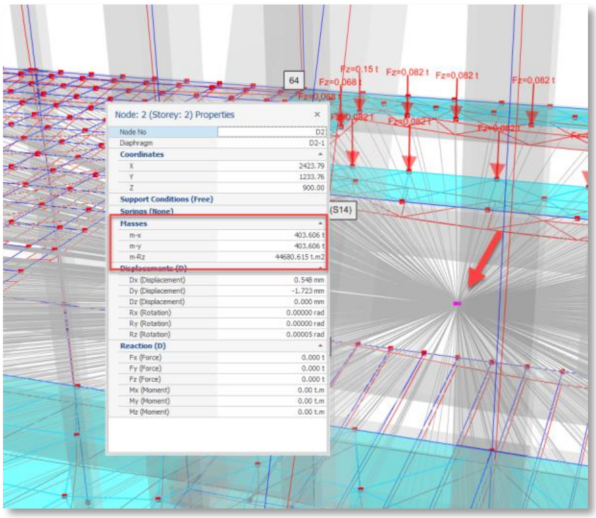
ProtaStructure automatically calculates the masses from dead loads, live loads and user-defined vertical loads (if the user specified them to contribute to mass). Loads on the structure are automatically decomposed and used as the mass source in lateral and vertical modal analyses.

Mass Distribution When Diaphragm Constraints Are Active

All translational masses calculated from seismic mass (such as G + n.Q) are lumped at diaphragm master nodes as M_X and M_Y In addition to translational masses, mass rotational inertias are calculated and assigned to the diaphragm master node as M_{RZ}. You can review the assigned mass values at the diaphragm master node and the slave nodes in the **Node Properties** window as explained in the pictures below.



(a) Nodal Mass values of a Slave Node



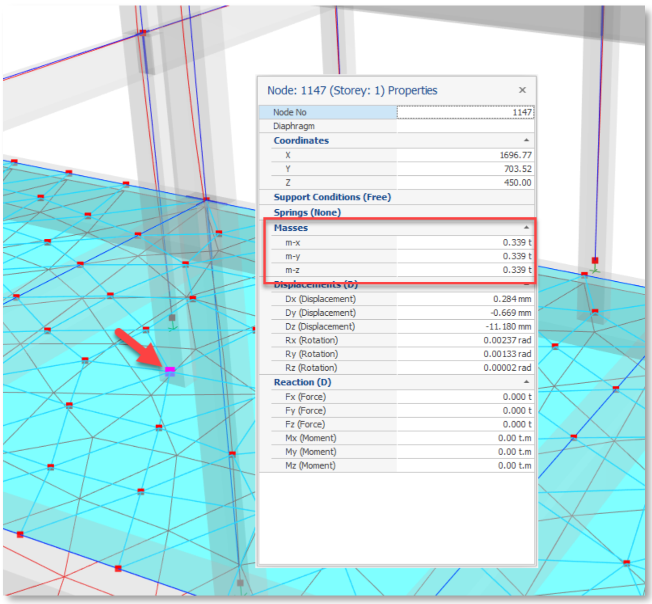
(b) Nodal mass values of a Diaphragm Master Node

Slave nodes will not have any translational M_X or M_Y mass in x and y directions since all the mass is lumped at the diaphragm master node. However, slave nodes will still be assigned M_Z mass in vertical direction. Diaphragm master node will have an M_{RZ} rotational inertia to capture the effect of nonuniformity in mass distribution and the rotation that it will cause. Diaphragm master node does not need to be assigned a vertical M_Z mass.

Mass Distribution When There is No Diaphragm (Or there is Flexible Diaphragm)

Since there will be no diaphragm constraint, there will not be a diaphragm master node. That means, there will be no mass lumping.

M_X, M_Y and M_Z masses will be distributed to free local nodes. There is no need to calculate rotational mass because the masses are already distributed and mass nonuniformity is automatically considered by local masses accurately calculated.



Nodal Mass Values of a Node when there is no diaphragm constraint

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