Building Subjected to Wind Loads

Computational Mechanics Tools Simulation Project

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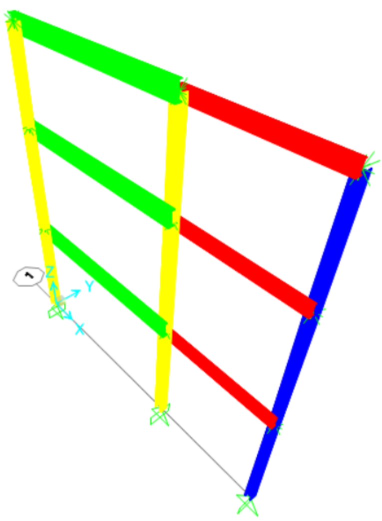

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1 Introduction

The course simulation project consists of performing static and dynamic analysis of a building subjected to wind loads through a finite element method simulation software, with the final purpose of analysing the change in the behavior of the structure under changing loading and restraints conditions.

A linear static analysis is one where a linear relation holds between applied forces and structure displacements. In practice, this is applicable to structural problems where stresses remain in the linear elastic range of the used material. In a linear static analysis the structure's stiffness is constant, and the solving process is relatively short compared to a nonlinear analysis on the same model. However, nonlinear analysis, despite having a higher computational cost, are often necessary to accurately model a structural problem. Therefore, for a first estimate, linear static analysis are often used prior to performing a full nonlinear analysis [1].

It is common practice in structural design to include plastic properties for the structural materials used in models but it is however considered that the presence plastic (permanent) deformations are the main criteria for structure damage and failure. This will also be the case for the analysis to be performed.

All real physical structures behave dynamically when subjected to loads or displacements. The additional inertia forces, from Newton's second law, are equal to the mass times the acceleration. If the loads or displacements are applied very slowly, the inertia forces can be neglected and a static load analysis can be justified. Hence, dynamic analysis is a simple extension of static analysis [2]. In order to evaluate the validity of modeling wind loads as static loads, they will be modeled as both static and dynamic loads for later quantifying the difference in the structural response to them.

The tool chosen for the analysis is SAP2000, a finite element software developed specifically for structural analysis, design and optimization [3].

2 Problem Description

The aim of this project is to analyze the static and dynamic response of the two-store building given in Figure 1 under the two loading conditions illustrated in Figure 2.

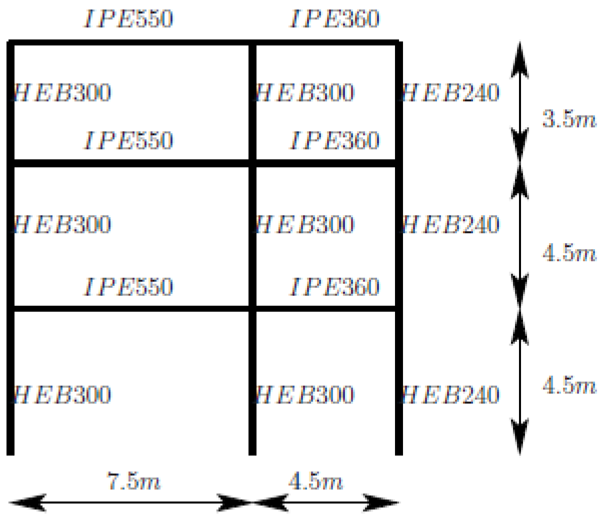


Figure 1: Geometry and beam profiles in the two-store building.

1. Static Analysis

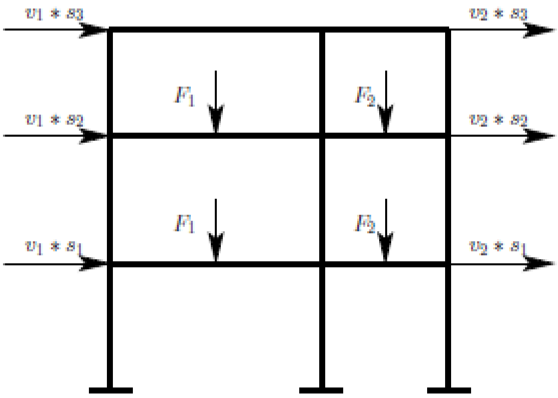
   a Generate the building geometry with the given beam profiles.

   b Analyze the resulting deformations, axial stresses and bending moments resulting after applying the loading cases 1 (wind + point load) and 2 (wind + distributed load), and with different support conditions (hinged/clamped) at the base of the columns.
   The value of the distributed load f is computed by using the following formula:

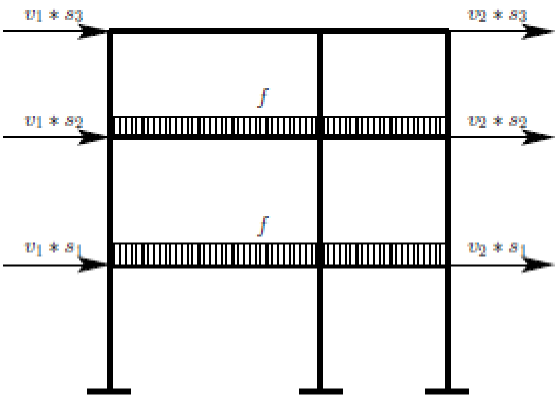
   $$f = \alpha_{dl} q_{dl} + \alpha_{ll} q_{ll} \qquad (1)$$

   where the nominal loads q_{dl} and q_{ll}, and the security factors q_{dl} and q_{ll} are given in Figure 3.
   Comment on which one of the loading cases and support conditions may be more critical.

2. Dynamic analysis:
   The frequency of the wind load is estimated to be below 2Hz.
   Determine whether this value may affect the dynamic response of the building for the different support conditions of the columns.



(a) Case 1



(b) Case 2

Figure 2: Loads considered in cases 1 and 2.

Loads			
Point Load	$F_1 = 324$ kN	$F_2 = 194.4$ kN	
Distributed load	$q_{dl} = 14.40$ kN/m	$q_{ll} = 28.80$ kN/m	
	$\alpha_{dl} = 1.35$	$\alpha_{ll} = 1.5$	
Wind Loading	$v_1 = 0.80$ kN/m^2	$v_2 = 0,50$ kN/m^2	
	$s_1 = 48.6$ m^2	$s_2 = 28.1$ m^2	$s_3 = 11.9$ m^2

Figure 3: Values of the loading parameters

3 Model Creation

3.1 Material definition

The material chosen for the model was A572 Gr. 50 structural steel, which is defined under the ASTM standard. This is one of the most widely used structural steels in the world and therefore it was considered a reasonable assumption. SAP 2000 presents the following predetermined mechanical properties for this material.

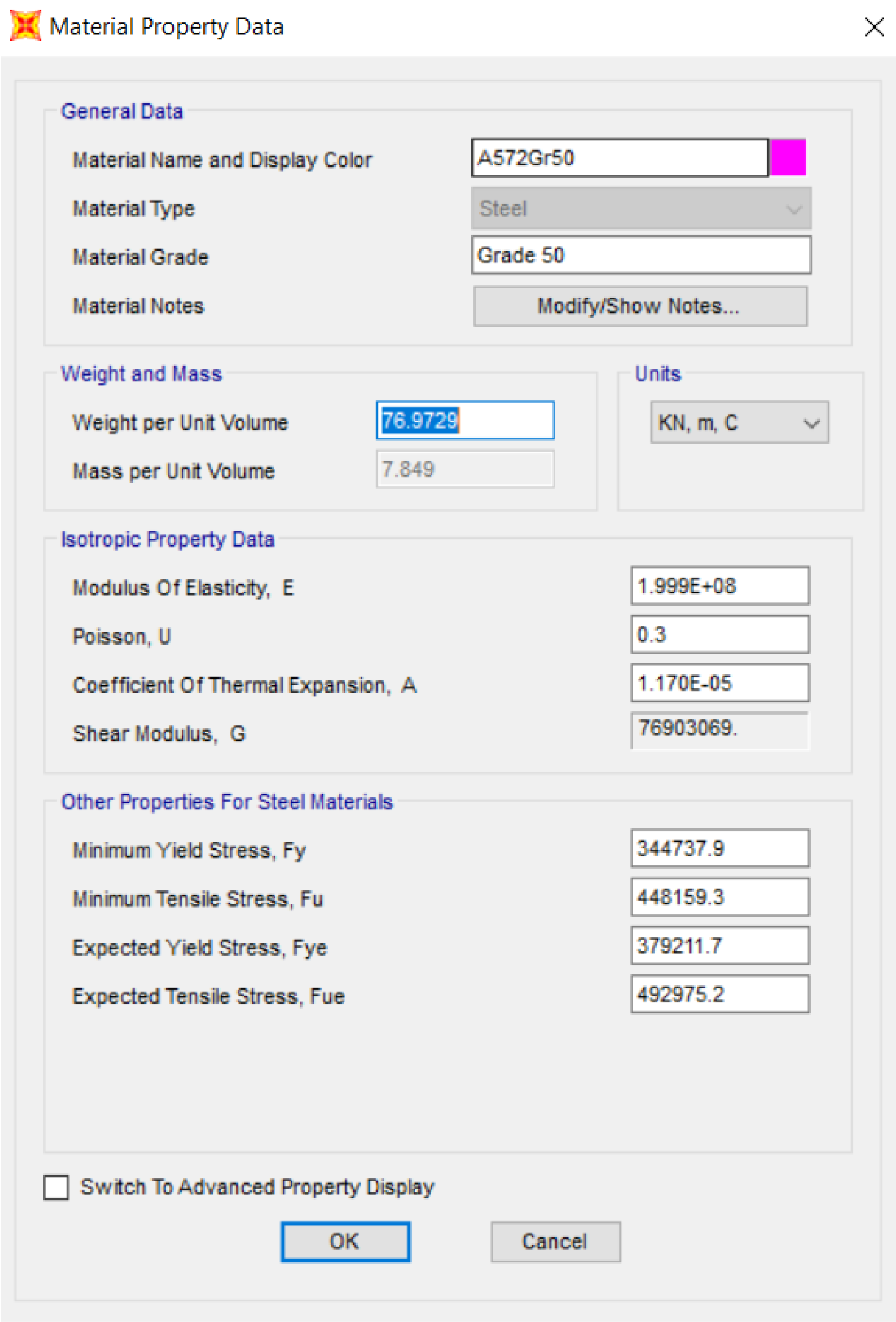


Figure 4: Material definition

3.2 Sections Definition

After the structural material is defined, it may be assigned to the four geometric sections present in the structure, which were defined as follows:

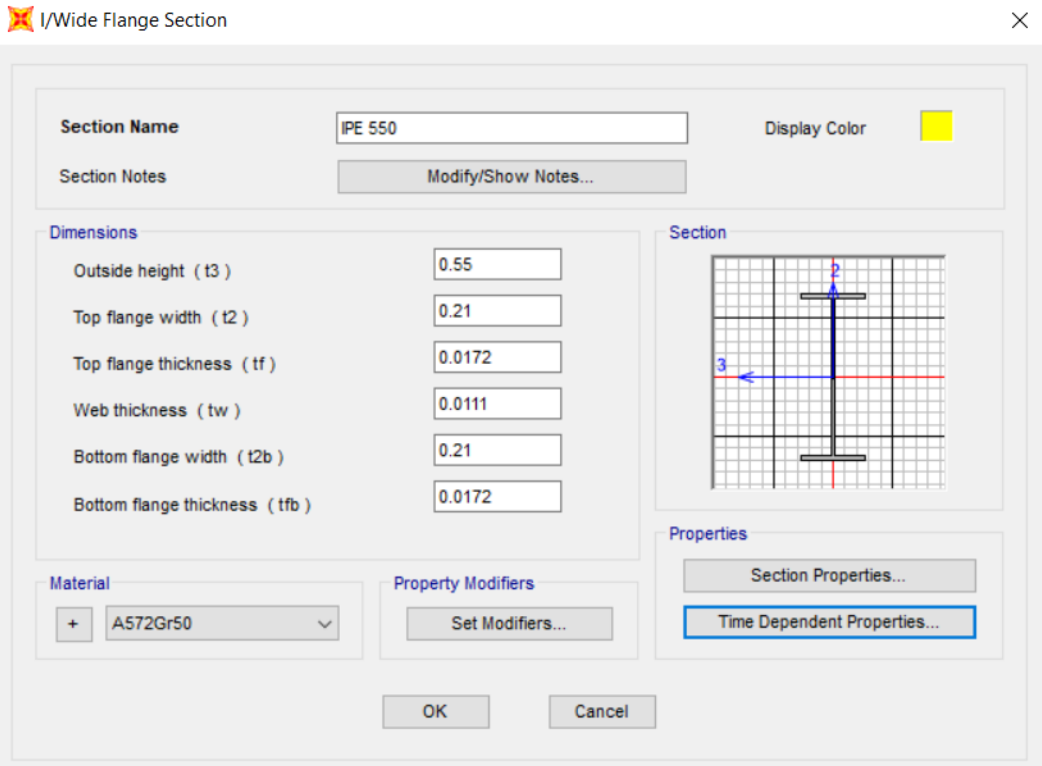


Figure 5: IPE 550 Section

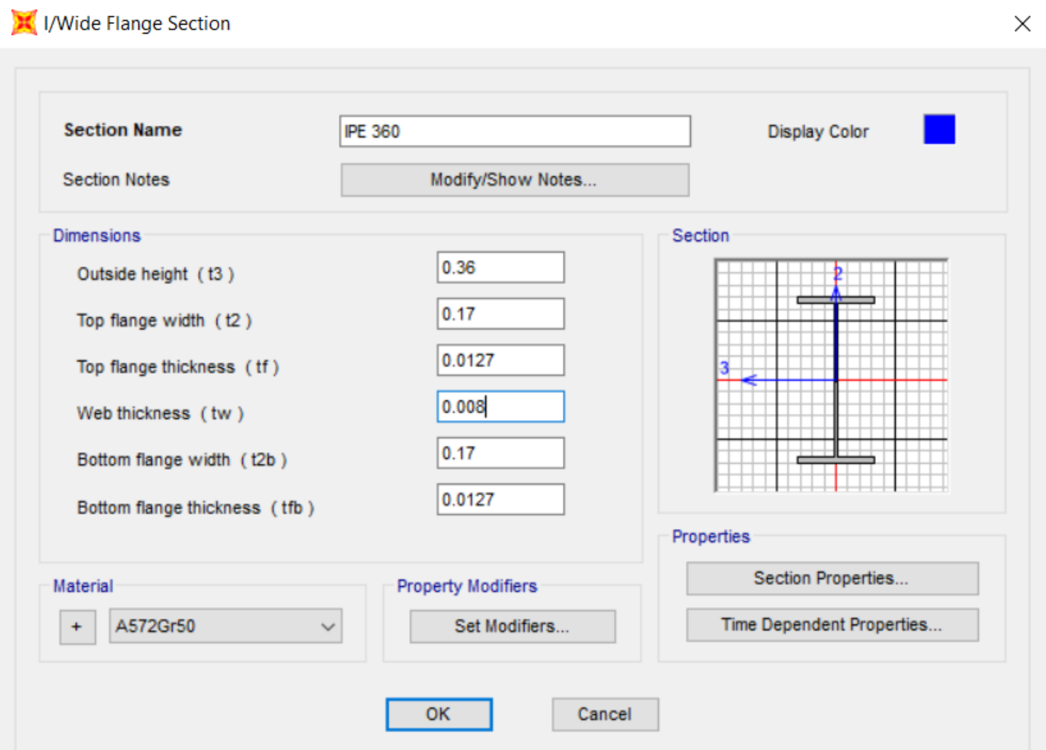


Figure 6: IPE 360 Section

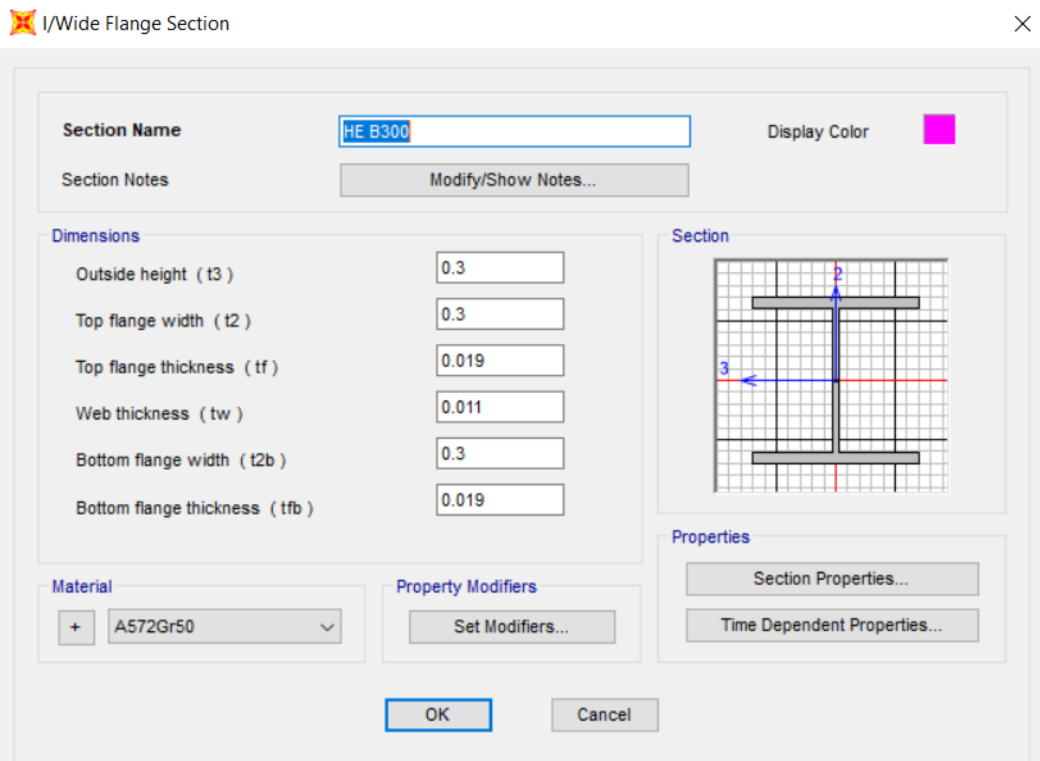


Figure 7: HBE 300 Section

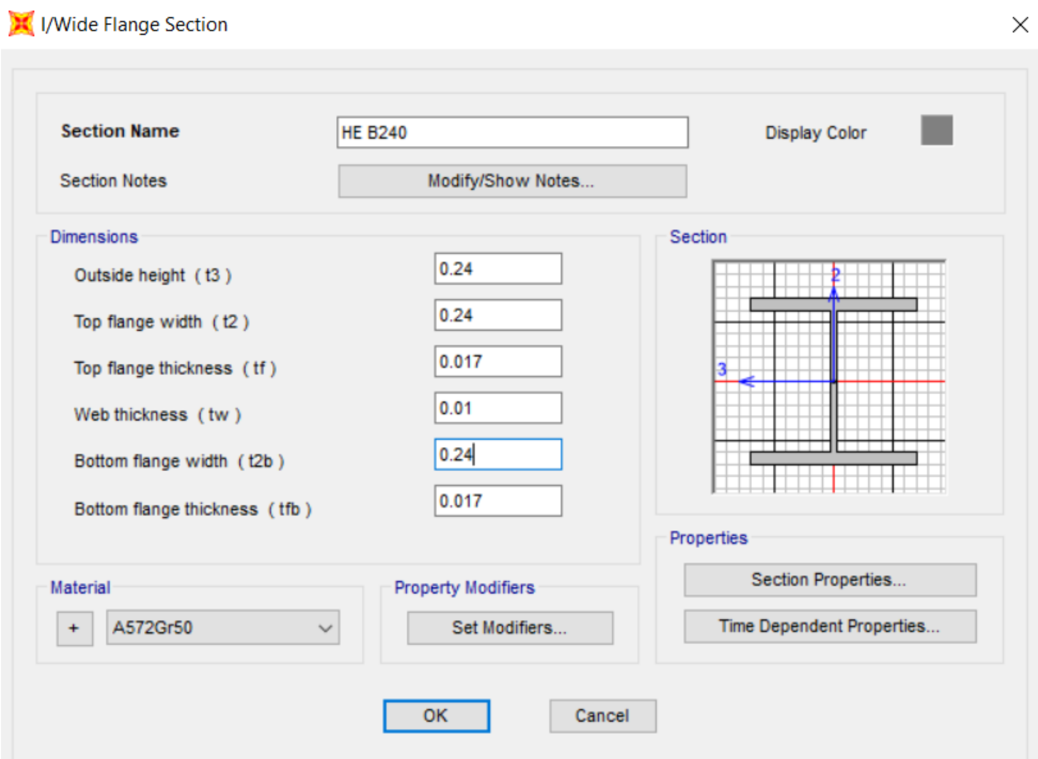


Figure 8: HEB 240 Section

3.3 Geometry

The previously created sections may then be assigned to the structural elements of the building, resulting in the following frame configuration:

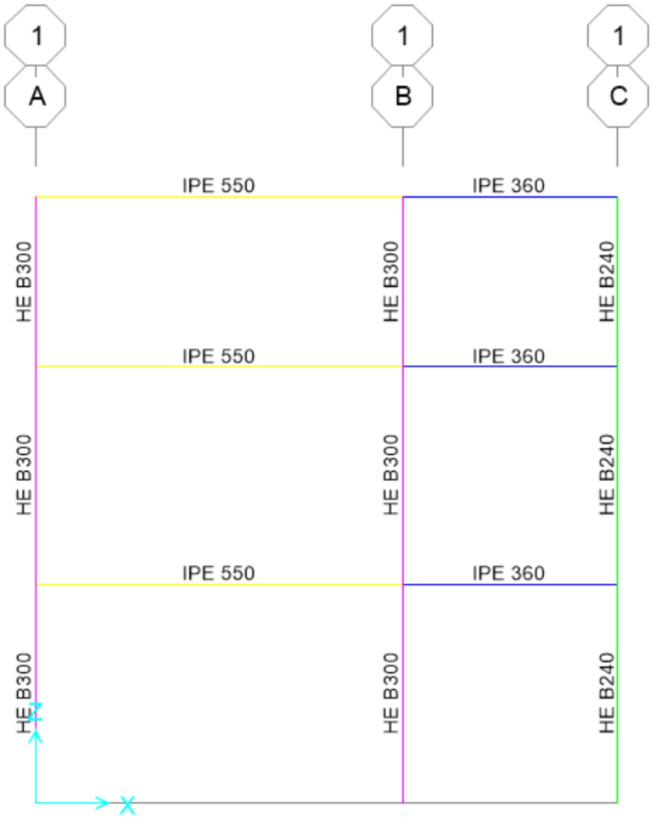


Figure 9: Structural Elements

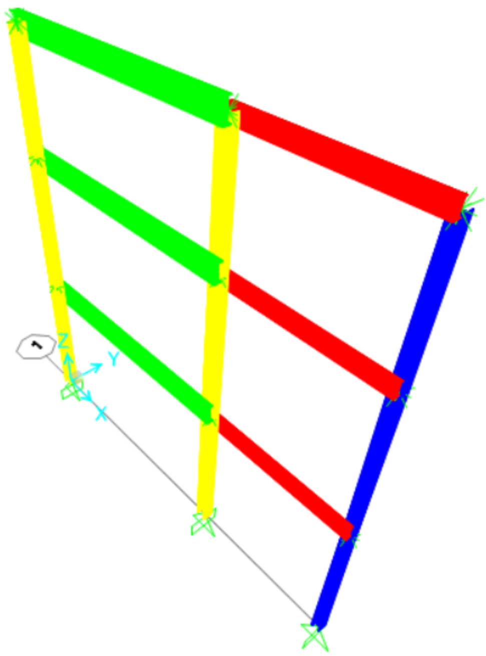


Figure 10: 3D Sections

In order to have a reference for the analysis of the results, we must take into account the elements (frames) and nodes numbering and connectivity. Which was automatically defined by the software as:

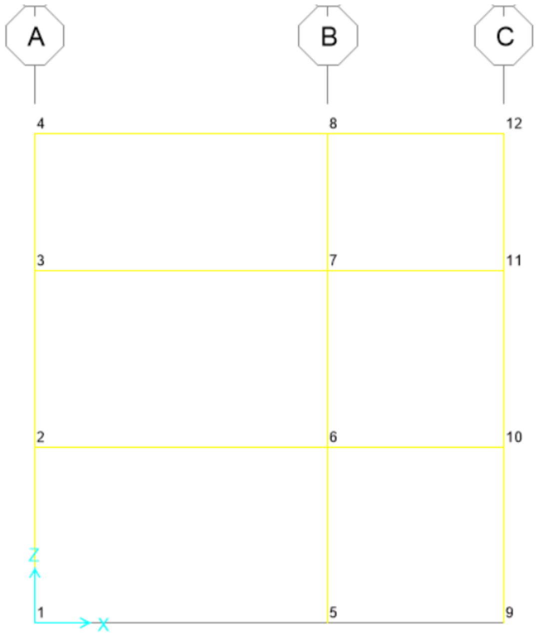


Figure 11: Node Labels

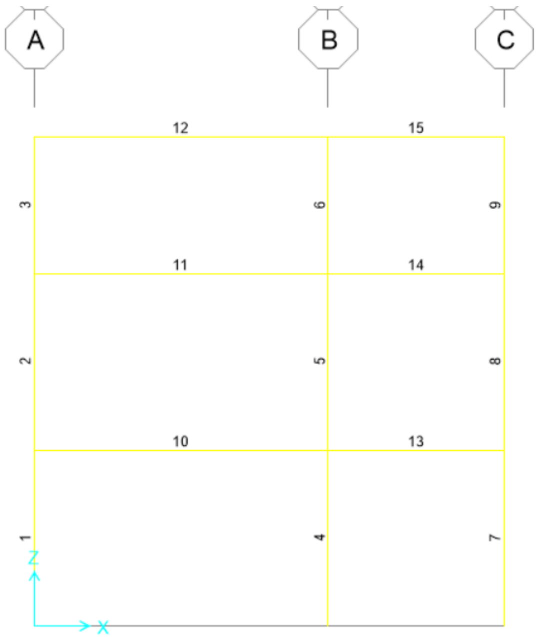


Figure 12: Frame Labels

The local axes of structural elements and nodes obey the following color convention in SAP 2000: Red (1), green (2), blue (3). The figures below illustrate the local axes directions for every element of the structure.

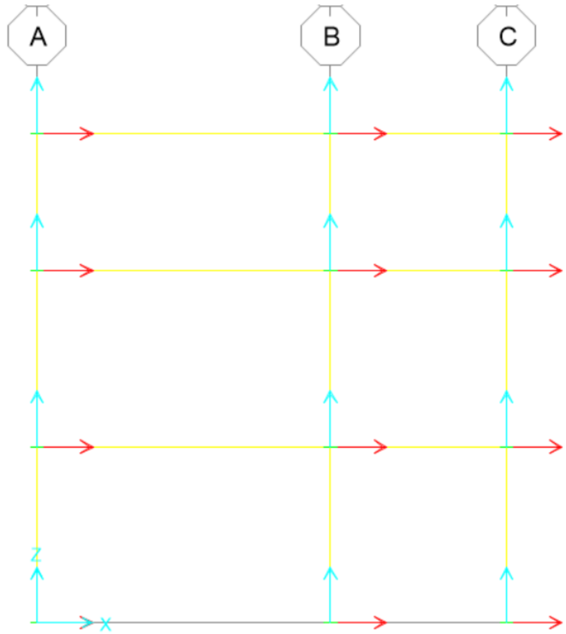


Figure 13: Node Local Axes

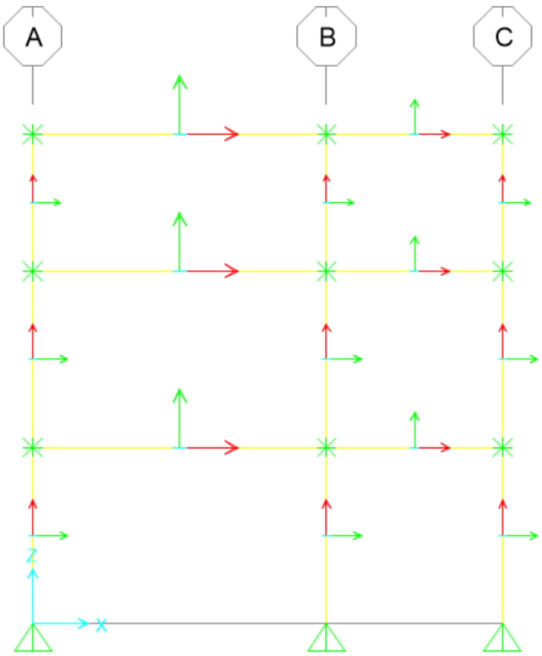


Figure 14: Frame Local Axes

3.4 Node Restraints (Dirichlet Boundary Conditions)

For this project, the are two different cases for the restraints on the nodes at the base of the building (y=0):

- Clamped: All displacements and rotations restricted.

Figure 15: Clamped boundary condition

- Hinged: All displacements restricted but free rotations.

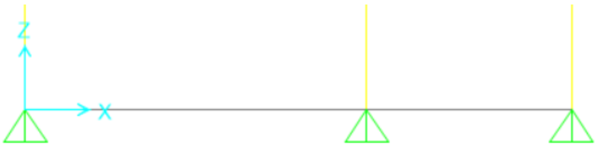


Figure 16: Hinged boundary condition

Additionally, in order to perform a 2D analysis of the building, displacements along the Y axis were restricted for all nodes, forcing all displacements to take place along the X-Z plane.

3.5 Additional Assumptions (Rigid vs. Flexible Diaphragm)

The situation that typically occurs in buildings is that the concrete slabs present on each level of the building act as infinitely rigid diaphragms in their own planes. These elements, although flexible in an orthogonal sense, exhibit in many cases a great rigidity in their own plane, which makes the horizontal displacements of the nodes with the same Z coordinates as them to be coordinated. This concept is further explained with the help of figures 17 and 18.

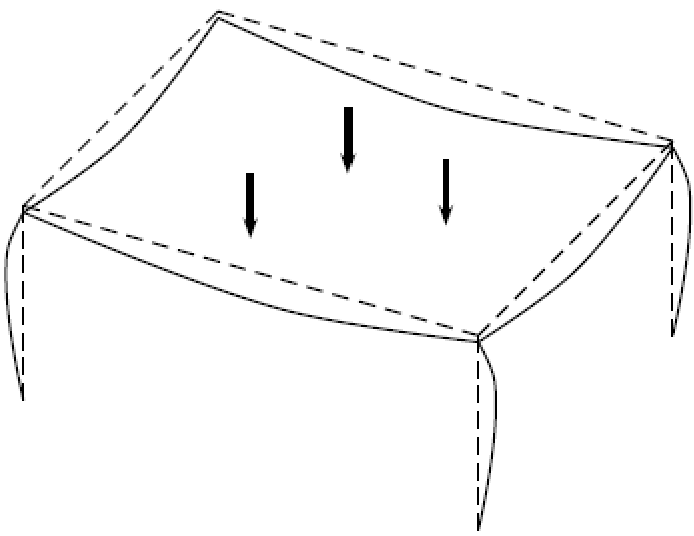


Figure 17: Flexible diaphragm in an orthogonal plane.

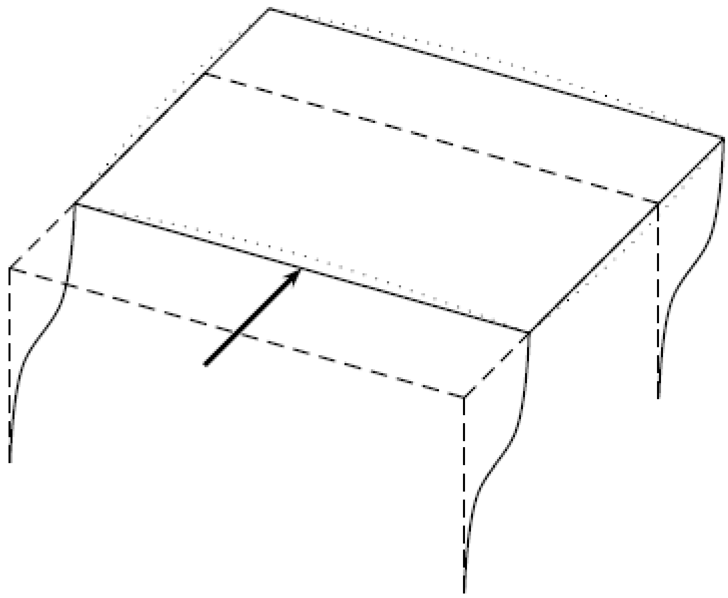


Figure 18: Flexible (· · ·) and rigid (——) diaphragms in its plane.

In the first one, the slab-space frame set is subjected to a group of vertical loads orthogonal to the slab's plane. In this sense the diaphragm can be considered as flexible. However, in many dynamic situations, such as those relevant to the thrust of the wind or horizontal acceleration caused by earthquakes, interest falls on the horizontal movements of the structure, which implies horizontal translation of the slabs. From this point of view, the diaphragm can be rigid or flexible, as illustrated in Figure 18, depending on the materials that constitute it, the separation of the support structures and the dimension of the diaphragm in the direction parallel to the action horizontal. In the case of a building, for example, there are typically concrete diaphragms, supported by vertical structures relatively close to each other and with dimensions comparable to such separations. Therefore, it is usual to adopt the rigid diaphragm hypothesis.

This differentiation between rigid and flexible diaphragms is of great importance, since in the former it is possible to ignore the deformations of the slab produced by horizontal loads, and consider it as a rigid body in its plane. This allows, in turn, to make use of a basic law of mechanics, according to which in a rigid body, the co-planar forces acting on it can be composed of a single resultant force applied at the center of mass of the diaphragm and a moment around the axis orthogonal to the plane.

Consequently, a structure with rigid horizontal diaphragms subjected to horizontal dynamic forces, can be modeled with three degrees of freedom at each level where a diaphragm is present [4]. Figure 19 illustrates how to consider a rigid diaphragm in the model.

The structure was analysed under both rigid and flexible diaphragm conditions in order to evaluate the influence of this assumption on its behavior.

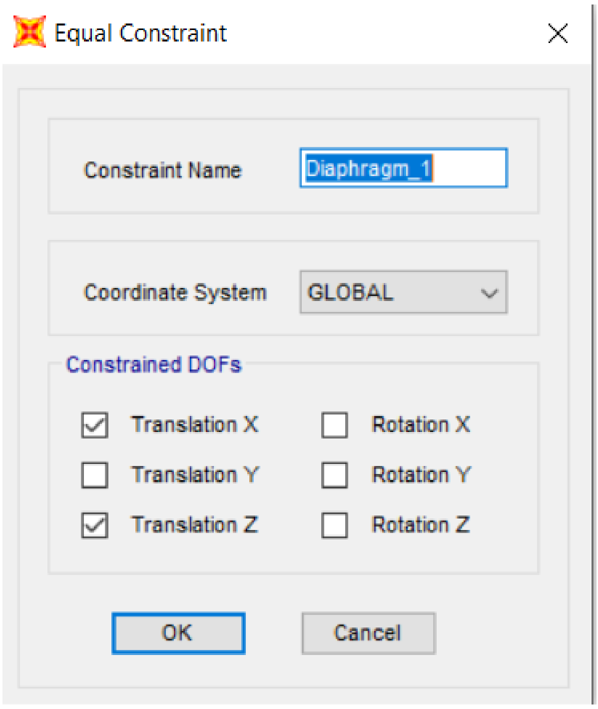


Figure 19: Rigid Diaphragm Definition

4 Static Analysis

4.1 Loads

From figure 3 and equation (1), the loads acting on the structural frame can be computed. Once the values are obtained, these loads have to be assigned as it is indicated in figure 1 to the different structural elements.

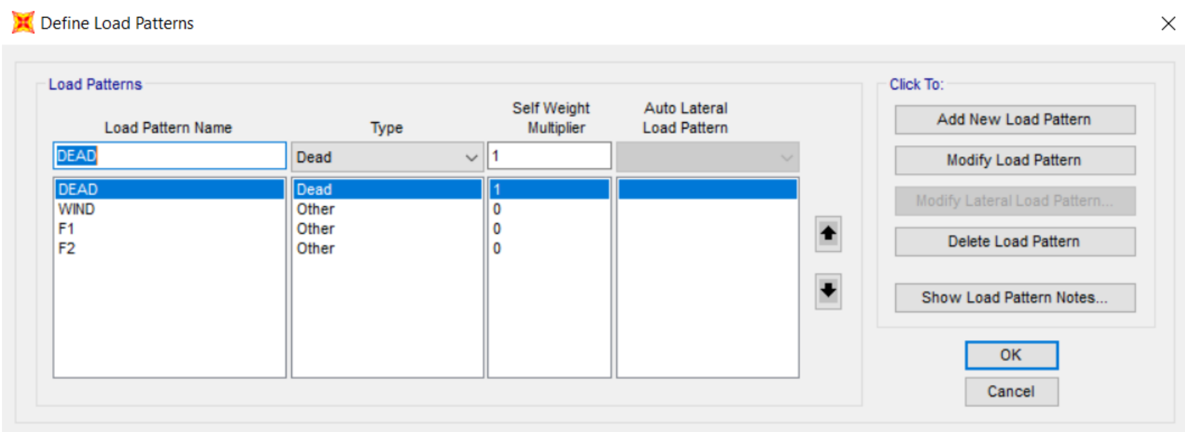


Figure 20: Load Patterns

Wind Loads:

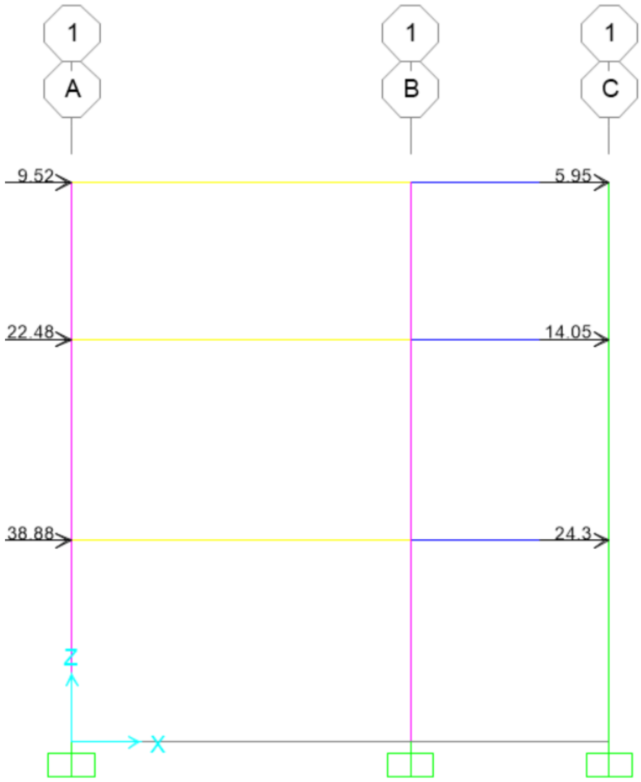


Figure 21: Wind Loads (KN)

Point Loads:

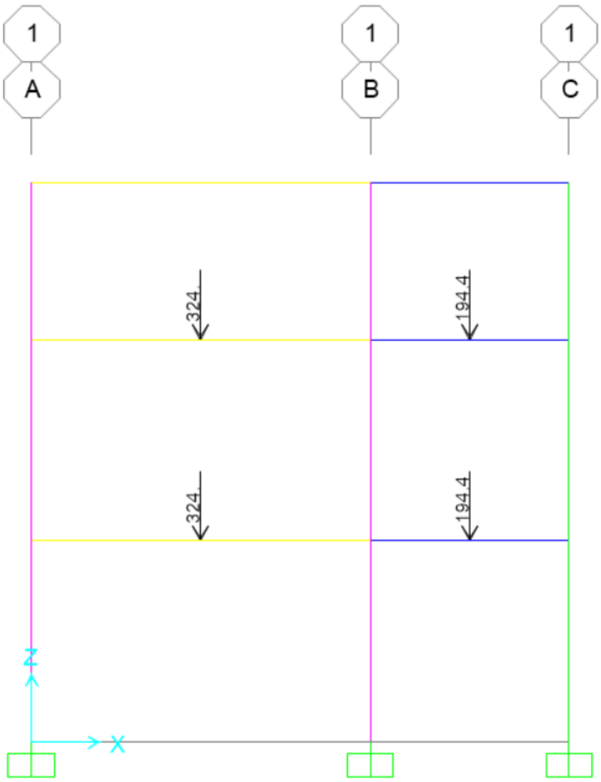


Figure 22: Point Loads (KN)

Uniform Loads:

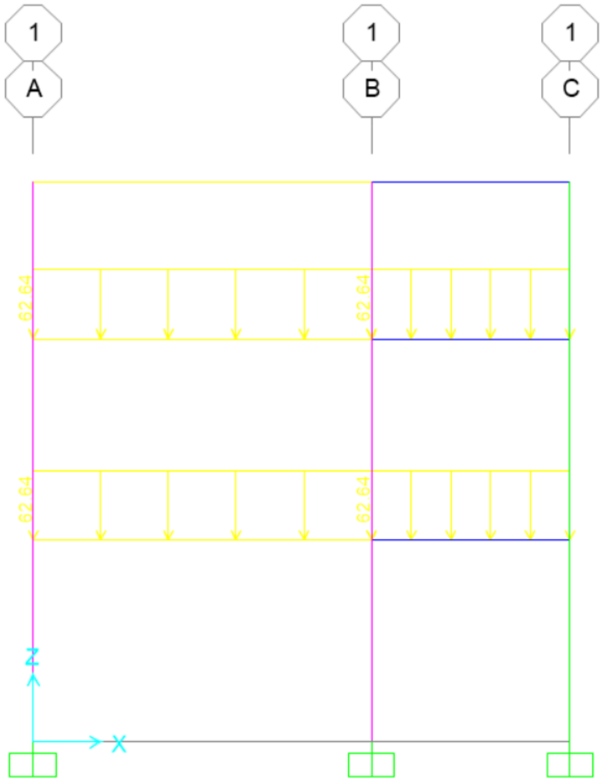


Figure 23: Uniform Loads (KN/m)

4.2 Load cases

Load cases have to be assigned as mentioned in the definition of the problem:

- Case 1: wind loads + point loads
- Case 2: wind loads + uniform loads

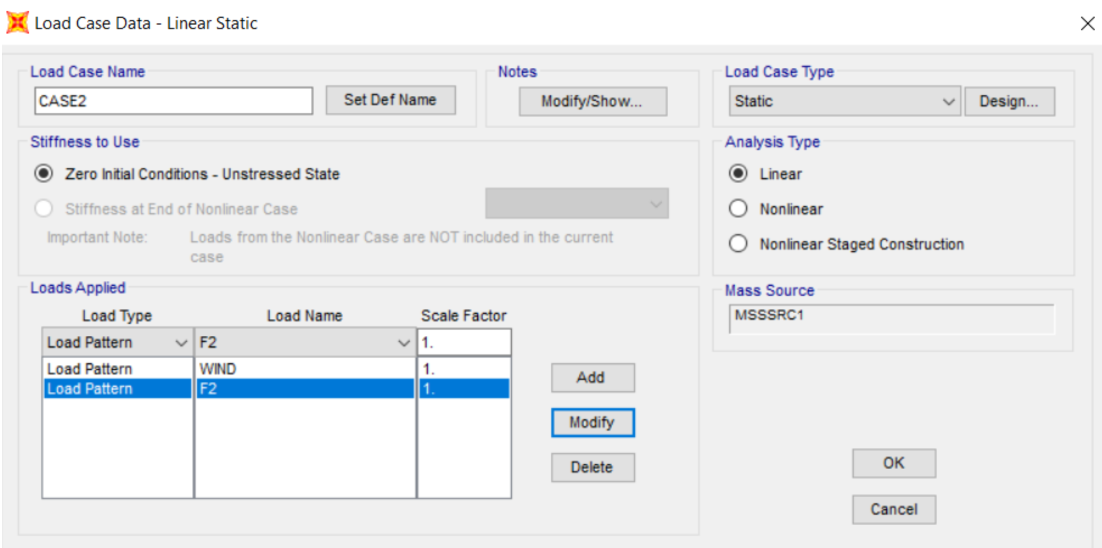


Figure 24: Load case 2 example

4.3 Model Analysis Results

The software creates different diagrams for all aspects of the performed analysis of the structures for each case. Results for the clamped structure with a flexible diaphragm are shown as illustrative examples.

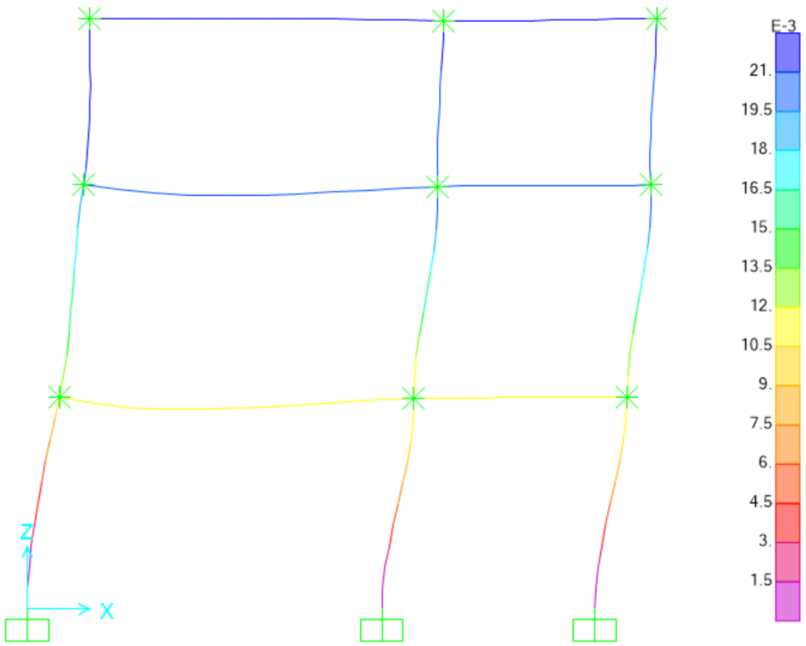


Figure 25: X Displacements Clamped - Flexible Diaphragm Case 1

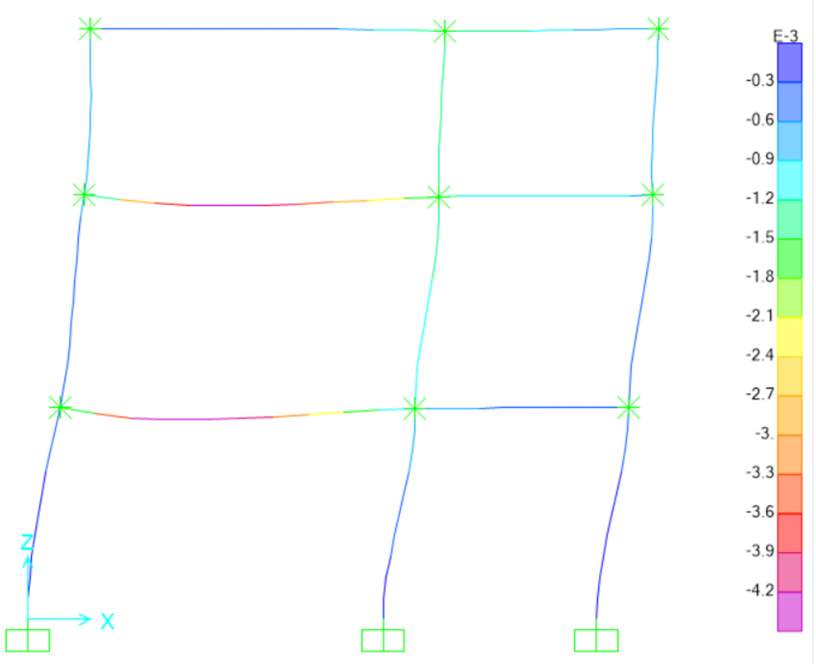


Figure 26: Z Displacements Clamped - Flexible Diaphragm Case 1

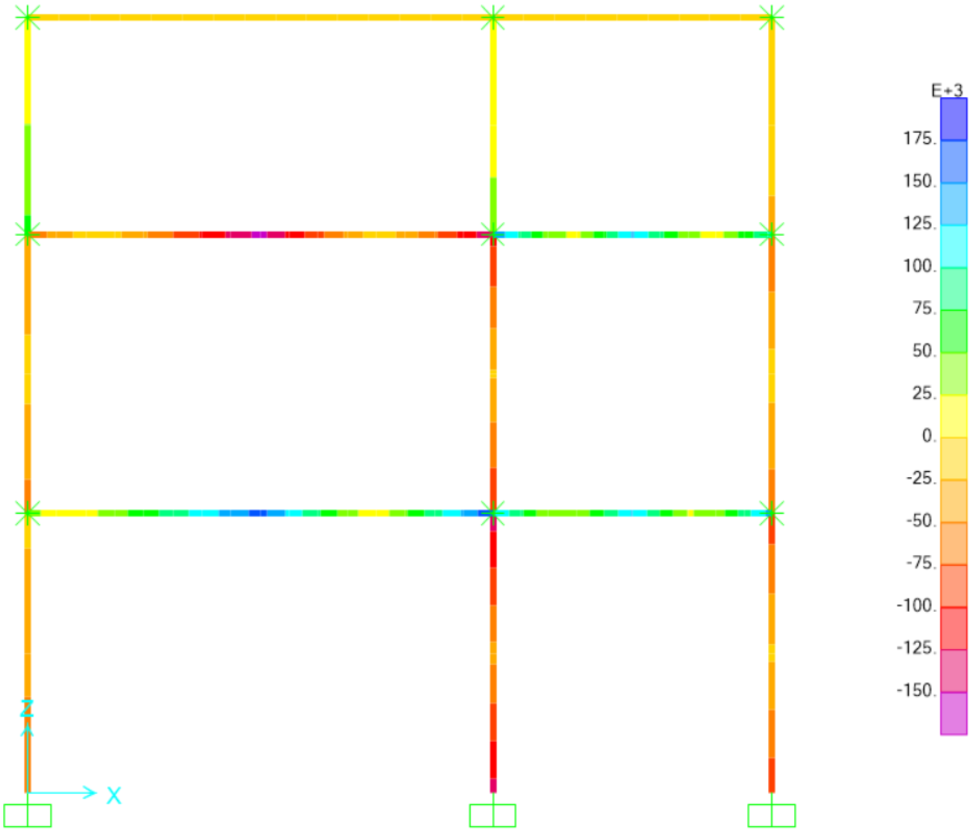


Figure 27: Axial Stress Clamped - Flexible Diaphragm Case 1

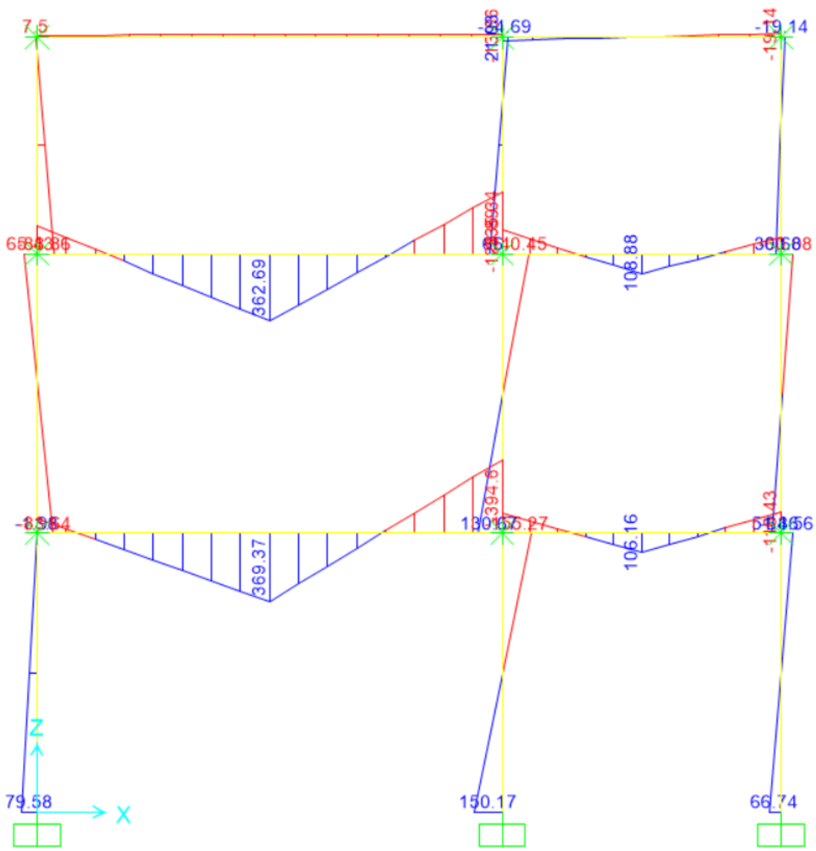


Figure 28: Bending Moments Clamped - Flexible Diaphragm Case 1

4.4 Results Synthesis and Discussion

The following tables display the maximum displacements, stresses, and bending moments present in each one of the analysis performed.

- Clamped Results

Case 1	X Displacements	Z Displacements	Axial Stresses	Bending Moments
Flexible Diaphragm	0.021817	-0.001366	171298.88	-394.5968
Rigid Diaphragm	0.021676	-0.000902	172139.9	-398.7682
Case 2	X Displacements	Z Displacements	Axial Stresses	Bending Moments
Flexible Diaphragm	0.021797	-0.001905	152306.44	-383.703
Rigid Diaphragm	0.021638	-0.001309	169776.19	-389.0845

Table 1: Results Synthesis for Clamped Restraints Model

- Hinged Results

Case 1	X Displacements	Z Displacements	Axial Stresses	Bending Moments
Flexible Diaphragm	0.054729	-0.001384	211697.59	-482.8386
Rigid Diaphragm	0.054444	-0.000902	209801.49	-486.8641
Case 2	X Displacements	Z Displacements	Axial Stresses	Bending Moments
Flexible Diaphragm	0.054696	-0.001922	226682.38	-471.9757
Rigid Diaphragm	0.054387	-0.001309	206006.36	-477.1795

Table 2: Results Synthesis for Hinged Restraints Model

For table 1 and 2, the units are defined as follows:

- X and Z Displacements: m
- Axial Stresses: KN/m^2
- Bending Moments: $KN \cdot m$

By comparing the results obtained for the models with the two different node restraints conditions, it is evident that the stresses, displacements, and moments are higher in the hinged model. Therefore, this model will be used as a reference for analysing the demand/capacity ratio of the structural elements. Tables 1 and 2 help us prove that the rigid diaphragm hypothesis can be done since no critical change on the demand of the stresses and bending moments was presented.

From the resulting diagrams showed before, it can be noticed that element 10 (see Figure12) is clearly the most demanded. Demand/capacity ratio will help us prove this statement.

4.5 Demand/Capacity Ratio

Given the fact that SAP 2000 is a tool for structural design and, as a consequence, it has the incorporated feature of structural demand/capacity ratios checking under a variety of standards from all over the world, it was a simple task to perform this analysis. The hinged model's ratio was checked with the LRFD (Load Resistance Factor Design) method under both load cases, applying the resistance reduction factors specified by the AISC 360-10 [5] standard to account for uncertainties in the model. The following results were obtained:

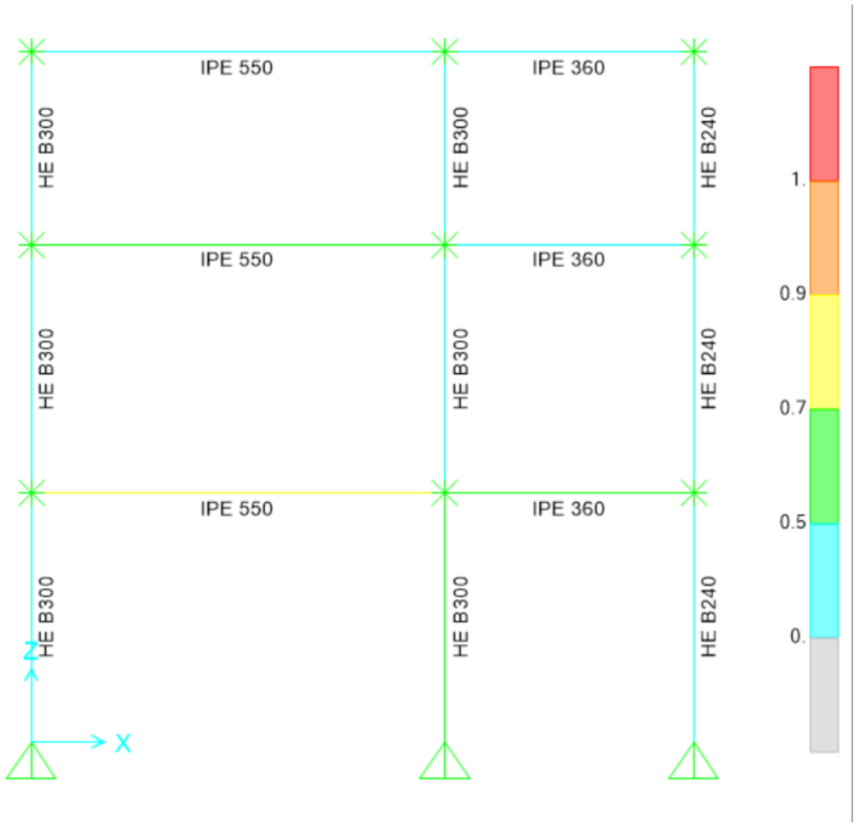


Figure 29: Demand/Capacity Ratio - Hinged Model

It may be observed that the most demanded element is the IPE 550 beam on the first floor of the structure. Its is however being stressed to under 90% of its capacity, which means that all structural elements remain in the elastic deformation range when subjected to the applied loads.

5 Dynamic Analysis

5.1 Modal Analysis

Since wind loads are dynamic and are expected to have a frequency of under 2 Hz, if there is affinity between this frequency and the structure's natural frequency, a certain degree of resonance could occur and the performance of the structure under these loads could be compromised. To evaluate the impact of dynamic wind loads on the structure's behavior, vibration modes and frequencies of both the hinged and clamped models were calculated. Since the modes were obtained from the models with rigid diaphragms, it is supposed that one vibration mode per floor (3 in total) of the 2D structure would be sufficient. However, 6 vibration modes were obtained for each model.

5.1.1 Clamped Model Vibration Modes

Mode	**Period (sec)**	**Frequency (Hz)**
1	0.205156	4.874342
2	0.063393	15.774590
3	0.038397	26.044006
4	0.014639	68.311942
5	0.005226	191.341530
6	0.003613	276.800819

Table 3: Vibration Modes, Clamped Model

The structure vibration frequency which is closer to that of the wind loads, is the one obtained for the first vibration mode (4.87 Hz). Since the ratio between the two frequencies is not harmonic, the wind loads should cause disruptive interference in the structure's vibration, instead of amplifying it.

5.1.2 Hinged Model Vibration Modes

Mode	**Period (sec)**	**Frequency (Hz)**
1	0.326704	3.060878
2	0.077253	12.944563
3	0.038938	25.682093
4	0.014639	68.311942
5	0.005226	191.341530
6	0.003613	276.800819

Table 4: Vibration Modes, Hinged Model

Since the frequency of the fundamental vibration mode decreased to 3 Hz, getting much closer to the frequency of the wind, the application of the dynamic wind load should have a bigger impact on the hinged model than on the clamped model. However, a dynamic analysis of both models was performed in order to test this hypothesis.

5.2 Dynamic Load

For the creation of the dynamic wind load, a time history of triangular pulses with a frequency of 2 Hz taking place in a time interval of 10 seconds. The horizontal wind loading was applied to the structure following this pattern, while the vertical loads were simultaneously applied statically.

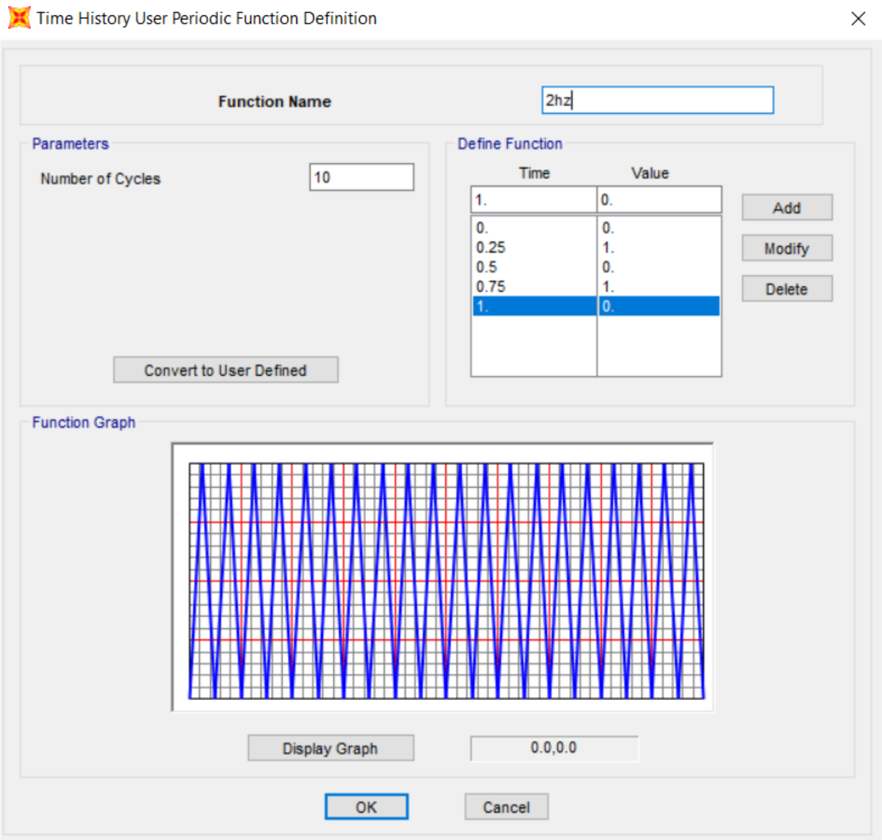


Figure 30: Dynamic Wind Load Time History

5.3 Results and Discussion

- Clamped Model

Load Case	X Displacements	Z Displacements	Axial Stresses	Bending Moments
1	0.022508	-0.000902	182021.61	-400.9345
2	0.02247	-0.001309	175954.12	-391.2508

Table 5: Dynamic Analysis Results for Clamped Model

In order to evaluate the pertinence of performing a dynamic analysis, the difference in the results of the static and dynamic analysis is illustrated in the following table.

Load Case	**X Disp. Increment (%)**	**Z Disp. Increment (%)**	**Axial Stress Increment (%)**	**Bending Moment Increment (%)**
1	3.84	0.0	5.74	0.54
2	3.84	0.0	3.64	0.56

Table 6: Dynamic vs. Static Analysis Comparison, Clamped Model

In this case, the change in the displacements between the static and dynamic analysis is not very large, which is an indicator that modeling a wind load with a frequency of under 2 Hz as a static load for this particular structure is a responsible simplification which will not affect the results in a significant way.

- Hinged Model

Load Case	**X Displacements**	**Z Displacements**	**Axial Stresses**	**Bending Moments**
1	0.066357	-0.000902	228332.99	-531.0997
2	0.066301	-0.001309	-233284.58	-521.4151

Table 7: Dynamic Analysis Results for Hinged Model

Load Case	**X Disp. Increment (%)**	**Z Disp. Increment (%)**	**Axial Stress Increment (%)**	**Bending Moment Increment (%)**
1	21.88	0.0	8.83	10.0
2	21.91	0.0	13.24	9.27

Table 8: Dynamic vs. Static Analysis Comparison, Hinged Model

The increment in horizontal displacements between the static and dynamic analysis is very significant in the hinged model. Modeling wind load as a static load considerably reduces its effects on the structure and, as a consequence, it affects how well adjusted the model is to the behavior this particular structure would have under this particular dynamic loading configuration.

5.4 Demand/Capacity Ratio

The demand on the structure has clearly increased since there are now two elements working at a range between 70% and 90% of their capacity. However, no structural element has a D/C ratio that exceeds 0.9 and therefore, the structure capacity is still sufficient for the applied loads.

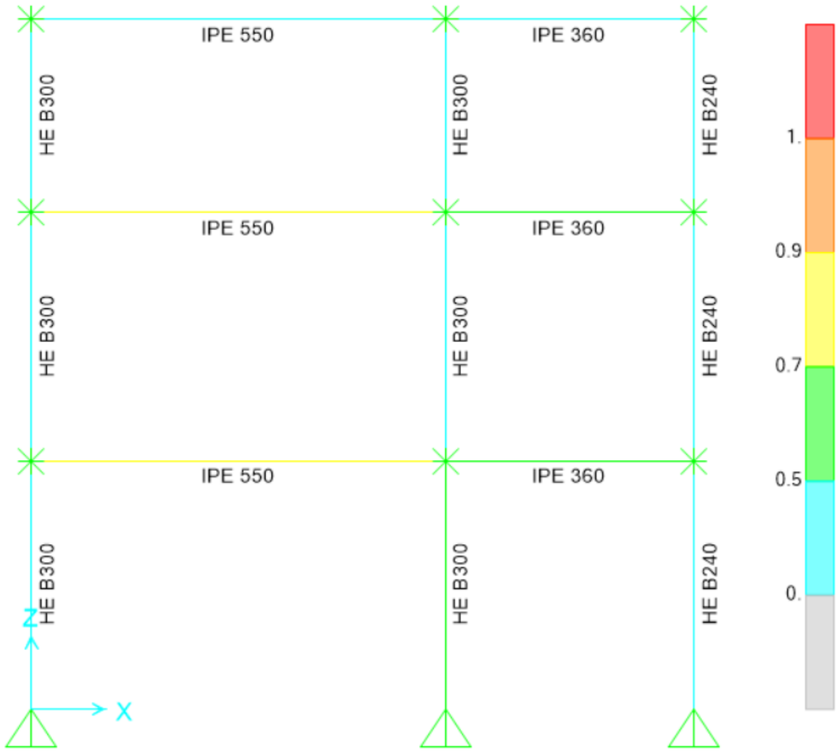


Figure 31: Demand/Capacity Ratio, Dynamic

6 Conclusions

- From the static analysis it can be noted that the rigid diaphragm hypothesis is valid, since the variation in the demand for displacements, stresses and bending moments are small between the models with rigid diaphragms and the ones without it.
- The difference between the demand obtained from cases 1 and 2 is not large, because the vertical point forces have a similar behavior to the uniformly distributed ones since the former could be considered as resulting forces from the latter.
- As a consequence of restricting rotations at nodes with $y = 0$ in the clamped model, the first vibration mode of the structure has a higher frequency than it does in the hinged model and therefore, in this case, the static analysis of the building would have been sufficient since the impact of the given dynamic wind loads was negligible.
- The hinged structure clearly has a lower and closer frequency to that of the wind, and as a result, the dynamic analysis was of great importance since there was a significant increase in the horizontal displacements of the structure when the wind loads were applied dynamically. Although this does not represent a great difference in the existing stresses and moments of the structure, the displacements might be too large to meet structural design safety standards.
- After analysing both structures under static and dynamic loads, it can be said that the proposed sections, geometry and material provide a structural configuration which has a satisfactory behavior under the applied loads and restraint conditions.

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