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Engineering in Three Dimensions: Differences in Structural Behavior between Plane and Space Frames in Terms of Bending Moments

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Abstract. With the continuous advancement of computational tools applied to structural engineering, it has become possible to represent structural behavior with greater accuracy, significantly contributing to the safety and the alignment of with real world conditions of building design. In this context, this study aimed to compare the structural behavior of planar (2D) and spatial (3D) frames through models developed using the Direct Stiffness Method. The first part of the study focused on the comparison of internal forces resulting from the application of vertical loads—representing self-weight and live loads—and horizontal loads due to wind action. This stage also included an evaluation of structural behavior under pinned connections using the DysTrucS software, for its efficiency in automatically generating load envelopes. In the second phase, a multi-story building was modeled under simultaneous vertical and horizontal loading conditions, with an emphasis on analyzing internal forces in specific structural elements. The results indicated significant discrepancies between 2D and 3D modeling approaches, with differences in bending moments reaching up to 13% in certain beams and reducing to approximately 6% when considering moment envelopes. The literature indicates that three-dimensional modeling provides a more accurate representation of structural behavior, particularly in cases involving geometric asymmetry and significant lateral loads, while planar frames remain suitable for regular structures primarily subjected to vertical loading. This study highlights the importance of careful selection and application of modeling strategies in structural analysis and their practical implications for structural design.

Keywords: Structural Analysis. Plane Frame. Space Frame. Direct Stiffness Method. Computational Modeling.

1 Introduction

One of the main stages in a structural design project is the so-called Structural Analysis, which involves calculating the internal forces and deformations of a structure by considering the effects caused by the actions to which it is subjected. This analysis provides the internal forces and deformations of each of the structure's components. To perform this analysis, computationally implemented structural models are used, which vary in complexity depending on the required level of accuracy. Among the most used models are planar frames, which represent structural elements in a single plane, and spatial frames, which allow for a more comprehensive three-dimensional representation.

When it comes to multi-story buildings, the analysis of their structural behavior has been the subject of numerous contributions in technical literature. As early as 1864, for instance, James C. Maxwell introduced a consistent matrix method for structural analysis ([1] apud [2]), and in 1915, [3] made significant contributions to the foundation of this method. It is worth noting that this was the pre-computer era, during which formulations were developed, but their application to large-scale problems was limited due to the vast amount of data involved. In that period, [4] also made significant contributions by highlighting the importance of considering the dimensions of joints in framed structures.

In Brazil, the doctoral dissertation by [5] is a particularly consistent and relevant work. The numerical analyses presented in that study were conducted using computational codes based on the Finite Element Method. More recent works, such as [6], [7], and [8], focused on comparing three-dimensional and two-dimensional frame models applied to steel and reinforced concrete structures. Along the same lines, CTEC/UFAL has produced relevant research, both in master's theses and undergraduate final projects. Noteworthy among these are the studies by [9], [10], and [11], which investigated the behavior of multi-story buildings by evaluating parameters of global stability, rigid cores, the influence of flexural-torsional effects, and the impact of rigid and semi-rigid connections in beams and columns, among other aspects.

More recently, [12] presented studies on the behavior of tall reinforced concrete buildings, examining the presence of rigid cores in various positions and evaluating global stability through the parameters defined in NBR-6118, with model implementations processed using TQS software. Additionally, [13] explored the optimization of rigid core positioning in tall buildings using a genetic algorithm.

This study compares the structural behavior of these two models—2D and 3D frames—based on the Direct Stiffness Method, aiming to assess their differences in terms of internal forces, particularly bending moments, under different loading conditions. The analysis is divided into two approaches: the first aims to analyze the behavior of the proposed structures using a three-dimensional model—a spatial frame—while the second performs the analysis using a two-dimensional structural representation—a planar frame—extracted from an originally three-dimensional structure.

Furthermore, typical loading assumptions were considered, including permanent, variable, and accidental loads represented by the self-weight of the structure, wind effects, and live load, respectively, to assess the behavior of the structures under different conditions. Additionally, the software DysTrucS [12], developed at UFAL, was used to automate the process of obtaining internal forces and deformations for the frame models under various load combinations, enabling the generation of force envelopes.

2 Theoretical Background

2.1 Structural Modeling

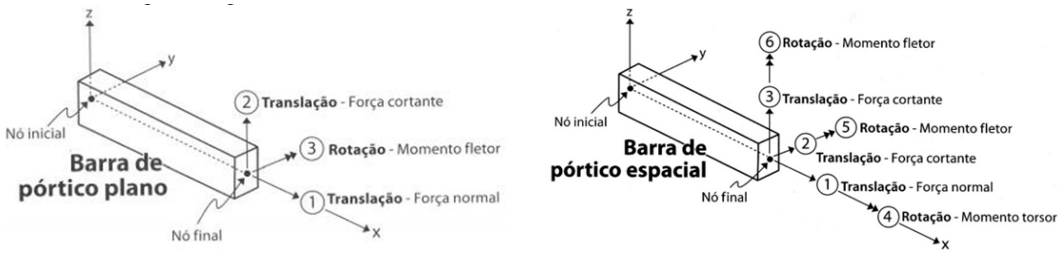
Structural engineering involves the planning, design, and construction of safe and economical structures [2]. To fully understand structural analysis—the focus of this study—it is essential to grasp the stages that precede it. The process begins in the planning phase, during which functional requirements, the structural arrangement, and materials to be used are defined, along with considerations such as aesthetics and environmental impact. Next, the preliminary structural design estimates the dimensions of elements based on standards and past experiences. The load estimation phase determines the expected actions (permanent, variable, and accidental), which are then used in the structural analysis. This latter phase predicts the structure's behavior under applied actions, verifying stress, moments, forces, and displacements, ensuring compliance with code requirements before construction begins.

The spatial frame—or three-dimensional frame—is a model capable of representing all the columns and beams in a building through bars connected at nodes. It allows the simultaneous application of vertical and horizontal loads, making it possible to analyze the building's behavior in all directions and orientations [14]. This model consists of bar elements with six degrees of freedom (DOF) at each node—three translational and three rotational—enabling the determination of bending and torsional moments, as well as shear and axial forces. As such, spatial frames require fewer corrections when compared to other models, since their elements closely represent the actual structure, making them the most complete and increasingly preferred models for structural analysis in design offices.

A planar frame, also referred to as a two-dimensional frame, is a simplified structural representation of a structure that is originally three-dimensional [15]. In other words, this model can be understood as a portion of the full structure, serving as a simplification that allows the study of the three-dimensional structure's behavior within a specific plane. Planar frames are also composed of bars—vertical ones simulating columns and horizontal ones simulating beams—connected by nodes, each with three degrees of freedom that allow for the analysis of shear forces, axial forces, and bending moments.

2.2 Direct Stiffness Method (DSM) and Load Assumptions

The use of computer programs in structural analysis has become a routine activity during the design phase, enabling the adoption of increasingly sophisticated methods [15]. In this context, the Displacement Method is particularly well-suited for computational implementation. Its matrix formulation—aimed at adapting its structure to the mathematical procedures commonly used in software—is known as the Direct Stiffness Method (DSM).



(a) (b)

Figure 1. Bar element highlighting degrees of freedom (relative to local coordinates): (a) node of a planar frame; (b) node of a spatial frame

Source: [14]

The method is associated with the definition of the stiffness matrix, which, for a given element, has a local coordinate system related to its local forces (**f'**), nodal displacements (**d'**)—as illustrated in Figure 1—and its stiffness matrix (**k'**) defined with respect to the local coordinates (x, y, z), as expressed in Equation 1:

$$\mathbf{f' = k'd'}. \tag{1}$$

However, when represented as in Equation 2, it refers to a global coordinate system (X, Y, Z), where the global stiffness matrix of the structure is denoted by **K**, the global nodal displacements by **d**, and the global forces by **F**, as follows:

$$\mathbf{F = Kd}. \tag{2}$$

Thus, the unknown displacements are obtained by solving the system of equations described in Equation 2. Once these displacements are known, the internal forces acting on the elements can be determined.

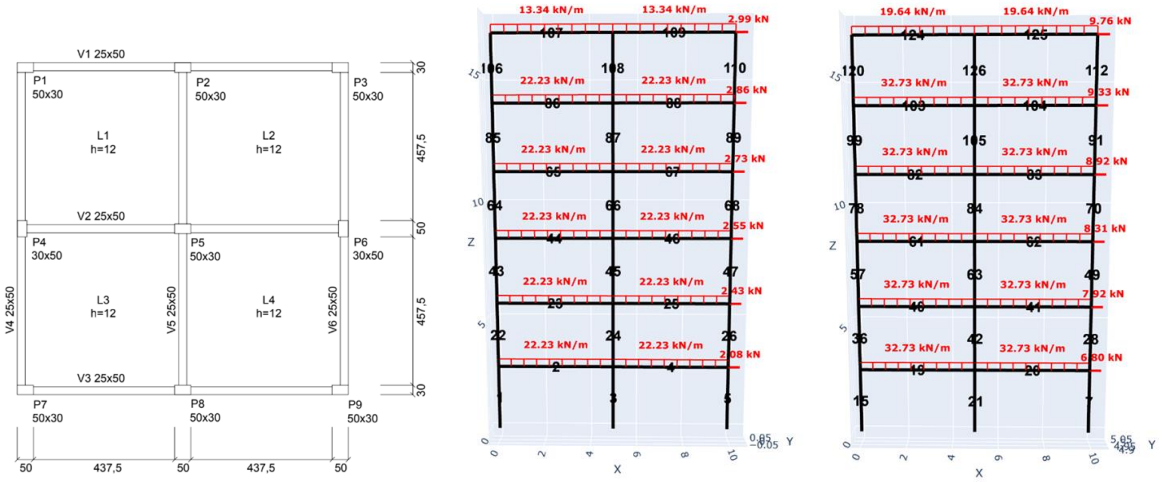
Regarding the load assumptions and the definition of **F** values, the Brazilian standard ABNT NBR 8681:2003 was adopted. It considers vertical loads corresponding to self-weight and live loads, as well as wind forces acting on the building façades. To ensure structural safety, the code requires the evaluation of ultimate limit states (ULS) and serviceability limit states (SLS) through load combinations that represent the most unfavorable conditions. This allows for the verification of stability and optimization of the structure's resources.

3 Applications and Results

The application consisted of the structural modeling of a multi-story building with the objective of analyzing the internal forces and the distribution of vertical and horizontal loads throughout the structure. The building in question included a ground floor, four typical floors, and a roof level. This configuration was chosen to represent a common building type found in urban environments, allowing for an analysis consistent with the practical reality of structural design projects.

The form plan was used, as shown in Figure 2(a). Additionally, Beams 2 and 3 were analyzed; in the three-dimensional modeling, they correspond to elements 103 and 104, and 86 and 88, respectively. These elements are located on the fourth typical floor of the central frame and the front façade. The planar frames derived from these beams are referred to as the Central Frame and the Façade Frame, as shown in Figures 2(b) and 2(c), which already include vertical and horizontal loads.

Two load scenarios were analyzed: one with only vertical loads, and another with both vertical and horizontal loads combined. Table 1 presents the results for the second scenario. Based on the results from both cases, the force envelope for the two beams was developed, as shown in Table 2.



(a) (b) (c)

Figure 2. (a) Form plan; (b) Two-dimensional modeling of the Front Façade frame with vertical and horizontal loads – Beam 3; and (c) Modeling of the Central Façade frame – Beam 2

Table 1. Bending moments (kN·m) in Beams 2 and 3 obtained from 2D and 3D analyses under vertical and horizontal loading

	2D Modeling				3D Modeling	
	BEAM 2	BEAM 3	Difference 2D vs 3D Beam 2	Difference 2D vs 3D Beam 3	BEAM 2	BEAM 3
Upper Left Vertical.	56.84	42.82	7.5%	-5.0%	52.89	45.08
Left Mid-Span	39.24	24.28	0.5%	0.2%	39.06	24.22
Upper Mid Left	67.55	45.92	-6.1%	5.1%	71.92	43.69
Upper Mid Right	88.37	52.04	6.5%	-4.7%	82.96	54.59
Right Mid-Span	40.30	24.82	2.3%	-1.0%	39.40	25.08
Upper Right Vertical	36.64	36.29	-13.4%	8.1%	42.31	33.58

Table 2**.** Bending moment envelope (kN·m) obtained from 2D and 3D analyses under vertical and horizontal loading

	2D Modeling				3D Modeling	
	BEAM 2	BEAM 3	Difference 2D vs 3D Beam 2	Difference 2D vs 3D Beam 3	BEAM 2	VIGA 3
Upper Left Vertical.	56.48	42.82	6.8%	-5.0%	52.90	45.08
Left Mid-Span	39.53	24.55	0.8%	-0.2%	39.23	24.61
Upper Mid Left	77.96	48.98	0.7%	-0.2%	77.44	49.09
Upper Mid Right	88.37	52.04	6.5%	-4.5%	82.97	54.49
Right Mid-Span	40.30	24.82	2.3%	-1.0%	39.40	25.08
Upper Right Vertical	46.56	39.56	-2.2%	0.6%	47.61	39.34

4 Final Considerations

In the present study, the structural behavior of a multi-story building was examined under the application of vertical loads and combined vertical and horizontal loads. The analysis focused on Beams 2 and 3, represented by elements 103 and 104, and 86 and 88, respectively, in the three-dimensional model, allowing a direct comparison between the internal forces obtained from the spatial model and its corresponding planar frames. It was observed that, even in more complex structures, the three-dimensional modeling presents significant differences in internal forces compared to planar frames, especially when horizontal actions such as wind are considered. Regarding the variation of bending moments in both 3D and 2D models, differences of up to approximately 13% were found. However, it was also noted that when analyzing the bending moment envelopes, these differences tended to become more uniform, decreasing to around 6%.

Overall, the results demonstrated that three-dimensional modeling provides a more accurate representation of structural behavior, particularly in structures subjected to significant horizontal loads or more complex geometric configurations. On the other hand, planar frames remain appropriate in situations dominated by vertical loads where the structure exhibits regularity and symmetry.

As suggestions for future work, it is proposed to extend the comparisons to shear forces as well as other internal forces. Additionally, the analysis of displacements should be included. Conducting studies involving different structural systems, such as spatial truss structures or buildings irregular in plan and elevation, could further highlight the differences between planar and spatial modeling. Furthermore, incorporating dynamic analysis considering seismic actions or the effects of wind-induced vibrations could broaden the scope of the results and enrich the conclusions about structural behavior.

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