A Numerical Investigation of the P-Delta Effect on Steel Frames with Semi-rigid Connections and Soft Stories

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Received: 15 February 2025 | Revised: 24 April 2025 | Accepted: 27 April 2025

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ABSTRACT

The physical and mechanical properties of a structure after a large displacement are significantly different from those of its initial state without deformation. The P-Delta analysis is particularly important for multi-story structures subjected to lateral loads. This study focuses on the numerical analysis of a steel frame using the finite element method. The proposed frame structures have been modeled in SAP2000 to evaluate the internal forces and lateral displacement of steel frames, subjected to concentrated lateral loads at the story levels. The P-Delta effects were evaluated and compared employing linear static analysis of a steel frame with and without soft story and semi-rigid connections. The results of the numerical method were compared with those reported in the literature. The novelty of the present study lies in the combination of semi-rigid connections, soft story, and P-Delta effect. This combination has a significant impact on the behavior of steel frames, especially on inter-story drifts.

Keywords-P-Delta effects; steel frame; SAP2000; soft story; semi-rigid connections; finite element method

I. INTRODUCTION

Steel structures represent one of the most extensively used structural systems in modern engineering, because of their exceptional load-bearing capacity, efficient manufacturability, and relatively straightforward installation processes. The performance and stability of these structures are profoundly influenced by the nature of the connections between columns and beams, typically categorized as rigid, articulated, or semi-rigid. Among these, semi-rigid connections are particularly noteworthy for their ability to provide controlled rotational flexibility, enabling partial redistribution of internal forces and enhancing the overall adaptability of the structure under varying load conditions. However, this inherent flexibility introduces nonlinear and complex behavioral characteristics, which complicate the design and analytical processes, necessitating advanced methodologies to ensure structural integrity and safety. A critical consideration in the stability analysis of steel structures, especially those incorporating semi-rigid connections, is the P-Delta effect, a second-order phenomenon arising due to the interaction between axial loads and lateral displacements. This effect becomes increasingly significant in tall or slender structures, where lateral displacements induced by applied loads generate additional moments, thereby amplifying the internal forces and potentially compromising stability. The P-Delta effect is especially noticeable in structures with soft stories, where diminished lateral stiffness leads to excessive deformations and heightened internal stresses; this problem has been studied by authors in [1, 2]. Consequently, understanding and accounting for this phenomenon is essential for the accurate assessment and design of steel structures, especially in scenarios where semi-rigid connections are utilized.

Since the 1990s, significant research has focused on semi-rigid connections and P-Delta effects. Authors in [3] initiated this field by proposing a unified method for analyzing 3D structures with semi-rigid joints. Authors in [4] introduced practical techniques for integrating semi-rigid connections and second-order effects in frame analysis. Further advancements were made by authors in [5], who assessed reliability, authors in [6], who developed simplified analysis methods, and authors in [7], who designed high-rise buildings with semi-rigid connections. Authors in [8] developed software for analyzing semi-rigid connections, while authors in [9] applied advanced algorithms for space frame optimization. More recently, authors in [10] refined reliability models and authors in [11] examined fire-exposed structures. Parallel advancements in P-Delta research have also shaped the field. Early contributions, such as those in [12], where the iterative analysis method was deployed for lightweight structures and in [13], where second-order frame analysis, laid the groundwork. Authors in [14] compared amplification factors for seismic design, and authors in [15] refined moment amplification methods. The 2010s highlighted the application of P-Delta analysis in software tools. Authors in [16] explored X-bracing systems, authors in [17] analyzed seismic responses in RC buildings, and authors in [18] emphasized the role of geometric nonlinearity. Authors in [19, 20] examined P-Delta effects in taller structures, while Authors in [21] integrated inelastic deformation considerations into practical design methods.

Recent studies have further emphasized the importance of considering the P-Delta effect when analyzing semi-rigid frame structures. Authors in [22] demonstrated that an approximate elastic-plastic method effectively predicts the load capacity of steel sway frames with semi-rigid connections, providing an accurate, yet simple alternative to complex analysis methods. Author in [4] proposed a practical method for analyzing plane steel frames with semi-rigid connections, incorporating second-order effects, as detailed by recent European and American codes. Authors in [23] introduced an analysis method for semi-rigid steel frames that accounts for non-linear connection behavior and P-delta effects, offering more economical and practical solutions compared to rigid connection models. Authors in [24] developed a simplified second-order analysis for semi-rigid steel frames, using rotation springs to model beam-column connection flexibility while considering P-delta effects. Authors in [25] explored the impact of semi-rigid connections on steel frames using finite element analysis, revealing that connection flexibility significantly influences moments and displacements. Authors in [26] evaluated the seismic performance of prefabricated reinforced concrete structures with partially fixed connections, highlighting the advantages of semi-rigid assumptions for more realistic assessments. Authors in [27] assessed the reliability of the buckling strength of steel structures with semi-rigid connections using Monte Carlo simulations. Authors in [28, 29] investigated the problem of seismic collapse capacity of the adjacent pounding structures with and without taking into account the P-delta effect.

This study focuses on analyzing the behavior of a steel frame with semi-rigid connections under the P-Delta effect, particularly in the presence of soft stories. It aims to explore the relationship between connection flexibility and the lateral stiffness of soft stories while assessing how lateral loads intensify structural damage. Advanced analytical modeling is employed to account for the nonlinear interactions of lateral loads. By addressing these challenges, the research emphasizes the importance of incorporating the P-Delta effect and soft story conditions in early design stages to enhance the safety, stability, and efficiency of steel structures under complex lateral loads.

II. NUMERICAL METHODS VALIDATION

A. *Steel Frames with Semi-Rigid Connections*

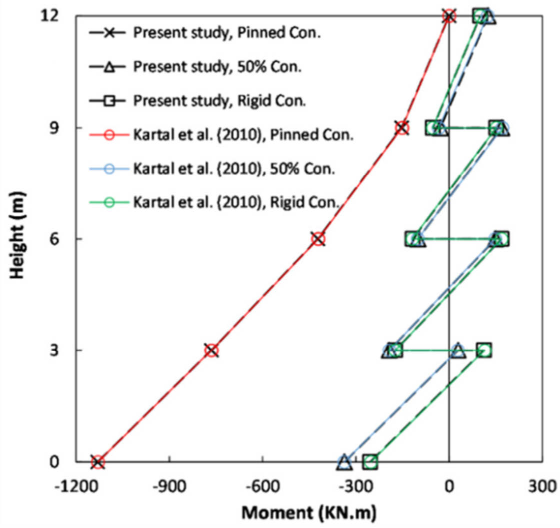
In order to validate the numerical process using SAP2000 software, the results of the current study are compared to those obtained in [8], where the influence of semi-rigid connections on the structural behavior of prefabricated systems composed of four stories with one span (Case 3.3) was investigated. This scenario examines the structural response of a prefabricated system featuring semi-rigid beam-to-column connections subjected to equivalent lateral loads. Authors in [8] employed a custom-developed finite element program, SEMIFEM, written in FORTRAN, to simulate the semi-rigid connections. These connections were modeled using connection ratios to account for the partial rigidity of the joints. In this validation, only three degrees of connection are taken into account: pinned, 50%, and rigid. The analysis was supported by a series of diagrams illustrating key structural parameters, including the moment, shear force, axial force, and horizontal displacement diagrams along the I–I axis. The current numerical results demonstrate strong agreement with those previously reported in [8], as shown in Figure 1 (a-d). Consequently, SAP2000 can provide reliable results for analyzing the effect of connection types between beams and columns for steel structures.

B. *P-Delta Analysis*

SAP2000 uses an iterative incremental method to calculate the P-Delta effects. The numerical process starts with the input of steel frame properties and both the applied vertical and horizontal loads taking into account geometric nonlinearity. The analysis process is divided into two phases. In the first phase, the results of the linear static analysis are determined, including first-order displacements and internal forces.

In the second stage, the additional moments (MP-Delta), due to the effect of vertical loads acting on the laterally displaced steel frame, are calculated for each element. To perform an iterative nonlinear analysis, SAP2000 updates the stiffness matrix of the structural steel model to introduce the value of moments (MP-Delta). This update of the system equations produces new values for displacements and internal forces, and the process continues to repeat until the solution converges.

(a)



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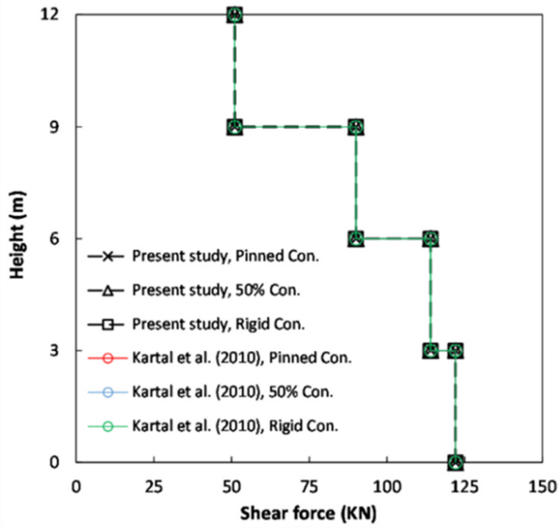

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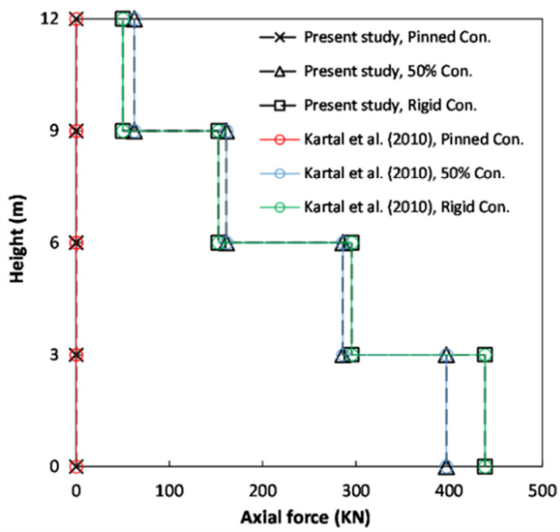

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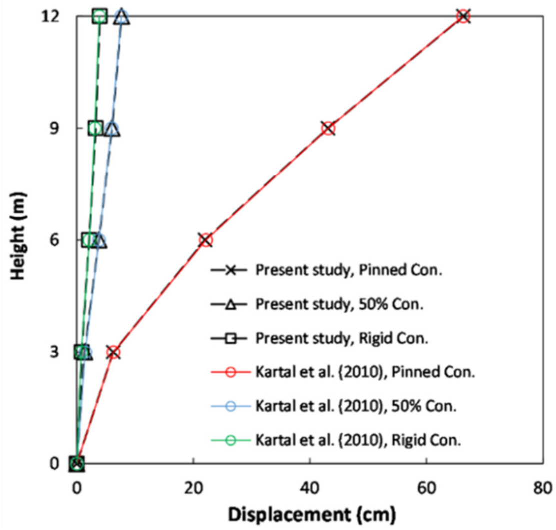

Fig. 1. Comparison of the results determined from the present study and [8] for different connection values: (a) moment, (b) shear force, (c) axial force, and (d) displacement.

The second order P-Delta effects are evaluated for the ten-story steel frame structure, as portrayed in Figure 2. The steel frame adopted in [30] is used to show the effectiveness of P-Delta results obtained by SAP2000 software. Authors in [30] used two methods for approximate P-Delta analysis: the direct P-Delta method and the iterative P-Delta method, demonstrating that both of them can accurately estimate the P-Delta effect. The estimated first and second order lateral displacements are presented in Figure 2. The numerical predictions obtained using SAP2000, are in excellent agreement with those in [30]. Therefore, it can be concluded that SAP2000 can provide exact P-Delta analysis results for steel frames.

III. GEOMETRY AND PROPERTIES OF THE STUDIED STEEL FRAME

The structural analysis in this study is based on a steel frame designed with precise specifications, as illustrated in Figure 3, including the properties of beams and columns and their vertical and horizontal loads, as summarized in Tables I and II. This description aims to present a model that simulates the structural behavior of multi-story buildings without semi-rigid connection (reference frame), with P-Delta effect, and with a soft story (i.e., second story level). The beams are distributed across multiple levels, based on their type and capacity to withstand vertical loads. The columns are designed to account for the distribution of both vertical and horizontal forces. In the case of the steel frame with a soft story, the height of the first and second story levels is defined at 4.5 m, as shown in Figure 3. However, in the case of the steel frame without a soft story, all the story levels have an identical height of 3.5 m.

Authors in [31, 32] mentioned that the soft story can be defined by its lateral stiffness, which must be less than or equal to 70% of that of the upper story, or less than 80% of the average stiffness of the three upper stories. The design varies between edge columns and internal columns, with sections differing based on the story levels. For example, the edge columns on the first story use the W14×109 section, while internal columns utilize the W14×159 section.

TABLE I. BEAM PROPERTIES AND VERTICAL LOADS USED IN THE MODELING ANALYSIS UTILIZING SAP2000

Floor	Type of beams	E (kN/m^2)	Vertical load (kN/m)
13	W16×40	2.01×108	100
12	W16×40	2.01×108	150
11, 10, and 9	W21×44	2.01×108	150
8, 7, 6, and 5	W21×50	2.01×108	150
4, 3, 2, and 1	W24×55	2.01×108	150

TABLE II. COLUMN PROPERTIES AND HORIZONTAL LOADS USED IN THE MODELING ANALYSIS USING SAP2000

Story level	Edge columns	Internal columns	E (kN/m^2)	Horizontal load (kN)	Story height (m)
13	W14×48	W14×68	2.01×10^8	243.16	3.5
12	W14×48	W14×68	2.01×10^8	225.24	3.5
11	W14×48	W14×68	2.01×10^8	207.33	3.5
10	W14×48	W14×68	2.01×10^8	189.41	3.5
9	W14×68	W14×90	2.01×10^8	171.49	3.5
8	W14×68	W14×90	2.01×10^8	153.57	3.5
7	W14×68	W14×90	2.01×10^8	135.66	3.5
6	W14×68	W14×90	2.01×10^8	117.74	3.5
5	W14×109	W14×109	2.01×10^8	99.82	3.5
4	W14×90	W14×09	2.01×10^8	81.91	3.5
3	W14×90	W14×109	2.01×10^8	63.99	3.5
2	W14×90	W14×159	2.01×10^8	46.07	4.5
1	W14×109	W14×159	2.01×10^8	23.04	4.5

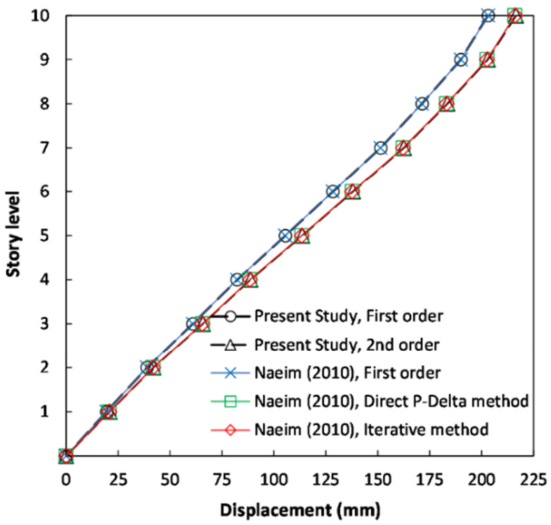

Fig. 2. Comparison of results determined from the present study [30] for different the methods deployed in the analysis of the P-Delta effect.

Horizontal loads increase progressively with the steel frame height, starting at 23.04 kN on the first level and reaching 243.16 kN at level 13, all beams and columns have a Young's modulus of 2.01E8 kN/m^2, reflecting the stiffness of the materials used. It should be noted that all beams for each level are rigid diaphragms, and this work has derived the results of internal forces from axis (2), as demonstrated in Figure 3. The updated framework specifications will be used to conduct a detailed analysis, focusing on the impact of semi-rigid connections under various conditions (P-Delta effect and soft story). The results are expected to provide insights into the structural behavior of the framework, ensuring its safety and performance under design loads.

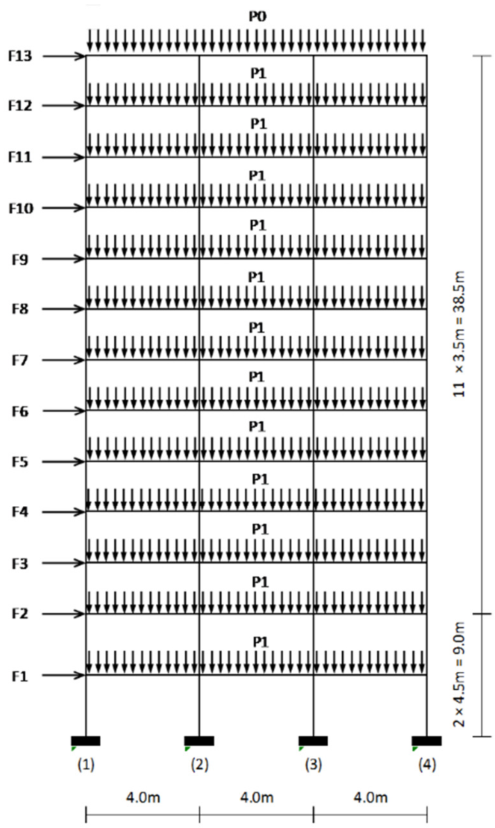

Fig. 3. Elevation of the 13-story steel frame subjected to both horizontal and vertical loads.

IV. RESULTS AND DISCUSSIONS

A. The Combined Effects of the Semi-Rigid Connections and P-Delta

Figure 4 presents the drift ratios, corresponding to the case of a 13-story steel frame, where each floor is characterized by three identical beams with the same span. The height of each story is equal to 3.5 m, giving a total height of 45.5 m. Two parameters are considered in this analysis. The first by/involves creating semi-rigid connections only in beams that provide partial resistance to moments, compared to the initial case of fully rigid connections. The second parameter is taken into account to/entails the analysis of the P-Delta effect on the behavior of the steel frame. Figure 4 indicates that in the case of rigid connections without P-Delta effects (Rigid Con.), the drift distribution along floor levels presents a slight curvature, with the maximum drift ratio being equal to 0.017 at level 6. However, the application of P-Delta effects on the steel frame leads to an increasing drift between floors, with a maximum rate of 18.54% corresponding to level 6, as displayed in the second case (Rigid Con. + P-Delta).

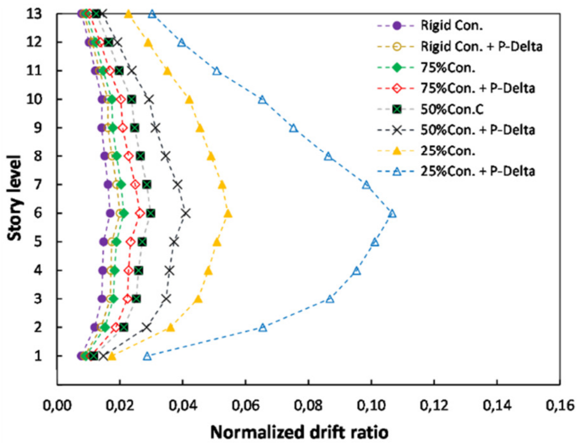

Fig. 4. P-Delta effect on drift ratios of steel frame with semi-rigid connections.

It has been shown that when the semi-rigidity is applied to 75% of rigid connections in beam joints, the drift ratios between floors are approximately equivalent to the second case, exhibiting an increase of 25.7%, which consists of rigid connections in conjunction with the P-Delta effect. It is noteworthy that in the case of 75% Con., the percentage increases more than twice that value when the P-Delta effect is introduced, as shown at level 6 in Figure 4. Figure 4 also demonstrates that by applying the P-Delta effect to the steel frame, the inter-story drift ratios become more significant when the rigid connections drop below 50%. A significant increase in drift ratios is evident at level 6, with percentages of 142% and 530%, respectively, compared to the initial case (Rigid Con.), corresponding to 50% rigid connections and 25% rigid connections with the P-Delta effect. It should be noted that the substantial increase in the inter-story drift ratio at level 6 is probably due to insufficient lateral stiffness at this particular level in comparison to the other floor levels. This case could lead to the implementation of corrective measures, such as the installation of diagonal supports.

Figure 5 illustrates the obtained results of the moments as a function of the height of the steel frame. These results correspond to different degrees of semi-rigidity with 100%, 75%, and 25% of rigid connections, respectively. It is noteworthy that these results are also calculated with the P-Delta effect. Figure 5 shows that the upper and lower moments of each floor level gradually increase from the top of the frame to level 6 in all cases with approximate values, which leads to the observation that there is no significant effect of semi-rigidity or P-Delta, except for the case of 25% Con.+P-Delta. As evidenced in Figure 5, the lower moments of each floor below level 6 are more significant in the case of 25% Con.+P-Delta. However, in the other cases, the values are approximate.

Figure 6 exhibits that the graph character of shear forces is gradual, which indicates that shear forces increase cumulatively until reaching the base of the seventh floor. It is worth noting that the values in all cases are almost equivalent, with the exception of the results corresponding to the case of 25% Con.+P-Delta, which are slightly larger. It is observed that on the fifth floor, large shear forces appear, indicating a possible decrease in stiffness at this specific height. This decrease in stiffness leads to an increase in lateral displacements, thus amplifying the internal forces. Furthermore, it can be seen that the effect of semi-rigidity on shear forces is almost non-existent in comparison to the P-Delta effect, as depicted in Figure 6.

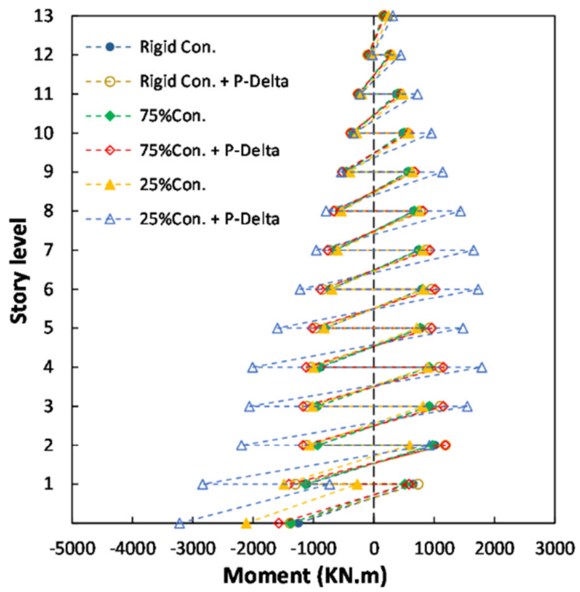

Fig. 5. P-Delta effect on moment diagram of steel frame with semi-rigid connections.

Figure 7 presents the distribution of axial forces in a multi-level frame. The results obtained from this study are calculated under the combined effects of vertical surcharges and horizontal forces as a function of different semi-rigid connections. The results reveal a stepped increase in axial force as the height decreases, reflecting the cumulative effect of vertical loads from upper levels that accumulate at lower levels, as well as the indirect contribution of horizontal forces to axial forces through induced bending moments and interaction with frame geometry. As can be seen in Figure 7, in all instances of semi-rigidity devoid of P-Delta effect, the step width variation of the axial forces assumes greater significance, since the semi-rigidity connections are augmented as the number of the levels decreases. However, the incorporation of the P-Delta effect results in minimum axial force values. This phenomenon can be attributed to the consequence of the lateral displacement of the frame, which engenders supplementary axial loads in vertical members due to bending-induced compression and tension.

B. The Combined Effects of the Soft First Story and the P-Delta

The results obtained from the present study indicate that the study of the P-Delta effect and the soft story is essential to ensure the safety and sustainability of a steel frame. The soft story is less resistant to lateral deformations, which amplifies the P-Delta effect. The additional moments created by this effect further increase the displacement of the soft story. The interaction between the soft story and the P-Delta effect can have significant consequences on the behavior of a steel structure. A thorough analysis of these effects is, therefore, essential to ensure the safety of buildings. The semi-rigid connections and the soft story contribute to an increase in the inter-story drift ratio, as shown in Figure 8. The P-Delta effect then amplifies these relative displacements. The drift ratios are not uniformly distributed over the height of the structure. The drift ratio is found to be higher for small values of semi-rigid connection ratios and on the fifth floor.

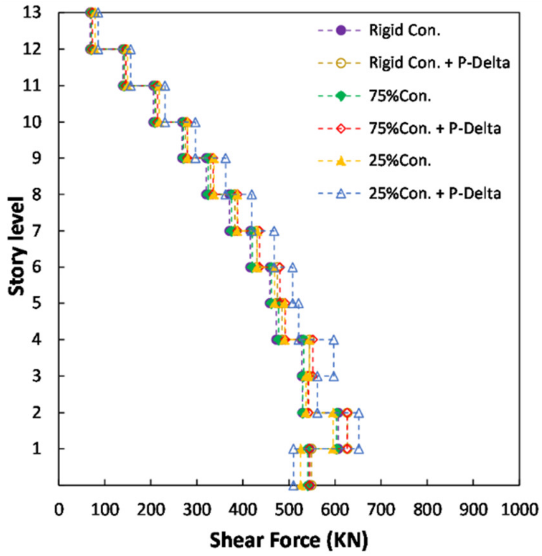

Fig. 6. P-Delta effect on shear force diagram of steel frame with semi-rigid connections.

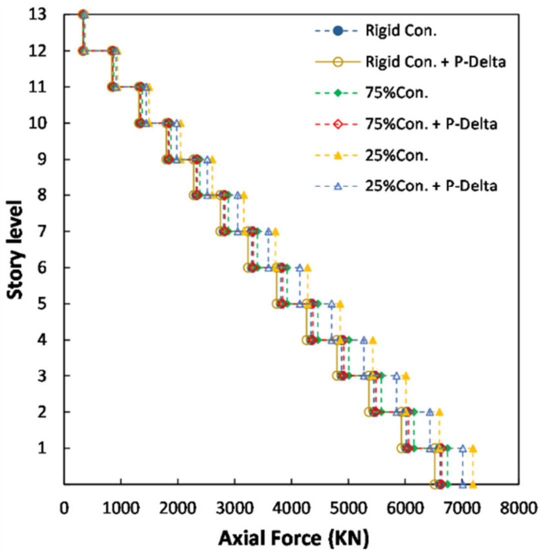

Fig. 7. P-Delta effect on axial forces of steel frame with semi-rigid connections.

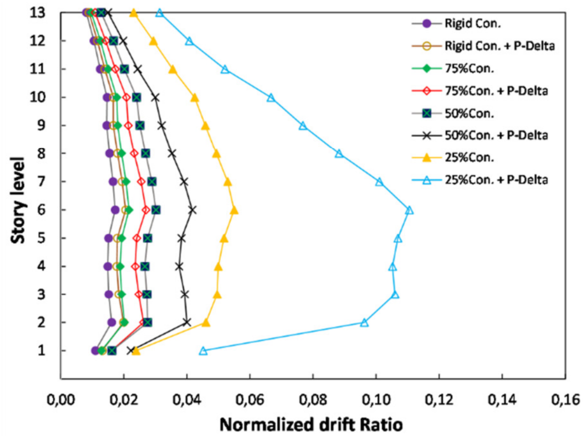

Fig. 8. P-Delta effect on drift ratios of steel frame with soft story and semi-rigid connections.

The effect of semi-rigid connections and soft story on the internal forces of steel structures is estimated, particularly when considering the P-Delta effect. The values for the three internal forces derived from the SAP2000 computation, in case of a soft story and semi-rigid connections are presented in Figures 9 and 10. It is worth mentioning that the semi-rigidity in the joints reduces the capacity of the structure to resist rotations. This means that the rotations at the nodes will be greater than in the case of rigid nodes, which further amplifies the bending moments. The displacements of the structure under lateral loads create additional forces, which increase bending moments in compressed elements. The moment diagram of a steel frame subjected to these effects will generally be larger than that obtained by considering only first-order effects. Furthermore, the flexibility of the story of a steel frame has a significant impact on internal forces, particularly bending moments and shear forces.

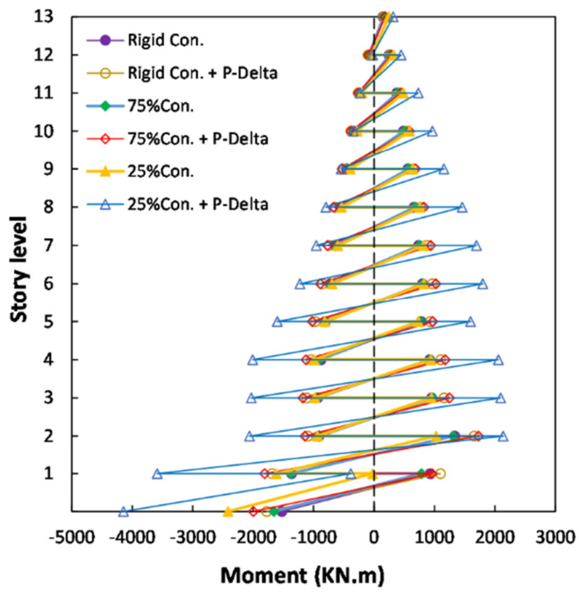

Fig. 9. P-Delta effect on moment diagram of steel frame with soft story and semi-rigid connections.

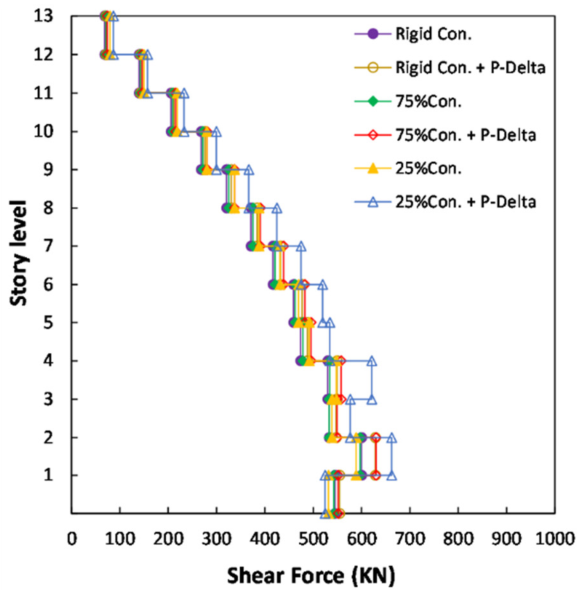

Fig. 10. P-Delta effect on shear force diagram of steel frame with soft story and semi-rigid connections.

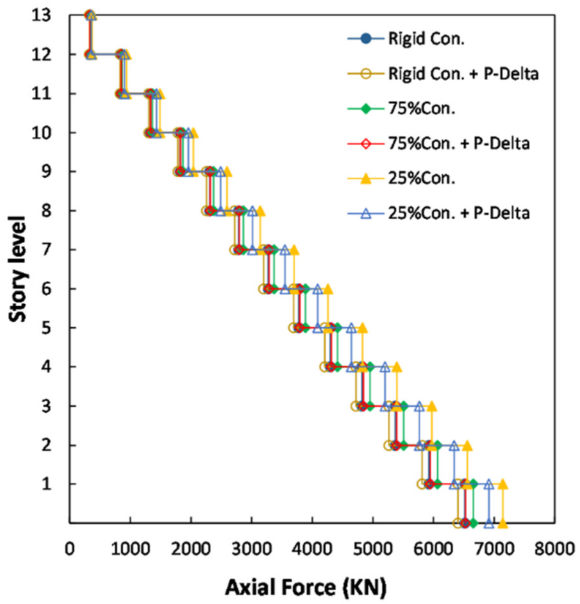

Fig. 11. P-Delta effect on axial forces of steel frame with soft story and semi-rigid connections.

V. CONCLUSION

In order to study the effect of P-Delta on steel structures characterized by semi-rigid connections, a series of numerical calculations were performed using the finite element software SAP2000. Two cases were examined to evaluate the displacements and the internal forces for an elevated steel frame with 13 stories: The first case presented the combined effect of P-Delta and semi-rigid connections without a soft story, and the second case was with a soft story. The values of the moment and shear force proved to be clearly increasing when a rigidity decrease of up to 25% occurred, while they increased more and very clearly in the presence of the P-Delta effect, contrary to the normal forces, where the P-Delta effect presence decreased the value of the normal forces. The drift distribution along all levels presented a slight curvature even in the presence of the P-Delta effect. Conversely, when the rate was below this threshold, the P-Delta effect was found to be significant, particularly in the case with a soft story. The same effect was observed on the internal forces.

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