Seismic Response of High Rise Steel Buildings Including Second-Order Effects

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Abstract:-

The objective of this research was to study the static and dynamic response of high rise steel buildings due to earthquake excitation considering second-order effects. Different analysis procedures were considered for response analysis including linear and nonlinear procedures. The “amplified first-order” analysis was investigated with the “second-order” analysis, which includes geometric nonlinearity and P-Delta effects. Second-order analysis with linear and nonlinear time history analysis including P-Delta effects was accounted for in this study. Different composite steel building models with different heights up to 50 story and different bracing configurations were analyzed. Finite element approach by using ETABS software was used to conduct this study.

The study revealed that the amplified first-order analysis results compare well with second-order analysis without P-Delta effect for buildings up to 30 stories, for taller buildings, generally, the amplified first-order analysis results for building displacements and story drifts were about 20% greater. Nonlinear second-order analysis with P-Delta effect showed that building displacements and story drifts were increased as the number of the building stories increased and that P-Delta effects were obvious and more significant for 20 story buildings or taller. For time-domain seismic analysis, nonlinear time-history analysis with P-Delta effects yield higher values for building lateral displacements and story drifts when compared with linear and nonlinear time-history analysis without P-Delta effect especially for buildings taller than 20 stories. Generally, including P-Delta effects in the nonlinear time-history analysis found to increase maximum building displacements by 10% and 8% as an average values for forty and fifty story buildings, respectively.

Keywords

High rise buildings, P-delta analysis, Finite element method, Seismic analysis, Story drift

Introduction

In recent years, a lot of high rise buildings around the world are constructed using concrete, steel or composite structures. The advantages of multistory buildings that take limit space with human capacity and relay on the function of the building as residential, office or others. The response of high rise buildings to lateral loading largely depends on the characteristics of the loading [8].

Most of engineers design building structures using conventional first order method that do not include lateral sway effect of the building or what is called the “P-Delta” effect. In the seismic design of multi-story structures allowance should be made for “P-Delta” effects [5]. These are the additional overturning moments applied to the structure resulting from the vertical weights “P” supported by the structure, acting through the lateral deflection “Δ“, which directly result from the horizontal seismic inertia forces. They are second order effects which increase the displacements, member forces and alter the dynamic response of the structure. The classical elastic analysis and design methodology may be inadequate if the additional destabilizing moments are not taken into account,

P-Delta effect typically involves large external forces upon relatively small displacements. If deformations become sufficiently large as to break from linear compatibility relationships, then Large-displacement and large-deformation analyses become necessary. The two sources of P-Delta effect are as follows [3]:

- P-effect, or P-”small-delta”, is associated with local deformation relative to the element chord between end nodes. Typically, “P-δ” only becomes significant at unreasonably large displacement values, or in especially slender columns.
- P-delta effect or P-”big-delta” is associated with displacements relative to member ends. Unlike P-δ, this type of P-Δ effect is critical to nonlinear modeling and analysis.

The subject of high rise buildings and P-delta effect was an area of extensive study. Recently, Dubey et al. [6], Rafael [10], Tabassum and Vanakudre [11], and Neeraj et al. [9] amongst others investigated the influence of P-Delta effect on the strength and stability of tall buildings.

In the present study, the dynamic response of high rise steel buildings was investigated for different types of analysis procedures that included first and second order with and without P-Delta and second order with linear and nonlinear time history analysis with and without P-Delta effect. Displacement and drift requirements were investigated for the different structural analysis procedures. The parameters adopted here include the type of the analysis, rise of the building, and bracing configuration.

Finite Element Modeling

i. Building Models

The building models adopted in this study consist of multi-story braced steel frame structure square in plane divided into 10 by 10 bays for each story. Each story height is fixed at four meters and the number of the stories considered is 10, 20, 30, 40, and 50 story. Dead load and live load for residential building is assumed to act on the building structure in addition to lateral forces due to earthquake base excitation. The structure of the buildings composed of steel columns with framing beams and girders. The floor system for the building models is assumed to be composite concrete deck slab of 150mm thick with shear stud connectors to connect the deck slab to the girder flanges and simulate full composite action. Lateral stability for the building frame structure is provided by x-type bracing system.

ii. Finite Element Discretization

The finite element code ETABS is used throughout this study to determine the structural behavior of the modeled steel building prototypes. The finite element model includes the composite deck slab, main girders, steel bracings, secondary beams, and steel columns.

Three-dimensional finite element models are used to discretize the proposed building models. The composite slab is divided into shell elements for each panel, and the framing beams are divided into the same numbers of slab elements in the "xy" plane. Four-node shell elements with six degrees of freedom at each node are used to model the concrete deck slab. Frame elements are used to model the main girders, cross bracings, secondary beams, and steel columns.

Fig. 1 shows typical finite element discretization for the proposed building model. **Fig. 2** shows the bracing system and elevations for the different building models used in the analysis. Building frame element section properties and bracing configurations shown in **Fig. 2** were selected based on comprehensive design process by using ETABS for the different building layouts to satisfy the minimum requirements for strength design limit according to LRFD load combinations [1], [2].

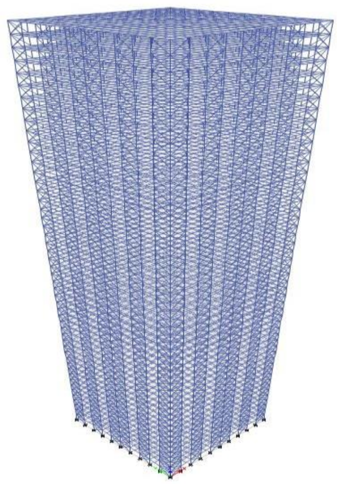

Fig. 1 Three-dimensional FE buildings model.

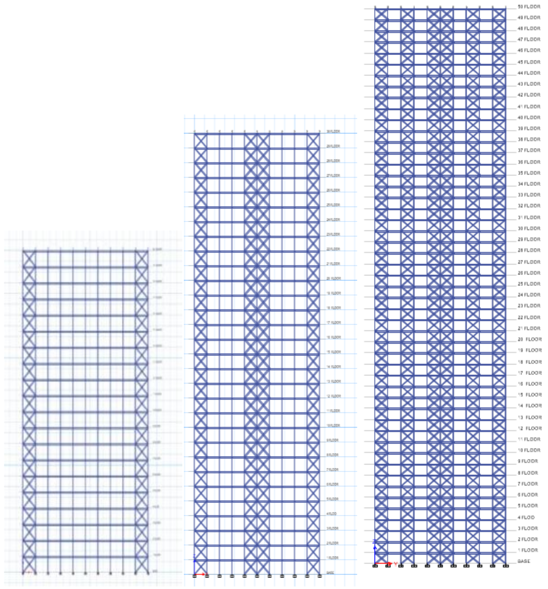

Fig. 2 Elevations and bracing system for the building models.

Story Drift

The design story drift Δ, as required by the ASCE 7-10, is computed according to the difference of the deflections at the centers of the mass at the top and bottom of the story under consideration [2]. The deflection at Level x "δx" used to compute the design story drift, "Δ", should be determined in accordance with the following equation:

$$\delta_x = \frac{C_d \, \delta_{xe}}{I_e} \qquad (1)$$

where

C_d= the deflection amplification factor in Table 12.2-1 of ASCE 7-10 [2],

I_e= the importance factor in accordance with ASCE 7-10 [2],

δ_{xe} = the deflection at the location required determined by the elastic analysis as shown in **Fig. 3**.

The design story drift (Δ), as determined in **Fig. 3**, should not exceed the allowable story drift (Δa) obtained from Table 12.12-1 of the ASCE 7-10 [2] for any story.

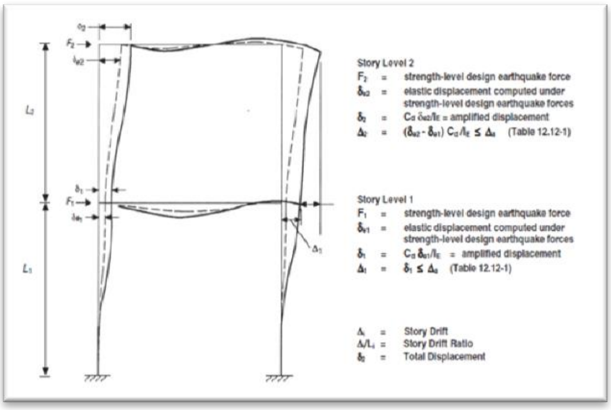

Fig. 3 Story drift determination, ASCE/SEI 7-10 [2].

Methods of Analysis

An analysis approach defines how the loads are to be applied to the structure statically or dynamically and how the structure responds linearly or nonlinearly, and how the analysis is to be performed [7]. In order to fully investigate the response of tall buildings due to seismic excitation different analysis approaches are adopted in this study including amplified first-order analysis, second-order analysis including geometric nonlinearity with and without P-Delta effect, and linear and nonlinear time history analysis.

The simplest procedure in any static or dynamic analysis is the first-order analysis in which the equations of equilibrium are written with respect to the undeformed "original" geometry of the structure. To account for the secondary effects in this analysis, i.e. P-Delta, an amplification for the first-order analysis results is recommended by design specifications. The amplified first-order elastic analysis method, as defined in the AISC 360-05 [1], is an accepted method for the analysis of braced, moment, and combined framing systems was used her. The second-Order analysis proceeds in a step by step incremental manner. The deformed geometry of the structure obtained from a preceding cycle of calculations is used as the basis for formulating the equilibrium and kinematic relationships for the current cycle of calculations. Geometric nonlinearity in the form of both P-Delta effects and large displacement / rotation effects are taken into account by the second-order analysis.

Time-history analysis is a step-by-step analysis of the dynamical response of structure to a specified loading that may vary with time. In order to conduct time history dynamic analysis to simulate seismic base excitation, the building models were analyzed for ground acceleration time history of the 1940 EL Centro California earthquake ground motion [4]. In the process of the numerical integration for the time-history analysis the differential equation of motions are solved step-by-step, starting at zero time, when the displacement and velocity are presumably known. The time duration of earthquake of interest is divided into discrete intervals and analysis progress by successively extrapolating the displacement from one time station to the next [7].

Analysis Results and Discussion

In the following summary for the main outcomes from the analysis results are presented and to highlight the important findings regarding the influence of the P-delta effects on the dynamic response of high rise buildings due to different analysis procedures

i. Static and Dynamic Analysis

Fig. 4 to **Fig. 7** presented maximum displacements and drift ratios for the top story in the different building models for the three types of analysis methods; amplified first-order analysis and the geometric nonlinear second-order analysis with and without P-Delta effect. Comparison shows that amplified first-order analysis and second-order analysis without P-Delta yield almost the same results for the dynamic response for buildings up to 30 story, whereas for taller buildings the amplified first-order analysis yield higher response values due to seismic excitation. On the other hand, results for the second-order analysis for the seismic response including P-Delta effects shown in these figures were higher when compared with the first-order and second-order analysis without P-Delta effects.

Moreover, results of the dynamic response in the x-direction are lesser than the response in the y-direction this is due to structural steel columns orientation. Furthermore, second-order analysis that takes into account the effects of the geometrical nonlinearity and P-Delta explicitly can be considered as more accurate method of analysis in comparison with the amplified first-order analysis that takes into account second order effects implicitly by amplifying the response resulting from elastic first-order analysis by using amplification factors.

Generally, the amplified first-order analysis underestimates the dynamic response when compared with second-order analysis including P-Delta effects, while in close agreement with second-order analysis without P-Delta effects for building up to 30 story height. Moreover, P-Delta effects due to nonlinear second-order analysis become obvious and well evident for buildings higher than 10 stories.

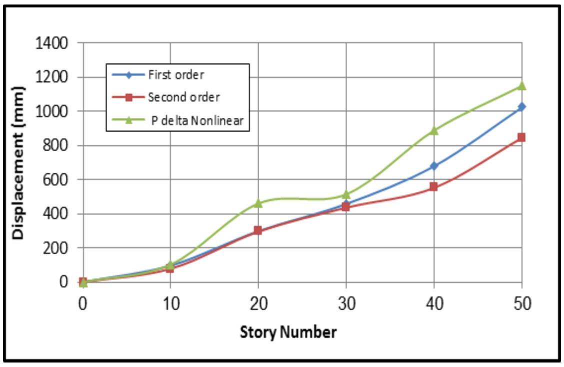

Fig. 4 Top story displacements in the X-direction for the building models.

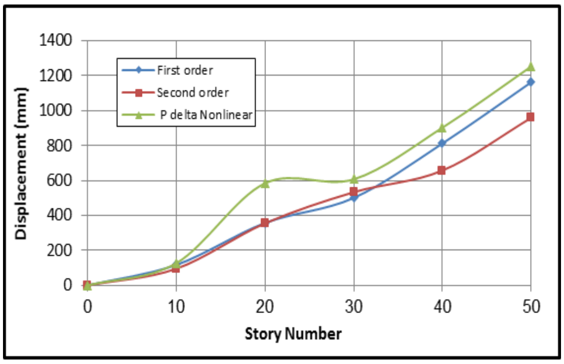

Fig. 5 Top story displacements in the Y-direction for the building models.

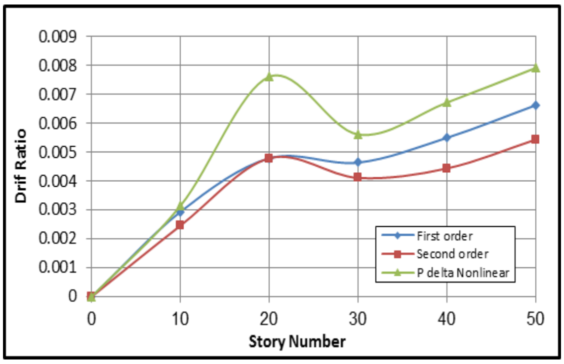

Fig. 6 Top story drift ratios in the X-direction for the building models.

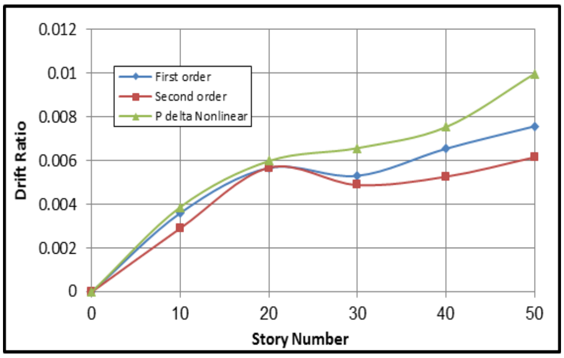

Fig. 7 Top story drift ratios in the Y-direction for the building models.

ii. Time-History Analysis

To discuss the influence of the P-delta effects in the time domain dynamic analysis, results for the linear and nonlinear time-history analysis with and without P-Delta due to 1940 EL Centro California earthquake ground motion are presented in **Table 1.** Seismic response for the linear and nonlinear analysis with P-Delta effect listed in Table 1 are also graphically presented in **Fig. 8** to **Fig. 11**.

Table. 1 Seismic Response for Different Time-History Analysis

Seismic Response	10 story Building			
	Xmax (mm)	*Ymax (mm)*	*Fx (kN)*	*Fy (kN)*
LTH	358.6	451.2	15790	16971
NLTH	362.9	451.2	16088	1706
NLTH +(P-Δ)	392.4	470.88	16284	16784
	20 story Building			
LTH	490.5	500.3	15696	16677
NLTH	490.5	500.3	15990	17069
NLTH +(P-Δ)	462	514.0	14420	15696
	30 story Building			
LTH	470.8	480.6	15764	17030
NLTH	470.8	480.6	15794	17030
NLTH +(P-Δ)	461.0	525.8	12458	15401
	40 story Building			
LTH	461.0	503.2	16775	15401
NLTH	461.0	500.3	16775	15401
NLTH +(P-Δ)	500.3	559.1	15499	13841
	50 story Building			
LTH	569.9	598.4	17108	15892
NLTH	569.9	598.4	17108	158829
NLTH +(P-Δ)	613.1	647.4	15166	13635

Where:
Xmax, Ymax = Top story displacement.
LTH = Second-order linear time history analysis.
NLTH = Second-order nonlinear time history analysis.
NLTH+(P-Δ) = Second-order nonlinear time history analysis + P-Delta effect.
Fx & Fy = Maximum story shear.

Analysis results revealed that nonlinear time-history analysis with P-Delta effects yield higher values for building lateral displacements when compared with linear time-history analysis especially for buildings higher than 30 story. This indicates that the P-Delta effect, which induce additional drift and lateral displacement, becomes more significant for such buildings. Moreover, linear time-history analysis yield close results as for nonlinear time-history analysis without P-Delta. This indicates that P-Delta effects has important impact on steel high rise building dynamic response.

Maximum story shear forces due to nonlinear seismic time-history analysis with P-Delta effect in the X and Y directions have smaller values when compared with linear time-history analysis. This result indicates that linear time history analysis produce higher values for the maximum story shear forces which reveal that linear time history analysis are more conservative for tall building design as compared to nonlinear analysis.

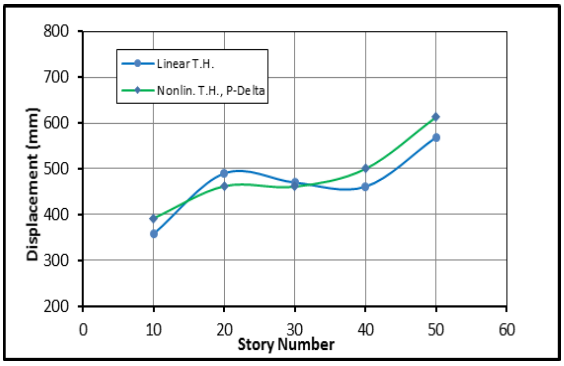

Fig. 8 Top story displacements in the X-direction due to time history analysis

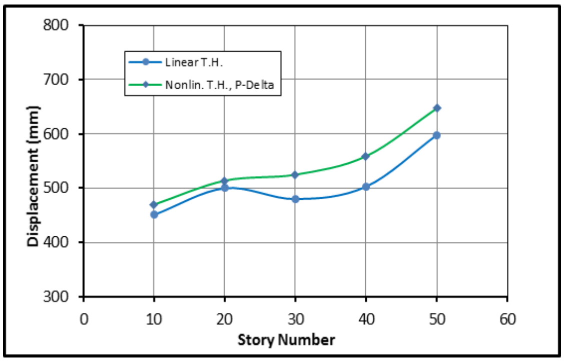

Fig. 9 Top story displacements in the Y-direction due to time history analysis

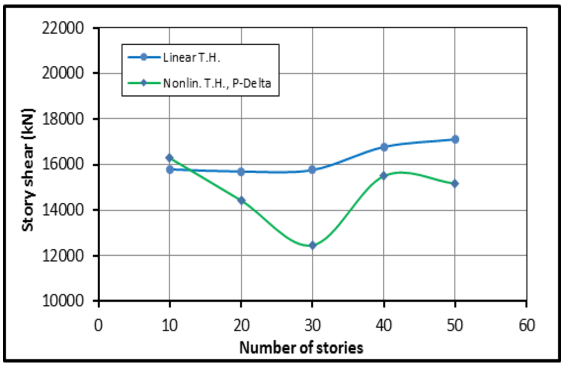

Fig. 10 Maximum story shear in the X-direction due to time history analysis

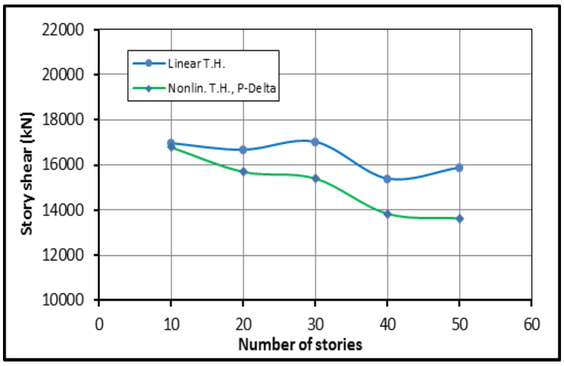

Fig. 11 Maximum story shear in the Y-direction due to time history analysis

Conclusions

In this paper, an attempt was carried out to investigate the effect of P-delta analysis on the seismic static and dynamic response of high rise composite steel buildings. Different building models with different heights were analyzed using different analysis approaches. Results showed that the P-Delta effect has a significant role in tall buildings response when subjected to lateral forces and almost inevitable when any vertically loaded structure undergoes lateral displacements.

Amplified first-order analysis underestimates the dynamic response when compared with second-order analysis including P-Delta effects, while in good agreement with the second-order analysis without P-Delta effects especially for building up to 30 story. Generally, results for the displacement and drift values showed that the effects of the P-Delta increased when the number of the building stories are increased.

Generally, the second order effects found to increase the story displacements and drift values at all levels of the building structure and get higher values than for the static analysis and that P-Delta effects become obvious and well evident for buildings higher than 10 stories.

Nonlinear analysis in the time domain with P-Delta effects yield higher values for building lateral displacements and story drifts due to seismic excitation when compared with linear time-history analysis especially for buildings higher than 30 story. Moreover, linear time history analysis found to be more conservative for tall building design when considering maximum story shear as compared with nonlinear P-Delta analysis.

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الاستجابة الزلزالية للابنية الفولاذية العالية متضمنا تاثيرات تحليل الدرجة-الثانية

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الخلاصة

ان هدف هذه الدراسة هو التحقق من الاستجابة الساكنة والحركية للابنية الفولاذية العالية بسبب الهزات الارضية مع الاخذ بالاعتبار تاثير تحليل الدرجة-الثانية. تم اعتماد عدة طرق للتحليل تتضمن الطرق الخطية والاخطية. تم التحقق من طريقة تحليل "الدرجة-الاولى المضخم" مع طريقة التحليل "الدرجة-الثانية", والتي تتضمن تاثيرات الاخطية الهندسية وتاثير بي-دلتا. تم ايضا في هذه الدراسة الاخذ بالاعتبار التحليل الخطي والاخطي في طريقة للاستجابة-الزمن متضمنا تاثير بي-دلتا. تم تحليل نماذج متنوعة من الابنية الفولاذية المركبة بارتفاعات مختلفة وحتى خمسون طابقا. استخدامت طريقة العناصر المحددة بواسطة برنامج ETABS 2013 لاجراء الدراسة الحالية.
اظهرت الدراسة ان طريقة تحليل الدرجة-الاولى المضخم مقاربة في نتائجها لطريقة تحليل الدرجة-الثانية بدون تاثير بي-دلتا بالنسبة للابنية حتى ارتفاع ثلاثون طابقا, اما بالنسبة للابنية الاكثر ارتفاعا فانه عموما طريقة تحليل الدرجة-الاولى المضخم تعطي نتائج بحدو 20% اكبر بالنسبة للازاحات وانحراف الطوابق. بينت النتائج ان الازاحة الجانبية للابنية وانحراف الطوابق تزداد بطريقة التحليل الاخطي لتاثير بي-دلتا بزيادة عدد الطوابق, وان تاثير البي-دلتا يكون اكثر وضوحا واهمية للابنية التي يبلغ ارتفاعها عشرون طابقا او اكثر.
بالنسبة لتحليل الهزة الارضية في مجال الزمن , ان التحليل الاخطي بواسطة طريقة الاستجابة-الزمن مع تاثير البي-دلتا يعطي نتائج اكبر للازاحات الجانبية للابنية وانحراف الطوابق عند مقارنتها مع التحليل الخطي والاخطي بواسطة طريقة الاستجابة-الزمن بدون تاثير البي-دلتا وخصوصا للابنية التي يزيد ارتفاعها عن عشرون طابقا. عموما, وجدت الدراسة ان تضمين تاثير البي-دلتا في طريقة التحليل الاخطي للاستجابة-الزمن يسبب زيادة في الازاحات القصوى للابنية بمقدار 10% و 8% كمعدل قيم للابنية بارتفاع اربعون وخمسون طابقا, على التوالي.

الكلمات المفتاحية

الابنية العالية, تحليل البي-دلتا, طريقة العناصر المحددة, التحليل الزلزالي, انحراف الطوابق