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SECOND-ORDER INELASTIC ANALYSIS OF STEEL PORTAL FRAME STRUCTURES

LIBRIATI BINTI ZARDASTI

A dissertation submitted in partial fulfillment of the
requirements for the award of the degree of
Master of Engineering (Civil-Structure)

Faculty of Civil Engineering
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MARCH 2011

I declare that this dissertation entitled "*Second-Order Inelastic Analysis of Steel Portal Frame Structures*" is the result of my own research except as cited in the references. The dissertation has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

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"Specially dedicated to my beloved Mak and Ayah,
sisters and brothers, nieces and nephews.
Thank you for your everlasting love and continuous encouragements."

ACKNOWLEDGEMENT

First of all, I am so grateful towards ALLAH the Almighty that bestowed me and giving me the strength and opportunity to finish my meaningful study entitled "Second-Order Inelastic Analysis of Steel Portal Frame Structures".

I would like to express my gratitude to my supervisor, PM Dr. Suhaimi Abu Bakar, who guided me along the process of finishing this study, who always there when I need help and very cooperative and always give satisfactory answers to all my uncertainties. I also indebted to Dr Roslida Abd Samat and all staff of Faculty of Civil Engineering, University Technology of Malaysia for guidance and the facilities provided to me had simplified my work throughout the study period. By upgrading the remaining facilities, I believe that a better study can be produced in the future.

I am very thankful for the prayer and everlasting love from the most important persons in my life, mak and ayah, Mrs. Hajah Nursinah binti Tanggi and Mr. Zardasti bin Dawi. Together with all my eight siblings, brothers in-law, nieces and nephews, for their supports and encouragements that gives me the spirit and energy to always think out of the box and become the best among the rest.

The last but not least, I would like to thank my friends, colleagues, and all who involved directly or indirectly during this study. Only ALLAH can repay all your deeds, kindness and assistance to me. Insha ALLAH. Thank you.

ABSTRACT

P-Delta effects are nonlinear effects that occur in every structure where flexure is introduced into an axially loaded member. Analysis of P-Delta effects can be done by direct and indirect method. The indirect method is simpler but it is still not economical to be implemented, especially on large and complex structures. The second-order elastic analysis is inadequate to produce safe and economical structures. Direct method of first- and second-order, elastic and inelastic analysis was implemented on a 4m wide and 5m height of steel portal frame model by the aid of MathCAD software. The material nonlinearity was included in second-order inelastic analysis and the plastic hinge method was applied. The comparison between interaction equation suggested in ASCE Manual (1971) and BS5950-1 (2000) for plastic hinge method was also discussed. It was found that as the end moments increased, the plastic hinges occur easily. Once the member stiffness decreased, the frame model swayed easier and horizontal displacement increased, simultaneously. The interaction equation depends on the member force and end moment. The maximum percentage of difference between factors of moment over plastic moment, f as suggested in ASCE Manual (1971) and BS5950-1 (2000) is only 14 percent and it was considered as small. As a result, the f value of 1.0, suggested in BS5950-1 (2000) is acceptable, reliable, and suitable to be used in this study. Besides that, direct method can be used to enhance indirect method because it produced lesser cross section capacity, which provides lesser safety factor. It was also found that the horizontal displacement on the frame model was produced without the presence of vertical load due to the P-Delta effect. The columns are easier to sway as the height increases. Shorter column is more stable and it fails at higher vertical load compared to longer column.

ABSTRAK

Kesan-kesan P-Delta adalah kesan tak lelurus yang berlaku pada setiap struktur di mana lenturan berlaku pada anggota menanggung beban paksi. Analisis kesan P-Delta dilakukan menggunakan kaedah langsung dan kaedah tak langsung. Kaedah tak langsung lebih mudah tetapi tidak ekonomik untuk dilaksanakan terutamanya pada struktur yang besar dan rumit. Analisis elastik peringkat kedua sahaja tidak mencukupi untuk menghasilkan struktur yang selamat dan ekonomik. Analisis elastik dan analisis tidak elastik; peringkat pertama dan kedua menggunakan kaedah langsung dilakukan terhadap satu model kerangka portal keluli selebar 4m pada ketinggian 5m berbantukan perisian MathCAD. Ketaklurusan akibat bahan dimasukkan dalam analisis tidak elastik peringkat kedua dan kaedah engsel plastik juga diaplikasikan. Perbandingan antara persamaan interaksi yang dicadangkan dalam Manual ASCE (1971) dan BS5950-1 (2000) untuk kaedah engsel plastik juga dibincangkan. Hasil kajian mendapati, apabila momen hujung meningkat, engsel plastik mudah terbentuk. Model kerangka mudah untuk huyung apabila kekukuhan anggota berkurangan seterusnya meningkatkan anjakan ufuk. Persamaan interaksi bergantung kepada daya anggota dan momen hujung. Peratusan perbezaan tertinggi antara faktor momen terhadap momen plastik, f yang dicadangkan dalam Manual ASCE (1971) dan BS5950-1 (2000) hanya 14 peratus dan ia dianggap kecil. Kesimpulannya, nilai f cadangan BS5950-1 (2000) iaitu 1.0 adalah boleh diterima, dipercayai, dan sesuai untuk digunakan dalam kajian ini. Selain itu, kaedah langsung boleh digunakan bagi meningkatkan kaedah tak langsung kerana ia menghasilkan keupayaan keratan rentas yang rendah dan turut memberikan faktor keselamatan yang rendah. Hasil kajian ini juga mendapati bahawa anjakan ufuk pada model kerangka terhasil tanpa kehadiran beban pugak akibat kesan P-Δ. Tiang lebih mudah untuk huyung jika ketinggiannya bertambah. Tiang pendek lebih stabil dan ia gagal pada nilai beban pugak yang tinggi berbanding tiang langsing.

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LIST OF ABBREVIATIONS

ASCE	-	American Standard Civil Engineering
BS	-	British Standard
CRC	-	Column Research Council
ECCS	-	European Convention for Constructional Steelwork
EID	-	Equivalent Initial Deflection
NIDA	-	Non-linear Integrated Design and Analysis
SCI	-	Steel Construction Institute

LIST OF SYMBOLS

A	-	Area of the element/ member section
A_g	-	Gross area of the member section
$dF1$	-	First load increment
$dF2$	-	Second load increment
dP	-	Incremental nodal point loads and reactions
$d\Delta$	-	Incremental nodal point displacement
E	-	Young's Modulus
$\boldsymbol{f}$	-	Factor of the ratio of the bending moment to the plastic moment
$\mathbf{G}$	-	Gradient matrix
$\mathbf{G_1}$	-	Gradient matrix for the portal frame element with the left end being on the yield surface
$\mathbf{G_2}$	-	Gradient matrix for the portal frame element with the right end being on the yield surface
h_i	-	Height of column
h_r	-	apex above the tops of the column,
H	-	Horizontal load
I_z	-	Second moment of inertia
k_1	-	Stiffness coefficients at the top part of the column
k_2	-	Stiffness coefficients at the bottom part of the column
k_b	-	Stiffness coefficients for beam
k_c	-	Stiffness coefficients for column
$\mathbf{k_e}$	-	Linear elastic stiffness for local coordinates
$\mathbf{k_T}$	-	Stiffness matrix for member
$\mathbf{K}$	-	Global stiffness matrix

$\mathbf{K_e}$	-	Linear elastic stiffness matrix
$\mathbf{K_g}$	-	Geometric stiffness matrix
$\mathbf{K_m}$	-	Plastic reduction matrix
L	-	Member length
L_e	-	Effective length
m	-	Ratio of bending moment to the plastic moment
m_x	-	Equivalent uniform moment factor,
M	-	End moments at joints/ maximum bending moment
M_{cx}	-	Section capacity of the member on major axis
M_{cy}	-	Section capacity of the member on minor axis
M_p	-	Plastic moment
M_x	-	Maximum bending moment in the member on major axis
M_y	-	Maximum bending moment in the member on minor axis
p	-	Ratio of axial force to the squash load
p_c	-	Compressive strength of buckling resistance with member imperfection
p_E	-	Elastic Euler buckling stress
p_y	-	Yield strength of the material
P	-	Nodal force/member force/axial force/vertical load
P_c	-	Member buckling load/actual buckling resistance/compression resistance
P_y	-	Squash load
q_{ij}	-	Unknown degree of freedom, i for member forces of j.
r	-	Radius of gyration
T	-	Transformation matrix
v_1	-	Horizontal displacement
Z	-	Plastic modulus
α	-	Parameter to adjust the amplitude of member imperfection
δ_i	-	Notional horizontal deflections for the relevant load case
δF_i	-	Unbalanced forces at unknown degree of freedom, i
δQ_{ij}	-	Incremental member force at unknown degree of freedom, i for member forces of j
δv_i	-	Incremental displacement at unknown degree of freedom, i

Δ	-	Nodal displacement
η	-	Perry factor
λ	-	Slenderness ratio
λ_{cr}	-	Lowest critical load factor for in-plane frame stability
λ_o	-	Limiting slenderness
λ_r	-	Load factor of frame stability
λ_{sc}	-	Smallest value that considering the result given by every column
φ	-	Angle between global axis and local axis of each member/member imperfection
σ_y	-	Yield strength of material/stress resultant
Φ	-	Convex function of axial force and bending moment on a cross section/interaction equation

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Researchers nowadays are struggling to find the simplest, accurate, yet economical structural analysis and design solution as a contribution in the world of research. As in the traditional method of steel design, as known as indirect method, the stability check of member was done individually. It is a high time consuming and less efficient to large and complex structures. Since the demand of that kind of building significantly increases throughout the years, it is not practical to be implemented. In contrast, in the checking purposes, traditional method is still accountable.

P-Delta effect is a nonlinear effect that occurs in every structure where flexure is introduced into an axially loaded member from the axial force acting through the side way of the frame and curvature of a member (Christopher and Hewitt, 2008). There are two types of second-order effects. They are P-Δ and P-δ effect. P-Δ effect is considered as the overall structure deflection, whereas P-δ is the member deflection. To have a simplified way of steel frame structure analysis and design, second-order effects is usually neglected by ensuring the stiffness and elements of structure are adequate to withstand the applied loading.

1.2 Problem Statements

P-Delta effect is also known as the second-order effect that applied in the analysis procedures of traditional design of steel frame, has taken to analyze every member individually in a structure stated in BS5950-1 (2000). This method is called indirect method of analysis. Each member requires different design parameters, such as load factor (magnification factor) and effective length, to incorporate with P-Δ and P-δ effects on each member, respectively. In addition, the design parameters of different members may be various, which basically depend on the restrained conditions, stiffness of the connected member, combination of loadings along the member, and the geometric of entire framed structure, etc (Iu et al., 2008). It is tremendously higher time consumed for the analysis procedures, especially for complicated and large structures, which behaving elastically and nonlinearly.

In order to have a simplified way of nonlinear analysis procedures, the indirect method of analysis, which commonly used in the design, is not economical if to be implemented on large and complex structures. Thus, direct method of analysis can be the best solution to enhance the indirect method. However, study was done regarding to direct second-order analysis usually considers the geometric nonlinearity only, significantly on high-rise and tall building. It called direct second-order elastic analysis, which was discussed in Oda and Usami (1997) and Iu et al. (2008) works. It is because the effect of changes in member material properties under load, known as material nonlinearity, is small if to be compared to the geometrical changes of the structure when load applied.

Since the application of direct second-order elastic analysis have no provision for detecting material nonlinearity (McGuire, Gallagher, and Ziemian, 2000), computation of overall structures, whether tall or short, simple or complicated structure should take material nonlinearity into consideration in the structural analysis, in order to have a safe and economic structures. By including the material nonlinearity, this analysis is known as second-order inelastic analysis of direct method, where all stiffness matrix of elastic linear, geometric, and material nonlinearity was included in the member stiffness of the structure.

Besides that, the ASCE Manual (1971) suggested that in the interaction equation in the process of determining yield locus, the factor of maximum moment over plastic moment ratio is 0.85, compared to 1.0 as suggested in BS5950-1 (2000). The value should be discussed and compared because the ASCE Manual (1971) suggested value commonly implemented in refined plastic hinge method of analysis. This is important because it is required to determine the location of plastic hinge for the steel portal frame structures. Since the design and analysis of steel in Malaysia is based on BS5950-1 (2000), the differences of this factor should be discussed further.

In order to analyze a complex structure using second-order inelastic analysis, a structural analysis and design software is needed. As an example, STAAD Pro is suitable to analyze nonlinearity, but it has no function to simulate material nonlinearity of a structural system in the structural analysis using STAAD Pro. It only considers linear elastic and the geometric nonlinearity of the analyzed structure. It shows that structural analysis by the aid of STAAD Pro software application is inadequate if second-order inelastic analysis is to be considered.

1.3 Objectives of the Study

The objectives of the study are stated as follows

i. To implement second-order inelastic analysis of direct method on the steel portal frame structures by the aid of MathCAD software application.
ii. To compare the result of the cross section capacity between indirect and direct method analysis of steel portal frame structures.
iii. To observe the behavior of the stability of steel portal frame structures analyzed by direct method of second-order elastic analysis using MathCAD software application.

1.4 Scope of the Study

In this study, direct method was implemented in the analysis of a simple steel portal frame structure. The frame model was analyzed by various method of analysis, such as first-order elastic analysis, second-order elastic analysis, first-order inelastic analysis, and second-order inelastic analysis. However, the analysis of this study was only concentrated on the second-order elastic analysis on the frame model.

In the direct method of second-order inelastic analysis, the linear elastic matrix must be included. For the geometric nonlinearity, the bending moment and axial force of the steel portal frame. For the material nonlinearity analysis, plastic hinge method is applied. In the recent work of Kim et al. (2004), the material nonlinearity considered was by using column research council (CRC) tangent modulus concept to account for gradual yielding due to residual stresses. However, they used the yield surface of interaction equation suggested in ASCE Manual (1971). In this study, the use of BS5950-1 (2000) interaction equation to obtain yield surface applied in the plastic hinge method. It is because Malaysia utilized BS5950-1 (2000) for the design and analysis of steel structure.

The manual calculation of the analysis was done by using MathCAD software application. It eases the analysis procedures and minimizes the time consumption for the analysis of steel portal frame structure using direct method. For the checking procedures, SAP2000 was applied because it has the function to consider nonlinearity of both geometric and material for frame model. It can provide the reliability of the result given by the analysis using MathCAD.

1.5 Significance of the Study

Regarding to structural analysis, as suggested in the traditional design of steel structures in BS5950-1 (2000), noted that the detailed recommendations for practical direct application of “second-order” methods of global analysis (based on the final deformed geometry of the frame) including allowances for geometrical imperfections and residual stresses, strain hardening, the relationship between member stability and frame stability and appropriate failure criteria, are beyond the scope of the document, which where indirect method was implemented. Since the direct second-order method was not discussed in traditional method, this study may enhance the indirect method by the analysis done, in order to observe the structural stability of the steel portal frame structure subjected to various loadings.

Furthermore, the direct method of second-order inelastic analysis consists of elastic, geometric and material analysis of a structural system. It can predict the actual behavior of the structure at the deformed stage. In addition, a study done by Kim et al. (2004) concluded that the analysis can practically account for all factors influencing steel frame behavior, such gradual yielding associated with flexure, and residual stresses and second-order effect, which can enhance the analysis and design of steel structure based on BS5950-1 (2000).

Besides that, this study utilized second-order inelastic analysis based on plastic hinge method based on BS5950-1 (2000) may ease the future structural analysis in Malaysia, especially regarding on the nonlinear analysis. Eventually, a safe and economic steel structure can be produced.