UNIVERSITI PUTRA MALAYSIA

BUCKLING AND POST-BUCKLING OF STEEL BOX SECTION USING FINITE ELEMENT METHOD

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By

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Typically components of structural member use combination of plate structures (i.e. plate elements) in many engineering applications. Many of these structures are subjected to in-plane compressive loading. During compression, the load increases while the stiffness maintained until it reaches the critical load whereby the out-of-plane deflections start to visible. As the load increases, the stiffness reduces to half of its pre-buckling stiffness and the deflections growth in stable manner. This is accompanied by continues alterations in the stress distributions within the cross section. It is therefore important to study the buckling and post-buckling behavior of such components. Most of the studies of square box-section struts in compression have been focusing on constant uniform thickness. This is due to the sections manufactured, available in the market and the standard used by the manufactures to form the sections. All square and rectangular sections have been formed with wall thickness uniform around the section. Nevertheless, it is possible to form the square box-sections with different thickness ratios. This gives more flexibility in design and reduce wastages. The research work sets out an investigation on behavior of the stress distributions of the plates and box section in the post-buckling region with regards to varying thickness ratios of the box section which are 1mm and 2mm. It was observed that the stress variations of box section with thickness ratio 1:1 and plate with thickness 1mm are similar while the stress variations of box section with thickness ratio 1:2 and plate with thickness 2mm are significantly different. A detailed account of the growth and redistributions of stresses across the section was given in the research work. The results from the finite element simulations were shown to compare well with the analytical method of analysis. The percentage difference of the numerical value for square plate model in this study was less than 10% when comparing with the theoretical value.

Abstrak thesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains

LEDINGAN DAN PASCA-LEDINGAN KE ATAS KOMPONEN BESI BERBENTUK SEGI EMPAT SAMA MENGGUNAKAN KAEDAH UNSUR TERHINGGA

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Biasanya komponen struktur anggota menggunakan kombinasi struktur plat (iaitu elemen plat) dalam banyak aplikasi kejuruteraan. Sebilangan besar struktur ini dikenakan beban pemampatan sesatah. Semasa pemampatan, beban meningkat sementara kekakuan dikekalkan sehingga mencapai satu beban kritikal di mana anjakan arah luar satah mulai kelihatan. Apabila beban meningkat, kekakuan berkurang sehingga separuh daripada kekakuan pra-ledingan dan anjakan luar satah bertambah dengan stabil. Ini disertai oleh perubahan berterusan dalam agihan tegasan dalam keratan rentas. Oleh itu, penting untuk mengkaji tingkah laku lekungan dan pasca-ledingan komponen tersebut. Sebilangan besar kajian mengenai strut berbentuk kotak dikenakan daya mampatan dengan memfokuskan pada ketebalan yang seragam. Ini disebabkan oleh pengilangan strut berbentuk kotak yang tersedia di pasaran dan standard yang digunakan oleh pengilang untuk membentuk bentuk kotak tersebut. Semua kotak bersegi empat sama dan bersegi empat tepat telah dibentuk dengan ketebalan dinding yang seragam di sekitar bahagian tersebut. Walaupun begitu, adalah mungkin untuk membentuk bentuk kotak dengan nisbah ketebalan yang berbeza. Ini memberikan lebih banyak pilihan dalam reka bentuk dan mengurangkan pembaziran. Kajian penyelidikan mengkaji tingkah laku taburan tekanan pada bahagian plat dan kotak di kawasan pasca-ledingan berkenaan dengan nisbah ketebalan yang berbeza iaitu 1mm dan 2mm. Telah diperhatikan bahawa variasi tegasan bahagian kotak dengan nisbah ketebalan 1:1 dan plat dengan ketebalan 1mm adalah serupa sementara variasi tegasan bahagian kotak dengan nisbah ketebalan 1:2 dan plat dengan ketebalan 2mm mempunyai perbezaan yang ketara. Laporan terperinci mengenai pertumbuhan dan pengagihan semula tekanan di seluruh bahagian diberikan dalam kajian penyelidikan. Hasil dari simulasi unsur terhingga menunjukkan perbandingan yang baik dengan simulasi bebas. Peratusan perbezaan bagi nilai berangka untuk model plat segi empat dalam kajian ini adalah kurang dari 10% apabila dibandingkan dengan nilai teori.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfillment of the requirement for the degree of Master of Science. The members of the Supervisory Committee were as follows:

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LIST OF ABBREVIATIONS

b	Width of plates
E	Young modulus
t	Thickness of plates
γ	Poisson's Ratio
P	Applied load
P_c	Critical load
ū	Applied end-shortening
L	Length of plate structure
D	Bending stiffness parameter
t_w	Thickness of web plate
t_f	Thickness of flange plate
σ_{cr}	Critical stress
δ	Displacement of plate
P^*	Non-dimensional load
u^*	Non dimensional displacement
$P_c{}^*$	Critical non-dimensional load
$u_c{}^*$	Critical non-dimensional displacement
λ	Eigenvalue
ν	Eigenvector
node	Node location of a plate
avg	Average location of a plate
crest	Crest location of a plate

FEM	Finite Element Method
Plate (t=1mm)	Plate with thickness 1mm
Plate (t=2mm)	Plate with thickness 2mm
NODE A	Flange plate at node
NODE B	Web plate at node
AVG A	Flange plate at avg
AVG B	Web plate at avg
CREST A	Flange plate at crest
CREST B	Web plate at crest

CHAPTER 1

INTRODUCTION

This chapter described briefly the research conducted which consist of the background of the research, problem statements, objectives of the research, and scope of the research and thesis outline.

1.1 Research Background

Researchers and engineers were curious to study the issue of failure in structural elements through buckling, as this issue was rising and generating. The basic underlying physical action creating the buckling of axially compressed columns was the reduction of its lateral stiffness to a value of zero. Complication in the prediction of buckling loads in actual engineering situations were affected by a number of intricacies. However, these structures were always associated with failure in structural elements after subjected to heavy loads and lead to buckling. Apart from that, this was a common issue, hence had attracted researchers and engineers to understand and assess the reliability of complex structures through the study of the buckling behavior of prismatic columns (Ziółkowski and Imiełowski, 2011).

Structures which were stiff in the loaded direction and slender in another direction were exposed to buckling phenomenon. Buckling loads were critical loads where certain kinds of structure become imbalance. As load was increased, there had been displacement in the slender direction causes by sudden increase in deflection in the loading direction. Besides, this happens at location that was initially stable in equilibrium and then known as bifurcation point. This point plays a crucial role for structural behavior to govern slender constructions and to reach plastic or elastic cross-sectional capacity. A structure was considered stable when there was no buckling at a certain load level (Bhoi and Kalurkar, 2014).

Some situations where wrinkling occurs at isolated location and some thin portions of the cross section buckle locally in compression were known as local buckling. Local buckling takes place before other modes of buckling occur and it may cause the cross section to be ineffective and the steel compression members to fail. For example, local buckling at thin flanges and web elements of an I-shaped cross section results in failure of column (Bhoi and Kalurkar, 2014). In addition, constituting elements that were small in thickness were then prone of getting flexural buckling. Excessive flexural deformation may also happen due to commonly used of built up and hot rolled steel compression members. Hence, this present study also included post-buckling response of the imperfect buckled structures.

There had been a few numerical simulation procedures and analytical studies done using the finite strip method of analysis, assuming that the plate components at the junctions were uncoupled and free to wave in their own plane along the junctions, while the plate's out-of-plane deflection disappears. However, these assumptions inflict stress-free in-plane conditions in the width direction of each plate and had violated the compatibility and equilibrium conditions along the junctions (Grave Smith, 1966). Hence, this present research work was to study the conditions of junctions between the flange and web plates of the cross sections along the lengths of the struts using the finite element method. This allows nodes at the section junction to be constraint-free and coupling of the in-plane and out-of-plane deflections of the section walls to happen and leads to waviness of the junctions along the length of the strut. Furthermore, this method had more ability to study the natural compatibility and equilibrium conditions at the junctions.

1.2 Problem Statement of the Research

Prismatic plates and plate structures were increasingly used as structural components in various branches of engineering, chief of which were aerospace and marine engineering. In aerospace particularly, the quest for efficient and light-weight structures often leads to risk of local buckling and post-local-buckling at design load levels. These structures were often subjected to in-plane compressive loading. Ovesy et al., (2006) had developed finite strip method to study post-local-buckling behavior of locally buckled I-beams with thin flanges. In addition, there were already many finite strip method developed by researchers such as Hancock (1981), Sridharan and Ali (1985 and 1986), and Graves Smith and Sridharan (1978) to study only post-local-buckling problems. Conversely, finite element method had larger number of degrees of freedom to give no limitations of boundary conditions and local discontinuities. It was a more dominant form of geometrically non-linear structural analysis and this present study gave considerable computational effort in structure discovery.

Loughlan et al., (2009) summarized that local buckling of the section walls can alter the compressional stiffness of thin-walled I-section strut. Cross-sectional shape and section all thickness affected the loss in axial stiffness of short strut compression members. The study further proved that high through-the-thickness bending stresses from local buckling and local imperfections were significant to cause simultaneous buckling yielding design (Loughlan et al., 2011). Hence, it was significant to study the effect local buckling and post-buckling in thin-walled box-sections with different thickness.

Rhodes (2002) illustrated using box-section tube with sides of unequal thickness that the rotational restraint was more significant at the point of buckling and in the initial stages of the post-buckling behavior. Thus, the author's study was to conduct the investigation on influences of the thin plate thickness towards the behavior of buckling and post-buckling of steel box-section struts under displacement. Appropriate thickness distribution resulted in substantial increase in critical local buckling loads of plates. Furthermore, his study was valuable as the analysis can help to come up with an economic design as plates of variable thickness were particularly used as aircraft wings and turbine discs.

In addition, the literature of study on the influence of thickness of thin plate towards behavior of buckling and post-buckling of steel box-section were least available. Most of the studies of square box-section struts in compression had been focusing on constant uniform thickness (Azhari et al., 2005). This was due to the sections manufactured, available in the market and the standard used by the manufactures to form the sections. All square and rectangular sections had been formed with wall thickness uniform around the section. Nevertheless, it was possible to form the square box-sections with different thickness ratios. This gave more flexibility in design and reduce wastages. Thus, this current work studied the behavior of box-section struts with different thickness ratios (i.e. t_w/t_f= 1 and 2) looking into the loading history and stress distributions during compression loading. Furthermore, the difficulties in determining the local buckling strength and behavior of such plates by using experimental method of analysis may be known as one of the reason for the problems. Therefore, a numerical method such as the finite element method would be the most suitable techniques for solving the problem based on the complication of the problems, such as lack of symmetry in the plate thickness and the axial load distributions.

1.3 Objectives of the Research

This research work was conducted by using the numerical method which was known as finite element simulation software, i.e. ABAQUS/CAE and had been chosen because of the simple and consistent interface for creating, monitoring and evaluating the results from the simulation. The main objective of this research was to investigate the influence of different plate thickness on the steel box-section strut buckling and post-buckling behavior. The objectives of this work were:

1. To develop non-linear finite element modelling strategy and solution procedures for the post-local-buckling analysis of the plates and box-section struts under uniform end shortening.

2. To verify and validate the developed finite element simulation.

3. To investigate the behavior of the stress distributions of the plates and box-section struts in the post-buckling region with regards to varying thickness ratios of the box-section struts.

1.4 Scopes of the Research

In order to achieve the objectives of the study, the understanding on basic buckling and post-buckling concept on steel box-section strut of different thickness ratio was conducted especially when subjected to axial loads. In current study, the method to conduct the analysis was by using the numerical method only, i.e. finite element analysis (FEA) software. In addition, this method was considered to be used in present study because it can save time to gain the results and saving cost. Since current study use the finite element analysis (FEA) software, i.e. ABAQUS/CAE to conduct the analysis, therefore the technique to use the software was learned.

In determining the best material for the current study, an investigation on the materials that had been used throughout the study was conducted through the literature study. The selection of the material for the study was based on the properties of the materials and its application that were widely used in recent industries especially in aerospace industry. The properties of the materials that had the highest demand in current industries was the material that poses high strength and light weight. Thus, the best material that had been selected to be used in the current study was steel due to its material properties and its typical application in aerospace industry.

Besides, there were two types of basic model geometry for current study, which were thin plate of 1mm thickness and thin plate of 2mm thickness. The size of the thin plate designed for current study was limited to 100mm x 100mm of length and width. The thin plates were constructed to a square box-section structure with different thickness ratio 1:1 and 1:2. Then, both geometry structure were analyzed by using finite element analysis software. The result predicted from the numerical analysis were verified and validated by referring to the existing theoretical data obtained from the literature study conducted. In order to ensure the results of the analysis was accurate and acceptable, thus the percentage difference considered for current study shall be below than 10%.

Finally, the results for all investigation conducted for current study was analyzed and discussed to investigate the behavior of the buckling and post-buckling of steel box-section with different thickness ratios when subjected to axial loads. In the meantime, the comparison between the behavior of buckling and post-buckling of box-section of thickness ratio 1:1 and 1:2 were determined. Lastly, the outcome for the study was concluded with some recommendation for future study.

1.5 Thesis Outline

The overall thesis outline contains five (5) chapters, and the content of these chapters are organized as following:

- Chapter 1: Introduction

  This chapter generally summarizes the background of the research conducted on the buckling and post-buckling of square box-section.

- Chapter 2: Literature Review

  This chapter is discussing the literature review based on the previous study conducted and published paper related with buckling and post-buckling of square box-section.

- Chapter 3: Methodology

  This chapter highlights the method implemented in the research by using FEA software with the verification and validation of the numerical data obtained.

- Chapter 4: Results and Discussions

  This chapter provides the results and some discussions of the research which relates to buckling and post-buckling behavior of square plates and square box when subjected to axial load.

- Chapter 5: Conclusions and recommendations

  This chapter presents a comprehensive conclusion based on the findings of the research conducted and some recommendation for future works.

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