PSZ 19:16 (Pind. 1/07)

# UNIVERSITI TEKNOLOGI MALAYSIA

## DECLARATION OF THESIS / UNDERGRADUATE PROJECT PAPER AND COPYRIGHT

Author's full name : **MOK HUN YEW**

Date of birth : **20 FEBRUARY 1981**

Title : **THE OPTIMIZATION OF SHEAR BUCKLING RESISTANCE OF TRAPEZOIDAL WEB PLATE**

Academic Session: **2007/2008**

I declare that this thesis is classified as :

| | | |
|---|---|---|
| ☐ | **CONFIDENTIAL** | (Contains confidential information under the Official Secret Act 1972)* |
| ☐ | **RESTRICTED** | (Contains restricted information as specified by the organization where research was done)* |
| ☑ | **OPEN ACCESS** | I agree that my thesis to be published as online open access (full text) |

I acknowledged that Universiti Teknologi Malaysia reserves the right as follows:

1. The thesis is the property of Universiti Teknologi Malaysia.
2. The Library of Universiti Teknologi Malaysia has the right to make copies for the purpose of research only.
3. The Library has the right to make copies of the thesis for academic exchange.

Certified by :

| | |
|---|---|
| **SIGNATURE** | **SIGNATURE OF SUPERVISOR** |
| **810220-14-5565** | **PM Ir. Dr Mohd. Hanim Osman** |
| **(NEW IC NO. /PASSPORT NO.)** | **NAME OF SUPERVISOR** |
| Date : **20 NOVEMBER 2007** | Date : **20 NOVEMBER 2007** |

**NOTES :** * If the thesis is CONFIDENTAL or RESTRICTED, please attach with the letter from the organization with period and reasons for confidentiality or restriction.

# THE OPTIMIZATION OF SHEAR BUCKLING RESISTANCE OF TRAPEZOIDAL WEB PLATE

MOK HUN YEW

A project report submitted in partial fulfilment of the
requirements for the award of the degree of
Master of Engineering (Civil – Structure)

Faculty of Civil Engineering
Universiti Teknologi Malaysia

NOVEMBER 2007

"I hereby declare that I have read this project report and in my opinion this project report is sufficient in terms of scope and quality for the award of the degree of Master of Engineering (Civil – Structure)"

Signature : ......................................................

Name of Supervisor : Associate Professor Ir. Dr. Mohd. Hanim Osman

Date : 20 November 2007

I declare that this project report entitled "*The Optimization of Shear Buckling Resistance of Trapezoidal Web Plate*" is the result of my own research except as cited in the references. The report has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature : ........................................

Name : Mok Hun Yew

Date : 20 November 2007

To my beloved mother and father

## ACKNOWLEDGEMENT

First and foremost, I wish to take this opportunity to express my heartfelt gratitude and appreciation to my supervisor, Associate Professor Ir. Dr. Mohd. Hanim Osman, for being a mentor, whose constant guide, advice, support, brilliant ideas and constructive comments has brought throughout the preparation of this study.

To my loving parents, I also reserve special thanks to my beloved family for their commitment, encouragement and patient throughout the whole duration of studies and the continued support. Without their continuous words of encouragement, it would have been difficult to complete this report.

Last, but not the least, I wish to thank every individuals especially my close friends, whose name are too many to be mentioned here, for all the assistance and support at various occasions received all this while.

Thank you.

# ABSTRACT

Efficient and economical design of plate girder normally requires thin webs. However, extremely slender web will cause the web to buckle. To overcome this, the corrugated girder or so called Trapezoidal Web Plate (TWP) girder can be used. In a trapezoidal web plate (TWP) girder, corrugated webs require no stiffening except at supports, so it permits the use of thinner plates with significant weight saving. Because of its high slenderness ratio, stability due to shear force should be concerned primarily. In absence of design guide, the British Standard BS 5950 usually used as the basic guideline for the design of a TWP girder but a number of simplification and conservativeness have to be made and consequently can lead to uneconomical design. Studies on shear buckling resistance of TWP girder carried out by previous researches are limited to condition which they have considered. Some geometric parameters are always be neglected. In this study, the behaviours of the TWP girders with different geometrical properties under shear force were examined. The numerical study of shear capacity of TWP was conducted by using eigenvalue buckling analysis in LUSAS Finite Element software. A series of eigenvalue buckling analyses were performed to obtain the critical buckling loads of TWP model and the respective buckling mode were identified and investigated. The parametric study which involves the depth of web ($d$), web thickness ($t_w$), corrugation depth ($h_r$), corrugation angle ($\theta$) and flat sub-panel ($b$) has been carried out prior to the derivation of new formula of shear buckling. A new formula of shear buckling capacity has been successfully derived and the formula is suitable for estimating the shear buckling capacity for other sections of trapezoidal web for the optimal design.

# ABSTRAK

Rekabentuk plat galang yang ekonomi dan berkesan biasanya memerlukan plat yang langsing. Walau bagaimanapun, masalah lengkukan akan berlaku jika plat yang terlalu langsing digunakan. Untuk mengatasi masalah lendingan tersebut, plat yang mempunyai profil berkelut yang berbentuk trapezium atau lebih dikenali sabagai *Trapezoidal Web Plate* (TWP) boleh digunakan. Rasuk TWP tidak memerlukan pengukuh web kecuali di bahagian penyokong. Oleh itu, rasuk TWP memungkinkan pengurangan berat rasuk dengan memungkinkan penggunaan web yang langsing. Oleh sebab tiada sebarang piawai yang khusus untuk rekabentuk rasuk TWP, biasanya BS 5950 dijadikan panduan dalam rekabentuk. Hal ini menyebabkan langkah rekabentuk yang konservatif perlu diambil dan rekabentuk akan menjadi tidak ekonomi. Sungguhpun penyelidikan tentang keupayaan lendingan ricih telah dijalankan oleh penyelidik-penyelidik sebelum ini, tetapi model-model TWP yang dikaji hanya dihadkan pada keadaan yang tertentu. Oleh itu, keupayaan lendingan ricih yang sepenuhnya masih tidak dapat diperoleh. Dalam kajian ini, keadaan lendingan rasuk TWP yang dipengaruhi oleh ciri-ciri rupabentuk rasuk TWP telah dikaji. Suatu kaedah analisis yang dikenali Eigenvalue Buckling Analysis dalam perisian unsur terhingga iaitu LUSAS telah digunakan untuk mengaji keupayaan lendingan ricih kritikal. Kajian parametrik rasuk TWP termasuklah tebal plat ($t_w$), kedalaman rasuk ($d$), sub-plat ($b$), kedalaman berkelut ($h_r$) dan sudut berkelut ($\theta$). Satu formula untuk menjangka keupayaan lendingan ricih kritical telah diterbitkan dan formula tersebut telah berjaya diperbaik dan sesuai untuk menjangka keupayaan lendingan kritical bagi rasuk TWP dengan pelbagai dimensi atau rupabentuk bagi tujuan rekabentuk.

# TABLE OF CONTENTS

## LIST OF FIGURES

# LIST OF SYMBOLS

| | | |
|---|---|---|
| $a$ | - | Spacing of transverse stiffness |
| $b$ | - | Flat sub-panel width |
| $C_b$ | - | Coefficient due to the effect of flat sub-panel width |
| $C_d$ | - | Coefficient due to the effect of depth of web |
| $C_{hr}$ | - | Coefficient due to the effect of corrugation depth |
| $C_{tw}$ | - | Coefficient due to the effect of web thickness |
| $C_\theta$ | - | Coefficient due to the effect of corrugation angle |
| $d$ | - | Depth of web |
| $E$ | - | Young's Modulus |
| $f_f$ | - | Mean longitudinal stress in the smaller flange |
| $h_r$ | - | Corrugation depth |
| $I_{ext}$ | - | Second moment of area due to the external force |
| $I_g$ | - | Second moment of area about the centerline of the web |
| $k$ | - | Buckling coefficient |
| $M_{pf}$ | - | Plastic moment capacity of the smaller flange |
| $M_{pw}$ | - | Plastic capacity of the web |
| $P_v$ | - | Shear resistance of the section |
| $p_{yw}$ | - | Yield strength of web |
| $q_{cr}$ | - | Critical shear strength |
| $q_e$ | - | Elastic critical shear strength of the panel |

| | | |
|---|---|---|
| $q_w$ | - | Post-bukling strength of web panel |
| t | - | Thickness of web of plate girder |
| $t_{min}$ | - | minimum required web thickness |
| $t_w$ | - | Web thickness |
| $V_b$ | - | Shear buckling resistance of plate girder |
| $V_f$ | - | Shear buckling resistance contribute by flange |
| $V_w$ | - | Shear buckling resistance of the web panel of plate girder |
| $\theta$ | - | Corrugation angle |
| $\lambda_w$ | - | Equivalent slenderness of web |
| $t_{cr}$, $t_l$ | - | Critical local buckling stress |
| $t_y$ | - | Shear stress equal to $0.6f_y$ |
| $t_i$ | - | Interactive buckling stress |
| $t_{pi,l}$ | - | Ideal buckling stress which influence by edge stress for local buckling |
| $\nu$ | - | Poisson ratio |
| $f_y$ | - | Yield strength |
| $\overline{\lambda}_{p,l}$ | - | Qualitative degree of slenderness for local buckling |

# CHAPTER 1

# INTRODUCTION

## 1.1 General

Economical design of girders and beams normally requires thin webs. However, if the web is extremely slender the problem of plate buckling may arise. Possible ways to reduce this risk are by using thicker plates, adding web stiffeners or strengthening the web by making it corrugated. By using thicker plates or adding web stiffeners obviously will increase the costs of fabrication. As early as 1920's, the idea of using beam girders with corrugated webs was seen to be another step along the path to economy [1]. However, the ability to fabricate these beams was found to be lacking. It has only been recently with the advance in welding technology, that uses of relatively thin corrugated webs have been possible.

The corrugated profile in webs provides a kind of uniformly distribution stiffening in the transverse direction of a girder. In trapezoidal web plate, the corrugated profile required no stiffening except at supports, so it permits the use of thinner plates. In comparison with plate girders with stiffened flat webs, a girder with a trapezoidal corrugated web enables the use of thin webs, thus for less cost at higher load-carrying capacity is achieved. Besides the convenience during manufacture, this should be the most important reason why the application of such girders can be widely increased, and is still increasing. Based on the configuration of the structure, trapezoidal web plate beam can offer substantial saving in the steel usage, and in some cases up-to 40% as compared to conventional rolled sections [1].

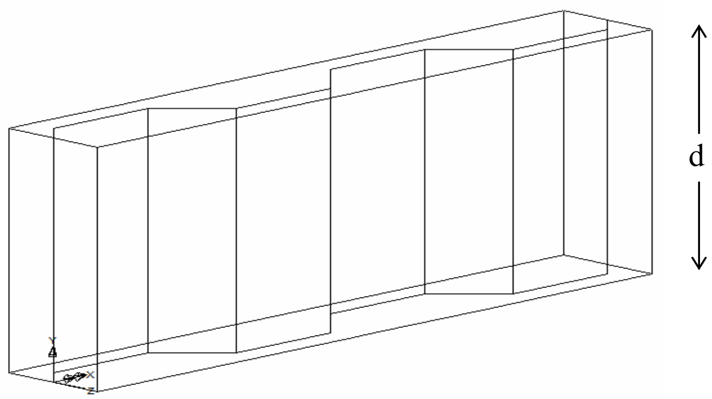
A trapezoidal web plate girder is normally designed to support heavy loads over long spans in situation where it is necessary to produce an efficient design by providing girders of high strength to weight ratio. The search for an efficient design produces conflicting requirements, particularly in the case of the web plate. To produce the lowest axial flange force for a given bending moment, the web depth must be made as large as possible. To reduce the self weight, the web thickness must be reduced to a minimum. As a consequence, in many instances the web plate is of slender proportions and is therefore prone to buckle at relatively low values of applied shear. Because of the high slenderness ratio of a trapezoidal web plate girder, stability due to shear force should be concerned primarily.

For girder with corrugated webs, studies have been conducted by previous researcher to find the best way to utilise corrugated webs. Studies on the behaviour of beams with corrugated webs subjected to shear have been conducted since early 1960's but the full capacity of corrugated plates is still underestimated and only since 1980 has its behaviour been studied in detail. However, the studies on the shear buckling resistance of the trapezoidal web plate girder have not been made as extensively as for plate girders with stiffened flat webs. In the absence of any specific design guide, the British Standard BS 5950 can be used as the basis for the design of the corrugated beams or girders. However, a number of simplification and conservativeness have to be made when using BS5950 for the corrugated web and consequently can lead to uneconomic in design. Although some formulae have been proposed by previous researches to estimate the shear buckling strength of the corrugated web plate, the application of the formulae are limited to certain corrugated web profiles for which they were derived.

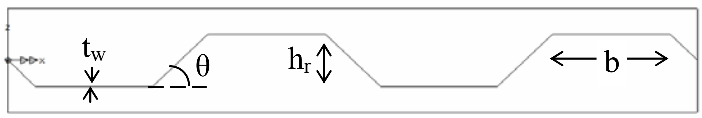
In this study, the shear capacity of trapezoidal web plate was numerically studied by using eigenvalue buckling analysis in finite element method. Emphasis was placed on the investigation of how geometric and other parameters influence the shear buckling patterns and the shear buckling resistance of trapezoidal corrugated webs. One goal of the study was to enhance buckling coefficient and to optimize critical shear buckling resistance formulae, which were proposed earlier by other researches. The new enhanced formula could be utilized to develop a properties table of the trapezoidal web plate girder with different corrugated profiles.

## 1.2 Trapezoidal Web Plate Girder

A trapezoidal web plate girder (TWP) is a built-up steel section made up of two flanges connected to a corrugated slender web. Figure 1.1 shows a trapezoidal web plate model. Figure 1.1(b) shows also the geometrical nomination for a TWP model. The web is corrugated at regular intervals into trapezoidal shape along the length of the beam. The corrugated profile in web provides a kind of uniformly distribution stiffening in the transverse direction of a trapezoidal web plate girder.




(a) Isometric view of a TWP model




(b) Plan view of a TWP model

**Figure 1.1: Isometric view of a trapezoidal web plate model**

Corrugated webs can be used in an effort to decrease the weight of steel girders and reduce its fabrication cost. Studies have been conducted in Europe and Japan and girders with corrugated webs have been used in these countries. The results of the studies indicate that the fatigue strength of girders with corrugated webs can be 50% higher compared to girders with flat stiffened webs. In addition to the improved fatigue life, the weight of girders with corrugated webs can be as much as 30% to 60% less than the weight of girders with flat webs and have the same capacity. Due to the weight savings, larger clear spans can be achieved. Beams and girders with corrugated webs are economical to use and can improve the aesthetics of the structure [1].

In late 1997, the beam with a corrugated web by the name Trapez Steg Profile (TSP) or Trapezoid Web Profile (TWP) Beam, was first introduced in Malaysia by Spelten Consulting GmbH. Germany together with Trapezoidal Web Profile Sdn. Bhd (TWPSB). The company has claimed that, based on the configuration of the structure, TWP Beam can offer substantial saving in the steel usage, and in some cases of up-to 40% as compared to conventional rolled sections. It is more so when there is a need for a column free, long span structural system, such as portal frames for warehouses, girder for bridges, floor and roof beam for high rise building, complexes etc [1].

TWP girders are used where high loading, rigidity, strength and clear span are the main criteria in construction [3]. Generally, the advantages of a trapezoidal web plate beam or girder as compared to the conventional plate girder includes

(a) The utilization of a very thin web and produce a light weight structure.
(b) Elimination the need of stiffeners, hence reduced the fabrication cost besides producing a light weight structure.
(c) Use of much slender or deep section with higher flexural capacity, wider span and less deflection.
(d) Increased of fatigue strength.
(e) The use of corrugated webs will increase the lateral stiffness of girder, thus Increase in lateral torsion buckling resistance.

Test carried out in cooperation with the Structural Steel Engineering Institute of the Technical University of Braunschweig have clearly shown that TWP girder reach same the strength value as conventional profile while saving 30% to 60% in weight per running metre. This can be comparing a typical IPE beam (European parallel flange beam) and TWP beam [3] as presented in Table 1.1.

**Table 1.1:** Weight Comparison between a typical IPE beam and a TWP beam [3]

| | IPE Section | TWP Section |
|---|---|---|
| Type | 400 | 11 |
| Moment of Inertia ($cm^4$) | 23.130 | 22.861 |
| Weight (kg.m) | 66 (100%) | 39 (60%) |

In this study, the shear buckling resistance of a TWP model is concerned. Among the many factors that may influence the ultimate strength and buckling mode of a TWP girder in shear, the geometric parameters are as follows (see Figure 1.1(b) for illustration):

(a) the depth of web, $d$

(b) the web thickness, $t_w$

(c) the flat sub-panel width, $b$

(d) the corrugation depth, $h_r$

(e) the corrugation angle, $\theta$

Other factors are initial imperfections and initial stresses introduced locally and globally during manufacture or installation; residual stresses due to cold-forming and welding, repeated loading, temperature, etc. In order to limit this study and keep it brief and clear, the study shall focus on effects of the geometrical parameters listed above.

## 1.3 Problem Statement

Studies on shear buckling resistance of trapezoidal web plate girder had been carried out by previous researchers. However, the full capacity of shear buckling resistance of corrugated web plate is still not being utilized. Some formulae had been proposed by previous researchers. However, the formulae are limited to the conditions which they had considered. Hence, some geometrical parameters such as the corrugation depth, corrugation angle, etc and their effects to the shear buckling resistance were always neglected.

Therefore, the study is necessary to understand the clear explanation of the effects due to each geometrical parameter of a TWP model to the shear buckling stress and to determine a new formula of shear buckling resistance and extend the knowledge.

## 1.4 Objectives of the Study

The main objectives of this study are:

(a) To study the behaviour of shear buckling of Trapezoidal Web Plate under different corrugated geometric parameters

(b) To propose a formula for the critical shear buckling resistance of TWP section based on different corrugated profiles.

## 1.5 Scope of the Study

The scopes in this study consist of:

(a) Eigenvalue buckling analyses on several Trapezoidal Web Plate model by using the finite element application (LUSAS).

(b) Identify the buckling mode of TWP models with different corrugated profiles.

(c) Derivation of a formula for critical shear stress induced by a vertical shear force on the TWP model using the results of analytical study.

# CHAPTER 2

# LITERATURE REVIEWS

## 2.1 Introduction

Modern plate girders are normally fabricated by welding together two flanges and a web plate to form an I-section. Such girders are capable of carrying greater loads over longer spans than is generally possible using standard rolled sections or compound girders. Plate girders are typically used as long-span floor girders in buildings, as bridge girders, and as crane girders in industrial structures. Generally a plate girder may not be require until the span exceeds 25 metres and recently numerous plate girders spanning 60 to 1000 metres have been constructed. Stiffeners are used to reinforce the web [4].

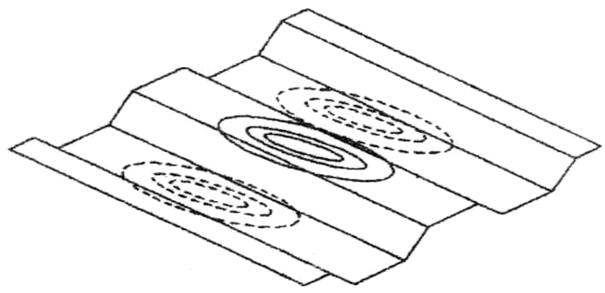
There are disadvantages in using stiffened thin plates in girders. High fabrication cost and a possible reduced life span due to fatigue cracking which may initiate at the welded connections between the stiffeners and flanges have been noted. It has only been recently, with the advance in welding technology, that the uses relatively thin corrugated webs have been possible. Corrugated webs required no stiffening except at supports. The corrugations act as transverse stiffeners, permitting the use of thinner plates with significant weight reduction. However, because of the high slenderness ratio of the corrugated web plate girder, the stability in shear buckling should be of primary concerned.

## 2.2 Shear Strength of Slender Web Plate

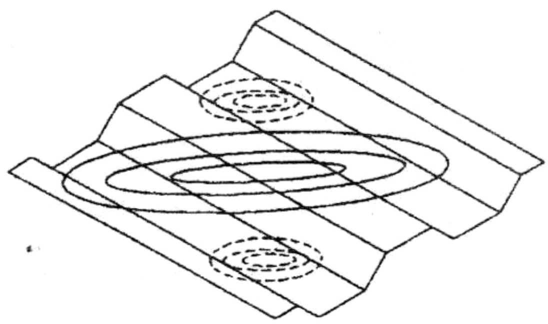
For efficient design, it is usual to choose a relatively deep girder, thus minimizing the required area of flanges for a given applied moment. This obviously required a deep web which area will be minimized by reducing its thickness to the minimum required to carry the applied shear. Such a web may be quite slender and may be prone to local buckling and shear buckling. Such buckling problems have to be given careful consideration in plate girder design. One way of improving the load carrying resistance of a slender plate is to employ stiffeners.

Web buckling due to shear is essential a local buckling phenomenon. Depending upon the geometry, the web plate is capable of carrying additional loads considerably in excess of that at which the web starts to buckle, due to post-buckling strength. Depending on the geometric parameters, two buckling patterns can occur in the corrugated webs, they are local buckling and global buckling. The local buckling is a kind of shear buckling occurs in the plane part of the folds and is restricted to this region only. The global buckling is a kind of shear buckling involves several folds, may sometimes occur with a nap-through in load-displacement responses and may rise to yield lines crossing these folds. In Figure 2.1(a) to Figure 2.1 (d), these two different buckling modes are illustrated [5].

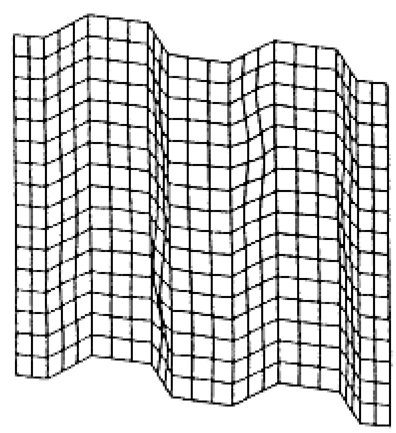
Usually, some kind of local buckling initiates the buckling process. However, a local buckling mode which initiates the buckling can reduce the post-buckling shear capacity. Moreover, in post-buckling stages, local buckling either directly develops and transforms to a global buckling mode, resulting in the failure, or extends from one sub-panel to another, first a zonal buckling mode and later transforming to a so-called tension field [6] (a narrow tension band in the diagonal direction of the girder) over the whole girder depth. In the latter case, the failure of the girder is due to material yielding within the tension field.



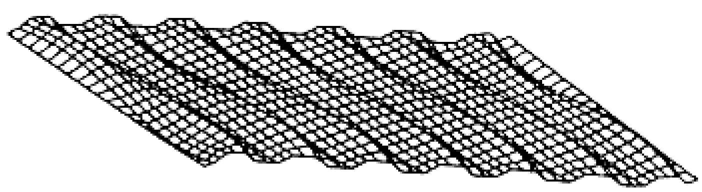
(a) Shear stress distribution of local buckling



(b) Shear stress distribution of global buckling



(c) Deformation pattern of local buckling



(d) Deformation pattern of global buckling

**Figure 2.1:** Common buckling patterns of a corrugated web

The theory of plate girder states that a web will resist an applied load in three successively occurring stages which are:

(a) First stage is a pure shear field as shown in Figure 2.2 (a). This is a situation prior to buckling. At this stage, equal tensile and compressive principal stresses are developed in the web. The shear buckling is calculated from elastic buckling theory [7].

(b) Second stage is membrane action as shown in Figure 2.2 (b). This stage is also known as post-buckling stage. At this stage, an inclined tensile membrane stress field is developed, at an inclination angle to the horizontal in the web. Since the flanges or the girder are flexible, they will begin to bend inwards under the pull exerted by the tension field. The load carrying action of the plate girder becomes similar to that of an N girder truss in Figure 2.3 (a) and (b). The action of the web panel is analogous to that of the diagonals of the truss [7].

(c) Third stage is the formation of plastic hinges as shown in Figure 2.2 (c). Further increase in the load will result in yield occurring in the web under the combined effect of the membrane stress field and the shear stress at buckling. Once the web has yielded, final failure of the girder will occur when mechanism comprising four plastic hinges has formed in the flanges [7].

In this study, the first stage which is the pure shear condition will be modeled for the linear analysis since the pure shear condition obeyed the elastic buckling theory.