EXPERIMENTAL AND FINITE ELEMENT ANALYSES OF 
CORRUGATED WEB STEEL BEAMS SUBJECTED TO BENDING LOADS

CHAN CHEE LEONG

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EXPERIMENTAL AND FINITE ELEMENT ANALYSES OF CORRUGATED WEB STEEL BEAMS SUBJECTED TO BENDING LOADS

By

CHAN CHEE LEONG

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EXPERIMENTAL AND FINITE ELEMENT ANALYSES OF CORRUGATED WEB STEEL BEAMS SUBJECTED TO BENDING LOADS

By

CHAN CHEE LEONG

September 2002

Chairman: Associate Professor Yousif A. Khalid, Ph.D.

Faculty: Engineering

The behaviour of beams with corrugated web has been investigated throughout this study. They are commonly used in structural steel works to enhance the moment-carrying capability and weight reduction. Experimental tests and finite element analysis were conducted on beams with plane web (PW), horizontally corrugated (HC) and vertically corrugated (VC) webs.

Throughout the experimental tests, semicircular shape corrugation of 22.5 mm mean radius and 4.0 mm thickness was used. Two cases were considered for the HC beams, one arc (HC1) and two arcs (HC2) corrugation, while semicircular wholly corrugated was used for the VC type beams. All specimens were fabricated using tubes and flat plates of mild steel material (AISI 1020). The Instron testing machine was used for the three-point bending tests where three tests for each case have been carried out to obtain the load-displacement relations. The plane web I-section beams
with the mass per unit length value of 19.3 (kgm\(^{-1}\)) was also tested to act as the benchmark result.

In the analytical work, finite element models were generated and analysed by using LUSAS software. The material datasets were defined based on the actual stress-strain data obtained from the tensile tests. A series of elastic-plastic nonlinear analysis were carried out with the boundary settings similar to the experiment setup. Three corrugation radii of 22.50 mm, 33.75 mm and 67.50 mm were considered for the HC beams while five radii, in the range of 11.25 mm to 33.75 mm for the VC beams.

From the results obtained, the VC beams has yield loads of 60.621 kN to 73.308 kN or 13.3% to 32.8% higher than the welded plane web beams and 1.32-1.89 times and 1.56-3.26 times higher compared to the HC1 and HC2 beams respectively. The yield load increases as the larger size of radius was used, which is true for the sizes taken in this study. Moreover, as much as 13.6% of reduction in weight was achieved for the VC beams at the largest value of corrugation radius. A good agreement was found between the experimental and finite element analysis results where the percentage difference obtained was 7.28% to 28.37%.
Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains

EKSPERIMEN DAN ANALISIS UNSUR TERHINGGA ALANG BESI BERALUN DIKENAKAN BEBAN MEMBENGKOK

By

CHAN CHEE LEONG

September 2002

Pengerusi : Profesor Madya Yousif A. Khalid, Ph.D.

Fakulti : Kejuruteraan

Kajian ke atas kelakuan alang beralun telah dijalankan. Ia biasanya digunakan untuk kerja-kerja melibatkan struktur besi dalam mempertingkatkan keupayaan menanggung beban momen dan mengurangkan berat struktur. Alang dengan bentuk rim tengah yang berbeza iaitu datar (PW), beralun melintang (HC) dan beralun menegak telah dikaji secara ujikaji dan analisis unsur terhingga.

Alunan berbentuk separuh bulatan dengan jejari min 22.5 mm dan tebal 4.0 mm digunakan dalam ujikaji. Bagi alang jenis HC, dua bentuk alunan dikaji iaitu satu lengkungan (HC1) dan dua lengkungan (HC2) dan alunan berbentuk separuh bulatan beralun menyeluruh bagi alang jenis VC. Semua spesimen dibikin dengan menggunakan bahan besi lembut (AISI 1020). Tiga ujian lenturan tiga-pin dijalankan ke atas setiap jenis alang dengan menggunakan mesin Instron untuk mendapatkan perkaitan di antara beban-sesaran. Alang biasa yang berbentuk I dengan rim tengah
yang rata juga diuji sebagai ujian kawalan. Berat semeter alang yang diuji ialah 19.3 kg/m.

Dalam kajian secara analitikal, model unsur terhingga dihasilkan dan diuji di bawah kesan lenturan tiga-pin dengan menggunakan perisian LUSAS. Sifat mekanikal bahan ditakrifkan daripada tegasan-terikan sebenar yang diperolehi dalam ujian ketegangan. Analisis-analisis tidak linear yang diprogramkan menyerupai keadaan dan susun eksperimen telah dijalankan. Sebanyak tiga saiz jejari alunan digunakan bagi alang jenis HC iaitu 22.50 mm, 33.75 mm dan 67.50 mm, manakala lima saiz dalam lingkungan 11.25 mm hingga 33.75 mm bagi alang jenis VC.

Daripada keputusan yang diperolehi, alang jenis VC mempunyai nilai beban alah sebanyak 60.621 kN hingga 73.308 kN atau 13.3% hingga 32.8% melebihi alang jenis PW yang dikimpal serta 1.32-1.89 dan 1.56-3.26 kali ganda nilai beban alah alang jenis HC1 dan HC2 masing-masing. Dengan menggunakan saiz jejari alunan yang besar, peningkatan dalam beban alah yang lebih ketara akan diperolehi. Tambahan pula, penurunan berat sebanyak 13.6% bagi alang jenis VC akan dicapai jika maksimum saiz jejari alunan digunakan. Perbandingan di antara keputusan eksperimen dan analisis unsur terhingga adalah memuaskan dengan peratus perbezaan yang diperolehi sebanyak 7.28% hingga 28.37%.
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Last but not least, I would like to thank my family and friends for their moral supports and encouragements that motivate me to relentless strive to succeed.
I certify that an Examination Committee met on 9th September 2002 to conduct the final examination of Chan Chee Leong on his Master of Science thesis entitled “Experimental and Finite Element Analyses of Corrugated Web Steel Beams Subjected to Bending Loads” in accordance Universiti Pertanian Malaysia (Higher Degree) Act 1980 and Universiti Pertanian Malaysia (Higher Degree) Regulations 1981. The committee recommends that the candidate be awarded the relevant degree. Members of the Examination Committee are as follows:

**WONG SHAW VOON, Ph.D.**
Faculty of Engineering, 
Universiti Putra Malaysia  
(Chairman)

**YOUSIF ABDULLAH KHALID, Ph.D.**
Associate Professor,  
Faculty of Engineering  
Universiti Putra Malaysia  
(Member)

**IR. BARKAWI BIN SAHARI, Ph.D.**
Associate Professor,  
Faculty of Engineering  
Universiti Putra Malaysia  
(Member)

**ABDEL MAGID S. HAMOUDA, Ph.D.**
Associate Professor,  
Faculty of Engineering  
Universiti Putra Malaysia  
(Member)

**SHAMSHER MOHAMAD RAMADILI, Ph.D.**  
Professor/Deputy Dean  
School of Graduate Studies,  
Universiti Putra Malaysia

Date: 15 OCT 2002
This thesis submitted to the Senate of Universiti Putra Malaysia has been accepted as fulfilment of the requirements for the degree of Master of Science. The members of the Supervisory Committee are as follows:

YOUSIF ABDULLAH KHALID, Ph.D.
Associate Professor,
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

IR. BARKAWI BIN SAHARI, Ph.D.
Associate Professor,
Faculty of Engineering
Universiti Putra Malaysia
(Member)

ABDEL MAGID S. HAMOUDA, Ph.D.
Associate Professor,
Faculty of Engineering
Universiti Putra Malaysia
(Member)

AINI IDERIS, Ph.D.
Professor/Dean,
School of Graduate Studies,
Universiti Putra Malaysia

Date:
DECLARATION

I hereby declare that the thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UPM or other institutions.

CHAN CHEE LEONG

12 OCT. 2002
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LIST OF ABBREVIATIONS

$A_{xy}$ Area of cross section in the $xy$ plane
$A_{zx}$ Area of cross section in the $zx$ plane
$b_f$ Width of flange
d Depth of beam
d_m Mean diameter of corrugated web
ep Effective plastic strain
e Strain
E Modulus of Elasticity
F Load
$F_U$ Ultimate load
$F_Y$ Yield load
H Corrugation amplitude
$I_{xx}$ Second moment of area with respect to $x$-axis
$I_{xx(EXP)}$ Second moment of area with respect to $x$-axis obtained from experimental tests
$I_{xx(FEA)}$ Second moment of area with respect to $x$-axis obtained from finite element analyses
$I_{xx(THEOR)}$ Second moment of area with respect to $x$-axis obtained from theoretical equations
L Beam length/span
M Bending moment
$M_o$ Moment measured in sectorial coordinate-$\omega$
$M_Y$ Yield moment
$M_U$ Ultimate moment
P Load applied on compression flange
$p$ Loading position on vertically corrugated web beam
r Corrugation radius
$r_i$ Inner radius/minor radius of arc
$r_o$ Outer radius/major radius of arc
S Elastic section modulus
t Web thickness at cross section
t_f Flange thickness
t_w Web thickness
V Volume
W Specific weight
w Weight per unit length
$\omega$ Sectorial coordinate
$\lambda$ Cycle length
$\sigma$ Direct stress
$\sigma_{max}$ Maximum bending stress
$\sigma_U$ Ultimate strength
$\sigma_Y$ Yield stress
$\delta$ Displacement
AISC American Institute of Steel Construction
ASD Allowable Stress Design
LRFD Load and Resistance Factor Design
CHAPTER 1

INTRODUCTION

1.1 Types of Structural Beams

Structural beams are common building materials and normally made of steel. In order to simplify the design and construction process, all characteristics or geometries of the beams are specified in accordance to the approved standards such as the American Iron and Steel Institute (AISI), American Society for Testing and Materials (ASTM) and British Standards (BS). The common commercial structural shapes available are hot-rolled cross sections (such as wide-flange, channels and angles), pipe and hollow structural sections (HSS).

1.2 Ordinary I-Section Beams

The I-section beam or H-pile plays an important role in the construction industry for building of structures such as bridges, water tank supports and towers. Its uniqueness in shape, which consists of two parallel flanges and a slender web, creates more versatility to suit most working environments. It is commonly made from steel materials through hot or cold form-rolling process of steel bloom.

In line with the development of construction and manufacturing industries, higher requirement and quality standard sets for these beams is essential. Designers and manufacturers have used numerous ways in producing an ideal beam that is safer, reliable and economical in materials and production cost. These include modifying
the ordinary shape of the beam and optimising the sizes to suit the demand. For instance, the hollow flange beam (HFB) was introduced in replacing the conventional beam type in certain application and usage of external or internal stiffeners to produce stronger structures.

However, these alternatives seem to be more expensive and added extra weight to the structure, making it impractical when delivery of materials is concerned. Some even appear to have contributed insignificant improvement to the beam's performance in comparison to the ordinary one.

1.3 Corrugated Web Beams

The beams with wholly corrugated web (WCW) has been introduced and used in building and construction industries. It could economise on materials and yet stronger in strength than the conventional beams. However, the information relevant to its mechanical behaviour and limitation in practice is inadequate. The effects of the corrugation parameters and beams' dimensions to the bending performance are still scarce.

Recently, as its application grew in many industries, especially construction, these parameters have been the main research subjects. The preliminary studies being carried out on such beams were mainly concentrated on the trapezoidal corrugation in the vertical direction. With reference to the available data from both experimental and analytical works, the corrugation has contributed equal stability to the web
regardless of the materials thickness. This applies for the major loading modes like bending, shearing and buckling.

However, manufacturing of these beams is difficult and bounded by the limitation and tolerances of the process, which would limit its usage in practice. This is especially true when standardization of sizes is concerned.

1.4 Manufacturing Process of the Corrugated Web Beams

The general shape-rolling process adopted for the ordinary beams with flat web cannot be implemented for the trapezoidal corrugated web type. At present, the web is welded continuously at the joints on the two flanges that produce an I-cross section. Nevertheless, strong joints could hardly be produced for beams with thinner web, even by the use of state of art welding technology that could possibly do the job. Higher cost will certainly be incurred that make it impractical especially for a longer span.

Thus, the curve wave-like corrugation was introduced to substitute the trapezoidal corrugation, as it seems more suitable to be manufactured. However, to date, the same welding method is being used in producing this corrugation shape where the hot rolled beam of the similar type has yet been produced by any manufacturer. Although, few successful in laboratory trials have been seen in some research works, but the design of the roll process and tools are not fully addressed. The design requirements of the roll tool for corrugated web beams are outlined as follow.