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FLEXURAL BEHAVIOUR OF COLD FORM STEEL OF STRUCTURES

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1.INTRODUCTION

1.1. BACK GROUND

Two main types of steel sections are currently used in building construction, namely, the hot-rolled and cold-formed sections (see Figures 1.1 (a) and (b)). The use of cold-formed steel sections has increased considerably as the world steel industry moves from the production of hot-rolled sections and plates to coil and strip, often with galvanised and painted coating. Steel in this form is more easily delivered from the steel mill to the manufacturing plant where it is usually cold-rolled into open and closed section members (see Figure 1.1 (c)). Compared with the conventional hot-rolled steel members, the cold-formed steel members have the advantages of easier delivery as mentioned above, enhancement of the tensile properties after cold-forming, lower weight (higher strength to weight ratio) and faster and simpler installation.

Unlike hot-rolled steel sections, the cold-formed steel sections are usually slender(thinner) and not doubly symmetric and hence they are susceptible to a range ofcomplicated buckling modes and their interactions. This has led researchers to focuson the steel sections with torsionally rigid hollow flanges in order to overcome theseproblems more effectively. O'connor et al. (1965) concluded that the improvement was due tothe increase in torsional rigidity. However, they did not consider the feasibility ofproducing such hollow sections.

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c) COLD FORMED STEEL MEMBERS USED IN BUILDING CONSTRUCTION

FIG 1.1 STEEL SECTIONS USED IN BUILDING CONSTRUCTION

Palmer Tube Mills Pty. Ltd. was the first to take advantage of this concept byproducing cold-formed, high strength steel sections with two closed triangularhollow flanges during the mid-1990s. These sections were called the hollow flangebeams (HFB) as shown in Figure 1.1 and were manufactured using a combinedcold-forming and electric resistance welding process. The HFB is a good example ofcold-formed steel sections with torsionally rigid hollow flanges. The HFB wasprimarily intended for flexural members and is ideal for use as portal frames in ruraland light industrial buildings. This new product was a result of the obviousinspiration of using an economical and effective I-beam in which the flanges providemost of the bending capacity whereas the web provides most of the shear capacity.

The HFB has the same advantages as an I-beam because the thin web saves materialyet is still able to provide the required shear strength. Furthermore, the inclusion ofclosed flanges improves both the torsional rigidity and local buckling behaviour. Thedoubly symmetric section shape can delay or eliminate some of the buckling modescommonly encountered by the conventional cold-formed open sections such as C-,hat and Z-sections. Earlier research conducted by Dempsey (1990) also showed thatHFBs were generally about 40% lighter than the hot-rolled sections, and performedbetter than the cold-formed C- and double C-sections. Consequently, the HFB can beconsidered to combine the benefits of hot-rolled I-sections with the high strength toweight ratio of conventional cold-formed sections.

The Hollow Flange Beam was released into the Australian markets in

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December1993. The section is defined by its depth, the flange width and the thickness, whichare expressed in the product designation as seen in Figure 1.2. For example,20090HFB28, where 200 means 200 mm depth, 90 means 90 mm flange width, HFBrefers to hollow flange beam and 28 means 2.8 mm thickness.Besides the HFB produced firstly by Palmer Tube Mills, other types of hollow flangebeam sections can be developed as shown in Figure 1.2. Preliminary investigationsinto their buckling behaviour using the finite strip analysis program THIN-WALLshows that they outperform the corresponding open sections in a similar way toHFBs. If these structurally efficient hollow flange beams can be producedeconomically, and appropriate design rules are available, they have the potential toreplace the currently used hot-rolled I-sections and cold-formed C- and Z-sections.

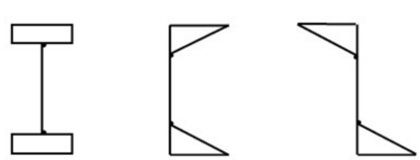

FIG 1.2 OTHER TYPES OF SECTIONS WITH TORSIONALLY RIGID HOLLOW FLANGES(single plate)

1.2 PROBLEM DEFINITION

The unique cross-sectional geometry and the complicated manufacturing process(cold-forming followed by electric resistance welding, which causes a complexdistribution of residual stresses) also make HFBs unique. The HFBs do not readilycomply with the current steel structural design standards such as AS/NZS 4600 (SA,1996) and AS 4100 (SA, 1998). Secondly, with a high torsional rigidity due to itstwo rigid triangular flanges, the flexural torsional buckling problem can be improved,but the HFB flexural member tends to undergo lateral distortional buckling failuresassociated with web distortion due to its relatively slender web. The use of suitableweb stiffeners will eliminate this problem (Avery and Mahendran, 1998), but somedesigners may not choose this option. Thirdly, even though the electric resistancewelding (ERW) method used by Palmer Tube Mills is adequate, it makes themanufacturing process complicated and expensive. This was one of the reasons

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forthe discontinuation of Palmer Tube Mill's Hollow Flange Beams in 1997. Hence theuse of new self piercing rivets (or self-drilling screws or spot welds), as shown inFigure 1.4, was considered to manufacture these advanced cold-formed hollowflange beams. Figures 1.4 (a) and (b) show the sections with triangular andrectangular hollow flanges made from a single plate while Figure 1.5 (c) shows thesection with rectangular hollow flanges made from three plates.

1.3 RESEARCH OBJECTIVES

Based on the identified problems discussed in the previous section, the overallobjective of this research was to investigate the buckling and ultimate strengthbehaviour of the advanced cold-formed steel sections with torsionally rigid hollowflanges (both triangular and rectangular) under axial compression including theeffects of different manufacturing methods (electric resistance welding, self-piercedriveting, screw fastening or spot-welding), and develop appropriate design methods.

Specific objectives of this research were as follows:

1.To conduct full-scale tests of the cold-formed steel sections with torsionally rigid hollow flanges under axial compression to study the buckling and ultimate Strength behaviour caused by local buckling/yielding and to assess the ultimate strength of these compression members. The effect of different fastening methods will be investigated. Tensile coupon tests of steel plates will also be undertaken.

2.To develop finite element analysis (FEA) models for all the possible steel sections with torsionally rigid hollow flanges and validate them using experimental results.

3.To use the FEA models to undertake a comprehensive parametric study to investigate all the possible parameters which were expected to affect the failure loads and the behaviour of cold-formed steel members with torsionally rigid hollow flanges.

The parameters include:

A. Method of fabrication including the number of plates for fabrication (single or three) and fastening methods (continuous electric resistance welds, lap-welds, self-

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piercing rivets or self-drilling screws or spot-welds).

B. Fastener size and spacing.
C. Section geometry.
D. Steel plate thickness.
E. Steel properties including yield stress and elastic modulus
F. To compare the FEA and experimental results with the predictions from currentdesign rules based on which to develop or propose new design procedures forthe different types of steel sections with torsionally rigid hollow flanges underaxial compression.

1.8 ADVANTAGES OF COLD FORMED SECTIONS

Cold forming has the effect of increasing the yield strength of steel, the increase being the consequence of cold working well into the strain-hardening range. These increases are predominant in zones where the metal is bent by folding. The effect of cold working is thus to enhance the mean yield stress by 15% - 30%. For purposes of design, the yield stress may be regarded as having been enhanced by a minimum of 15%. Some of the main advantages of cold rolled sections, as compared with their hot-rolled counterparts are as follows:

• Cross sectional shapes are formed to close tolerances and these can beconsistently repeated for as long as required.

• Cold rolling can be employed to produce almost any desired shape to anydesired length.

• Pre-galvanised or pre-coated metals can be formed, so that high resistance tocorrosion, besides an attractive surface finish, can be achieved.

• All conventional jointing methods, (i.e. riveting, bolting, welding andadhesives) can be employed.

• High strength to weight ratio is achieved in cold-rolled products.

• They are usually light making it easy to transport and erect.

It is possible to displace the material far away from the neutral axis inorder to enhance the load carrying capacity (particularly in beams).There is almost no limit to the type of cross section that can be formed. It is obvious thatthinner the section walls, the larger will be the corresponding moment of inertiavalues (Ixx and Iyy) and

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hence capable of resisting greater bending moments. Theconsequent reduction in the weight of steel in general applications produceseconomies both in steel costs as well as in the costs of handling transportationand erection. This, indeed, is one of the main reasons for the popularity and theconsequent growth in the use of cold rolled steel. Also cold form steel isprotected against corrosion by proper galvanising or powder coating in thefactory itself. Usually a thickness limitation is also imposed, for components likelipped channels.

2. LITERATURE REVIEW

These investigations are described briefly as follows.

1.Geometry optimisation and section properties (Dempsey, 1990, 1991). Their study confirmed the choice of a triangular shaped flange and associated dimensions. A performance comparison with other structural steel sections for which the ERW-HFB may be substituted was also carried out. The ERW-HFBs were generally found to be 40% lighter than the hot-rolled sections and performed better than the conventional cold-formed C- and double C-sections.

2.ERW-HFB Design Manuals (Dempsey, 1993). These design manuals were based on a conservative design approach using the cold-formed steel structures code AS1538 (SA, 1988) due to the limited test and analytical results for the ERW- HFBs.

3.Buckling analysis of the ERW-HFBs (Heldt and Mahendran, 1992). This study was based on a linear buckling analysis program, and hence had its limitations. It was also aimed at developing an ERW-HFB purlin system rather than fully understanding the buckling characteristics of the ERW-HFBs. The study showed that tension flange restraint could improve significantly the lateral buckling behaviour of ERW-HFBs. But this important outcome requires further verification.

2.1 SPECIAL CHARACTERISTICS OF COLD-FORMED STEEL MEMBERS

2.1.1 GENERAL

Cold-formed steel structural members have many advantages in applicationscompared with conventional hot-rolled steel members. However, the

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cold-formedsections are usually thinner than hot-rolled sections and hence have a variety ofinstability problems which are not commonly encountered in normal structural steeldesign. In addition, the cold-forming process often produces structural imperfectionsand residual stresses which are quite different from those of traditional hot-rolled andwelded members. Consequently, design specifications are required specially for cold-formed structural members.

2.1.2 COLD-FORMING PROCESSES

In general, cold-formed steel members are manufactured by one of the two processesthat are roll forming and brake pressing. Roll forming consists offeeding a continuous steel strip through a series of opposing rolls to deform the steelplastically to form the desired shapes. It is often used to produce sections where largequantities of a given shape are required. The shortcoming of roll forming is the highinitial costs and the difficulty of changing to a different size section. Brake pressingnormally involves producing one complete fold at a time along the full length of asection. Usually for sections with several folds, it is necessary to move the steel platein the press and to repeat the pressing operation several times. Therefore brakepressing can be used to produce a variety of shapes with low volume production. Butthe problems of this method are higher labour fees and the limitation of producingcontinuous lengths about 5 metres compared with roll forming method.

2.1.3. MECHANICAL PROPERTIES

The mechanical properties of the steel sections are affected by the cold work of forming, in particular in the regions of bends. In these regions, the material ultimate tensile strength and yield strength are enhanced. The enhanced yield strength of the steel may be included in the design based on Clause 1.5.1.3 of AS/NZS 4600 (SA, 1996). In particular, for cold-formed square, rectangular or dog-bone hollow sections, the flat faces will also have undergone cold work as a result of forming the section into one or two circular tubes and then reworking it into the desired shape. In this case, it is hard to compute theoretically the enhancement of yield strength in the flats and so a reliable experimental test is needed.

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2.1.4. INSTABILITY PROBLEMS

2.2.4.1 General

The plates are joined along their edges and form different shapes dependingon the purpose of use. The common property of thin-walled structures is that they aremuch lighter than other alternative structures. Some of these shapes such as boxgirders have high torsional rigidity, and others such as plate girders have high in-plane rigidity but low out-of-plane rigidity. As the structures become more slender,they suddenly fail by out-of-plane buckling under certain magnitudes of compressiveand/or bending actions. The phenomenon of twisting and deflecting laterally out-of-plane is called flexural-torsional bucking which is described in a number of books onsteel structures (Trahair and Bradford, 1988). Trahair (1993) describes differenttypes of buckling including:

1. Flexural buckling is resisted by the flexural rigidity EI_y and EI_x of the member. Flexural buckling occurs when the second-order moments caused by the product of the axial compression force P with the transverse displacements u or v are equal to the internal resistance moment $EI_y d^2u/dz^2$ (see Figure 2.5a).
2. Flexural torsional buckling occurs when the external work caused by bothdisplacement u, v and twist rotations φ are resisted by the combinations of thebending resistances $EI_y d^2u/dz^2$ and $-EI_x d^2v/dz^2$ and the torsional resistances$GJ d\varphi/dz$ and $-EI_w d^3\varphi/dz^3$ (Figure 2.5b).
3. Torsional buckling occurs when second order torques $P\gamma_{02}\, d\varphi/dz$ caused bythe axial compression force P and the twist $d\varphi/dz$ are equal to the sum of theinternal torsion resistances $GJ d\varphi/dz$ and $-EI_w d^3\varphi/dz^3$ (Figure 2.5c). GJ is thetorsional rigidity and EI_w is the warping rigidity of the member.
4. Distortional buckling describes a buckling mode intermediate between thoseof local and flexural buckling. It involves web flexure and correspondingrotation of the flanges which vary along the member length.
5. Considering the relevance to this research project, local buckling, distortionalbuckling, flexural buckling and flexural-torsional buckling of compression membersare discussed in the following sections.

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2.2 DESIGN OF COMPRESSION MEMBERS

Generally, compression members can be classified into three regions, i.e., short, longand intermediate members. Short columns are dominated by the strength limit of thematerial (σc = F/A). Long columns are governed by the elastic limits (Euler'sformula). Intermediate columns are bounded by the inelastic limit of the member,which are normally predicted by using tangent modulus theory or reduced tangentmodulus theory.

2.3 CONNECTIONS

The behaviour of connections is extremely important in structural design, influencingboth the structural efficiency and cost. Due to the comparative thinness of thematerial, connection technology plays an important role in the development ofstructures formed using cold-formed sections. The conventional methods ofconnection, such as bolting and arc-welding are, of course, available but aregenerally less appropriate and the new special techniques are more suited to thinmaterial in the face of tremendous pressure on the construction industry to reducecost, improve quality, and build faster. Light duty connection methods such as spot-welding, self-pierced riveting and screwing are the newfastening technologies, which can be used for HFBs to replace the conventionalcontinuous welding method. It will be discussed in the following section.

2.4 FINDING FROM THE LITERATURE REVIEW

A comprehensive literature review as described in the above sections of this chapterhas enabled the accumulation of the required knowledge for this research. The ERW-HFBs were reviewed first in this chapter to gain a preliminary understanding of thisresearch. The chapter presented the characteristics of the cold-formed steel structuresincluding the forming process and material properties, the geometric imperfectionsand residual stresses, the instability problems such as local buckling, distortionalbuckling and global buckling. The theory and the current design procedures forcompression members were also reviewed. Furthermore, the analytical methods,experimental and finite element

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analysis methods and their applications were alsodiscussed in the last part of the chapter. Following is a summary of the findings fromthe literature review.

1. The ERW-HFBs developed by Palmer Tube Mills are the only structural products of the cold-formed steel sections with torsionally rigid hollow flanges to date. Very limited studies have been conducted to investigate the flexural and compressive behaviour of the sections with torsionally rigid hollow flanges.
2. Current steel design codes do not cover the ERW-HFBs as flexural and compression members. Avery et al. (2000) found that the ERW-HFBs did not comply with the current design codes due to their unique manufacturing procedures and shape.
3. The residual stresses in the ERW-HFBs caused by the continuous electric resistance welding are higher than that in the traditional cold-formed steel sections. Fastening methods using screws, self-piercing rivets and spot-welds are commonly used in the cold-formed steel structures. These fasteners could be used to replace the electric resistance welding method used in the ERW-HFBs.