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DESIGN OF C- SECTIONS AGAINST DEFORMATIONAL LIP BUCKLING

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ABSTRACT

Deformational lip buckling is one of the considerations affecting the choice of cross-section dimensions which were adopted for the C-section chord members of a space frame system. No guidance on lip buckling of channel sections is given in the current British design specification. A method was therefore required for determining the lip buckling resistance of the members when subjected to axial compression or bending. A design procedure was formulated in which the lips are represented as a strut on an elastic foundation, the stiffness of which depends on the deformational stiffness of the section. The critical buckling stress and the wavelength of buckling can then be determined. By assigning imperfections to the nominally straight lips, the critical lip buckling stress can be introduced into the Perry-Roberston formulation for the strength of columns, and the lip buckling strength can be estimated. Comparative results from the design formulation, experiments, and non-linear elasto-plastic finite element analysis are given. It is shown that the proposed design model is satisfactory but conservative.

1 INTRODUCTION

The Harley space frame was invented in 1980 by an Australian architect, Edwin Codd. He identified three essential requirements: that the connections and construction be simple, that the components be amenable to automated production, and that the resulting system be cost effective. These considerations led to the use of chords consisting of orthogonally intersecting back-to-back channels, and tubular diagonals whose flattened ends are clamped between the channels as shown in Figure 1. The continuity of the chords at the nodes enables the eccentricity moments to be resisted. An equal square-on-square arrangement is commonly used but other arrangements are possible. Many such structures have been built in Australia.

The Harley space frame system was introduced into the European market by the Conder Group in 1989. Conder approached Imperial College to formulate and validate design rules which would accord with European practice and loading, and which would permit the use of increased spans and nodal distances.

From the outset it was apparent that various phenomena existing in the Harley frame were not covered by the British design code BS5950 (1987). A series of experiments on frames and components were conducted concurrently with numerical analysis and with the formulation of design rules. The three activities were mutually beneficial in providing insight as well as quantitative data into the local and overall buckling behaviour of cold-

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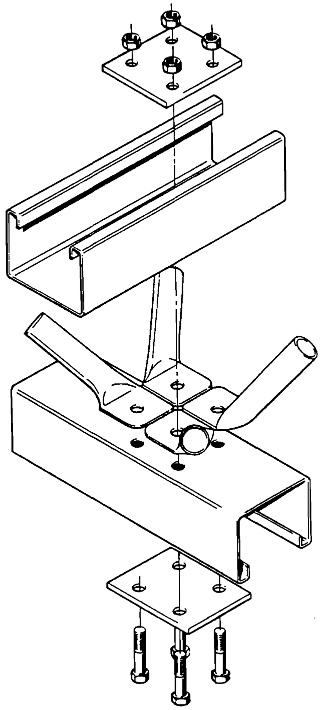


Figure 1 Typical Space Frame Node

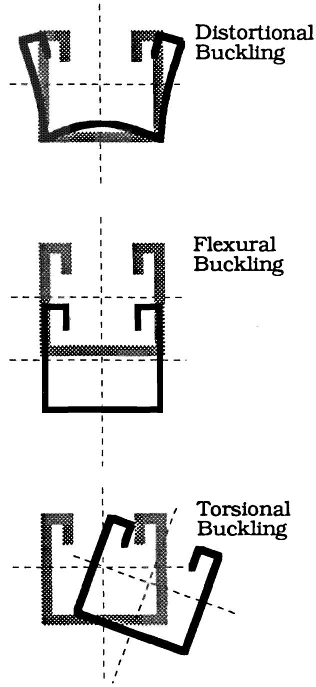


Figure 2 Buckling Modes

formed channel sections. Some of the phenomena studied were specific to the Conder-Harley frame, but several can occur in other structures having cold-formed components.

Lip buckling involves deformation of the cross-section (Figure 2), unlike flexural buckling or torsional buckling of thin-walled open sections. The wavelength of lip buckling is usually intermediate between the wavelength of local buckling of the table and webs of the section and the wavelength of overall buckling. Lip buckling resistance is introduced as a chord property at the beginning of the chord strength calculation, and a simple treatment was required at an early stage of design development. This paper presents the method adopted.

A subsequent literature search showed that Douty (1962) and Haussler (1964) had used a similar strut on an elastic foundation idealisation to determine the distortional lip buckling stress (Yu 1991). Desmond et al (1981), Hancock (1985), Lau and Hancock (1988), Seah and Rhodes (1990), and Seah et al (1991) have all suggested variations of a modified effective width approach, whilst explicit analytical expressions based on an approximate distortional buckling model have been derived to predict the ultimate lip buckling stress of thin-walled columns and beams by Hancock (1987) and Serrette and Pekoz (1991).

In this paper, lip buckling strength is estimated on the basis of a notional imperfection. This approach is consistent with the method of column design which is well established in the UK and also permits comparison with finite element analysis in which the same imperfection is assumed. Initial verification of the critical stress idealization and the imperfection approach as applied to the particular cross-section which it was proposed to use, was provided by experimental results. Subsequently, verification over a wider geometrical range was provided by non-linear elasto-plastic finite element analysis. It was assumed that the deformational stiffness of the cross-section would not be diminished as a result of local buckling of the table and webs of the section, provided that the local buckling wavelength was small compared to the lip buckling wavelength. An additional purpose of the investigation was to determine whether that assumption was justified.

It was also assumed that the lip buckling resistance would be the same whether the compressive stress resulted from compression or from bending. Both forms of loading were therefore considered.

2 DESIGN MODEL

Lip buckling is caused by compression in the lip, and is restrained by the deformational stiffness of the section. The lip can therefore be idealised as a strut with continuous elastic restraint. The "strut" is not of course a separate entity, and its assumed effective extent required verification. A disturbing force F has been assumed to act at the centroid of the lip section, and to cause a unit deflection Δ (Figure 3). The transverse stiffness is assumed to be that of uncoupled transverse strips of unit width, which gives a conservative estimate of the actual stiffness. No distinction is made between lip stress caused by axial compression or by bending. The mid-thickness dimensions of the section, as shown in Figure 3, are used in evaluating the lip buckling stress.

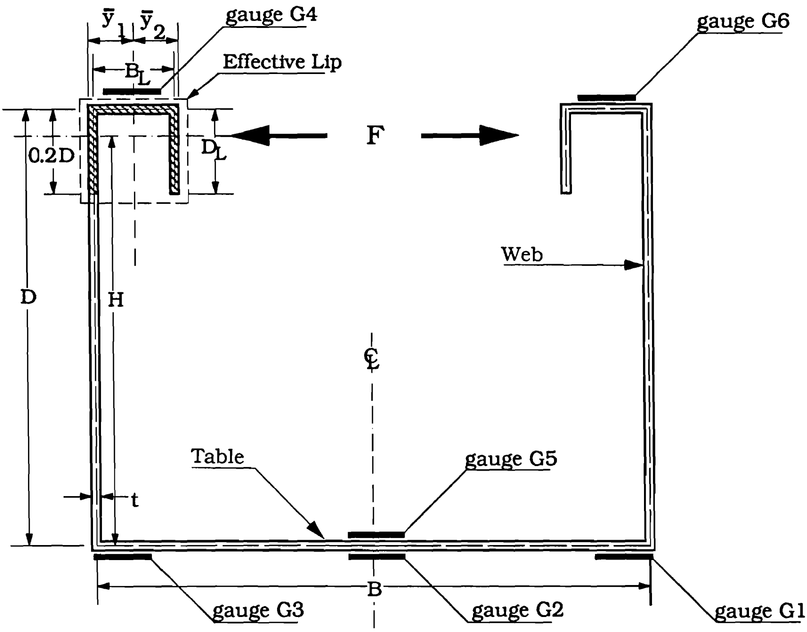


Figure 3 Channel section - Strain Gauge Positions

The resistance given by the transverse stiffness can be expressed as a "foundation modulus" β

$$\beta = \frac{E\,t^3}{2H^2\left(1-v^2\right)[3B+2H]} \qquad \ldots(1)$$

where

β=F/Δ Foundation modulus
B Breadth of section to mid thickness
F Disturbing force per unit length
H Height of the lip centroid above the mid thickness of the table
E Modulus of elasticity (205 kN/mm^2)
t Thickness of section
Δ Transverse deflection caused by force F
v Poisson's Ratio

The elastic critical buckling stress for a long strut on an elastic foundation, in which the preferred wave length is free to develop, is given by (Timosenko,1963).

$$\sigma_{crL} = \frac{2\left(E\,I_L\,\beta\right)^{1/2}}{A_L} \qquad \ldots(2)$$

Alternatively

$$\sigma_{crL} = 2\,r_L\left(\frac{E\,\beta}{A_L}\right)^{1/2} \qquad \ldots(3)$$

where

A_L Effective area of lip
I_L Second moment of area of lip about the local Y axis of effective lip
r_L Radius of gyration of lip about Y axis
σ_{crL} Elastic critical lip buckling stress

It can be seen from Equation 3 that for a given β and A_L, σ_{cr} is proportional to r_L. The preferred half wave length of buckling for a long strut is

$$L_B = \left(\frac{\pi^4\,E\,I_L}{\beta}\right)^{1/4} \qquad \ldots(4)$$

For a finite length of member the number of half waves m must be an integer. The preferred number of half waves is then obtained by minimising the critical elastic lip buckling stress given by Equation 5 with respect to L_{cr}.

$$\sigma_{crL} = \frac{\pi^2 E}{\left(\frac{L_{cr}}{r_L}\right)^2}\left(1+\frac{\beta\,L_{cr}^4}{\pi^4\,E\,I_L}\right) = \frac{\pi^2 E}{\left(\frac{L_{cr}}{r_L}\right)^2}\left(1+\left(\frac{L_{cr}}{L_B}\right)^4\right) \qquad \ldots(5)$$

where L_{cr} is the half wave length for lip buckling, and L_{cr} = L/m

The lip buckling stress of a section may be increased by providing point restraints to the lip L_R apart, where L_R is less than L_{cr}. The critical elastic lip buckling stress can then be found from Equation 5 writing $L_{cr} = L_R$.

The resistance of a section to lip buckling is assumed to be given by a modified Perry-Robertson formulation, in which the imperfection parameter η has been chosen by reference to experimental and finite element results.

$$\sigma_{uL} = \frac{1}{2}\left[\left\{\sigma_d + (1+\eta)\,\sigma_{crL}\right\} - \left[\left\{\sigma_d + (1+\eta)\,\sigma_{crL}\right\}^2 - 4\,\sigma_d\,\sigma_{crL}\right]^{1/2}\right] \qquad \ldots(6)$$

where

σ_{uL} Lip strength
σ_d Design strength (the smaller of σ_o or 0.84 σ_u)
σ_{crL} Obtained from Equations 3 or 5
η Imperfection parameter, based on test results and numerical analysis

$$\text{For} \quad \frac{L_{cr}}{r_L} \le C\left(\frac{\ell}{r_L}\right)_o, \quad \eta = 0$$

and

$$\text{For} \quad \frac{L_{cr}}{r_L} \ge C\left(\frac{\ell}{r_L}\right)_o, \quad \eta = \frac{2\bar{y}}{B_L}\,0.002\left(\frac{L_{cr}}{r_L} - C\left(\frac{\ell}{r_L}\right)_o\right)$$

where the critical slenderness is

$$\left(\frac{\ell}{r_L}\right)_o = \left(\frac{2\pi^2 E}{\sigma_o}\right)^{1/2}$$

and

C A constant which defines the value of L_B / r_L at which the resistance is equal to the yield stress
$\bar{y}$ The greater distance of $\overline{y_1}$ or $\overline{y_2}$ from the vertical lip centroidal axis to the vertical surface of the lip (Figure 3)
B_L Breadth of lip to mid thickness
ℓ Lip half wave of buckling
L_{cr} Either L_B, L/m or L_R
$\left(\frac{\ell}{r_L}\right)_o$ The critical slenderness - the slenderness for which the critical buckling stress σ_{crL} is equal to the yield stress σ_o.

The constant 0.002 is chosen to conform to current UK formulations for column design. For design purposes, the applied stress is taken as the stress acting at the mid-thickness of the lip table. The constant C determines the ratio ℓ/r_L at which the resistance to lip buckling becomes equal to the yield stress. The limiting slenderness must be less than the critical slenderness $(\ell/r_L)_o$. The relation between design strength and ultimate stress is shown in Figure 4.

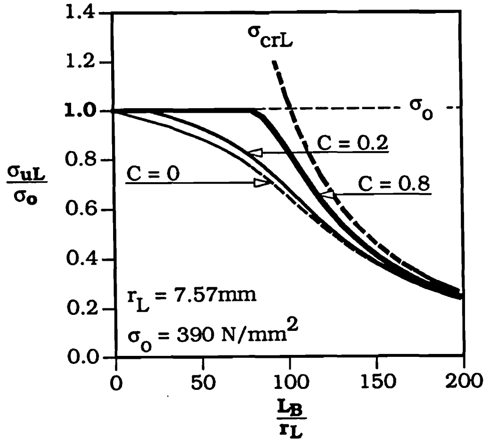


Figure 4 The effect of imperfection parameter C on the Design Ultimate Stress σ_{uL} (Equation 6)

3 CRITICAL ELASTIC BUCKLING

Critical buckling solutions were obtained using a general purpose non-linear elasto-plastic finite element program FINASIC (1990). FINASIC employs doubly-curved, eight-noded isoparametric shell elements having six degrees of freedom per node. The element formulation is based on Mindlin theory which assumes that the out-of-plane direct stress is zero and the out-of-plane shear stress is constant through the thickness. The member analysed was 122mm wide and 1220mm long. The depth and thickness were varied. The purpose was to examine the validity of Equations 1 to 5. The length was chosen such that sufficient elements could be used to describe local buckling as well as lip buckling. Possible interaction between the two buckling modes would then be revealed in the non-linear solutions for initially imperfect members. The symmetric nature of the buckling modes permitted modelling of half the cross-section. For axially loaded members, overall bending and rotation of the section were prevented, whilst for sections subject to uniform bending, overall rotation was prevented. Deformation of the cross-section was prevented at each end, but the lip was allowed to rotate in plan.

For sections having large width to thickness ratios the first and many subsequent buckling modes (eigenvectors) correspond to local buckling of the table, with smaller carry-over deformations of the webs and lips. The critical lip buckling stress is given by the first eigenvector which displays overall lip buckling. The lowest mode (local buckling), as well as the critical lip buckling modes for a 122mm x 97mm x 1.5mm thick section, are illustrated in Figure 5. Overall lip buckling of this section occurred as the 22nd mode. For the given range of thicknesses and depths, the first lip buckling mode was a single half wave, except for those cases noted in Figure 6, which compares the critical stress for axial loading with that given by Equation 5. As the pre-buckling stress distribution is uniform, the critical lip buckling stress is given by the axial load divided by the gross cross-sectional area.

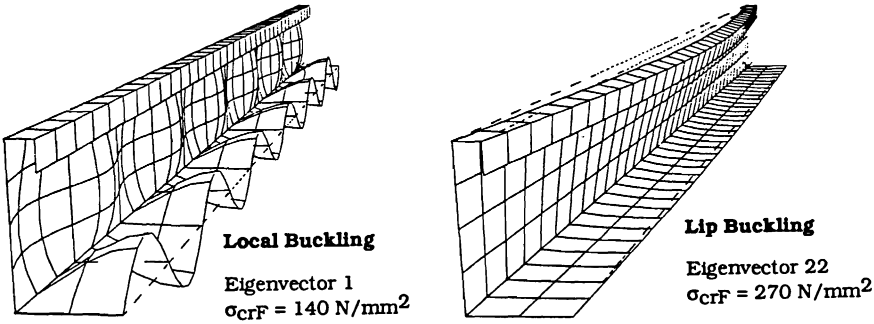


Figure 5 122 x 97 x 17 x 18.5 - 1.5 mm thick channel buckling modes

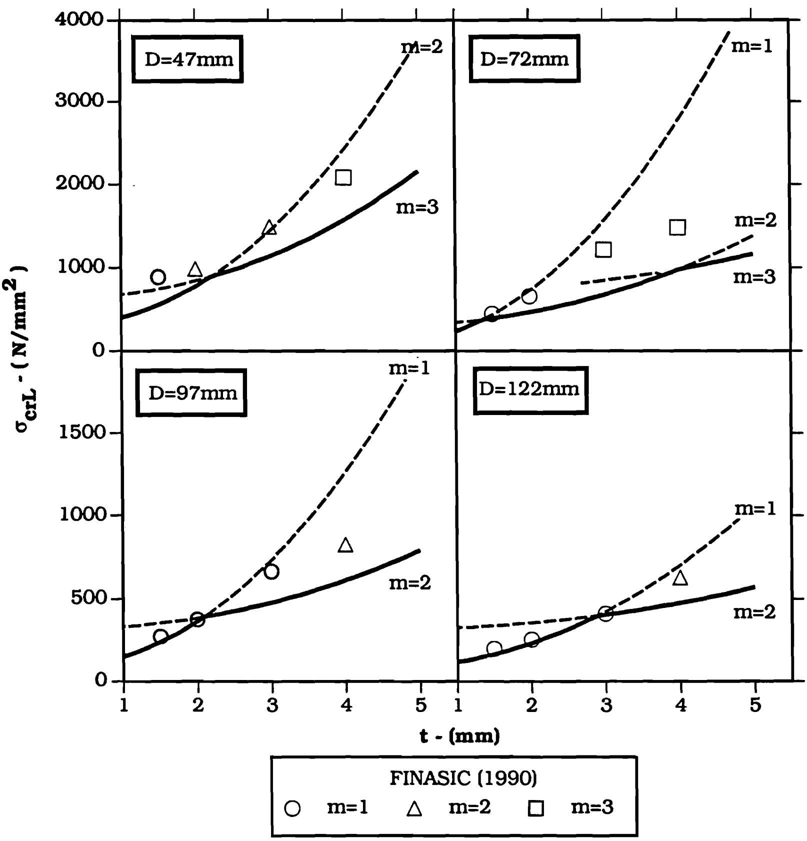


Figure 6 Comparison Equation 5 with Finite Element Analysis, Axial Loading (B=122mm, B_L=17mm, D_L=18.5mm, L=1220mm)

Bending solutions were also obtained for the 122 x 97 section, for four different thicknesses. The results are compared with Equation 5 and with results for axial loading in Figure 7. The critical bending stress is taken as the critical moment divided by the gross section modulus at the mid thickness of the lip table. As expected, the critical stresses (so calculated) for bending are higher than for axial loading.

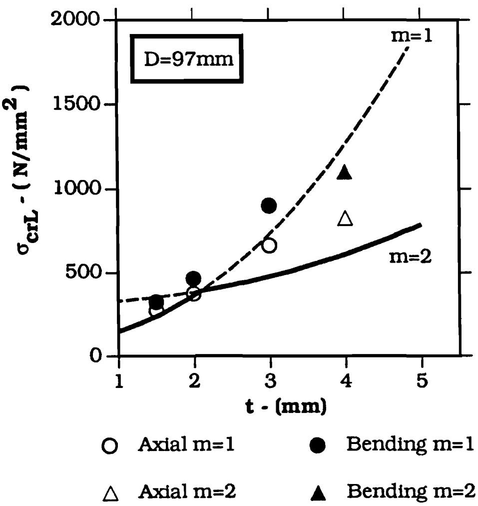


Figure 7 Comparison of Equation 5 for Axial and Bending Loads with Finite Element Analysis (B=122mm, B_L=17mm, D_L=18.5mm, L=1220mm)

For axially loaded members, the lip buckling displacement described by the eigenvector was in most cases inwards but in some instances the displacement was outward. For bending the lip displacement was always inwards. If the effective lip is symmetric about the vertical axis, the centroid and the shear centre will both be on that axis, and the lip will have no preferred direction of buckling. If the shear centre is not on the centroidal axis the tendency for torsional buckling will predispose the lip to rotate in one direction or the other. For the lip considered, where the downturn is 20mm, it might be supposed that the direction of buckling is not strongly predisposed.

The effect of variations in thickness for a given depth, and of variations in depth for a given thickness, on the preferred wave length and on the corresponding critical stress, according to Equations 3 and 4, are shown in Figure 8. An axially loaded member 122mm x 97mm x 3mm thick, 3 metres long was also analysed. The first lip buckling mode had three half waves (P_{crF} = 674 kN) whilst the second had four half waves (P_{crF} =684 kN). The critical stresses for both the lip buckling modes are compared with Equation 5 in Table 1.

The agreement between Equation 5 and the finite element solutions could probably be improved by adjusting the assumed extent of the web contributing to the effective lip, the level at which the disturbing forces is assumed to act, and the level at which the bending stress is calculated. The effect of coupling the transverse strips might also be included at the cost of complicating the model. However, the present model is satisfactory for the sections considered, remembering that the model for estimating the lip buckling resistance of a section must also incorporate assumptions regarding magnitude and mode of initial imperfection.

m	$\frac{L}{m}$ (mm)	σ_{crF} (N/mm^2)	$\frac{\sigma_{crF}}{\sigma_{crL}}$
3	1000	581	1.08
4	750	589	1.32

Table 1 Comparison of Critical Lip Buckling stress (FE analysis) with Design Model
122mm x 97mm x 17mm x 18.5mm - 3mm thick, L = 3000mm,

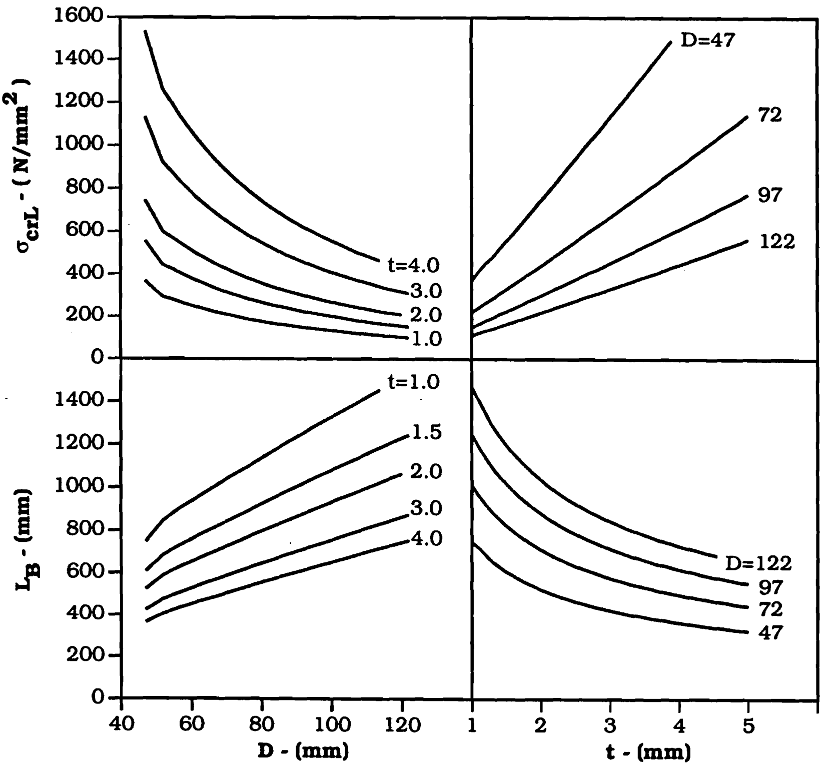


Figure 8 Variation of Critical Buckling Stress and Critical Lip Buckling Length with D and t (Equations 3 and 4)
(B=122mm, B_L=17mm, D_L=18.5mm)

4 NON-LINEAR ELASTO-PLASTIC ANALYSIS

The same sections were also analysed elasto-plastically to find the axial loads and moments, and the corresponding lip stress, at first surface yield and at maximum resistance. An initial single half-wave outward lip imperfection of w_o=L/1000 was assumed for the 1220mm long members. The lip buckling stresses at first surface yield and at maximum resistance were determined. The buckling resistances were taken to be the total force on the effective lip divided by the effective area of the lip, A_L.

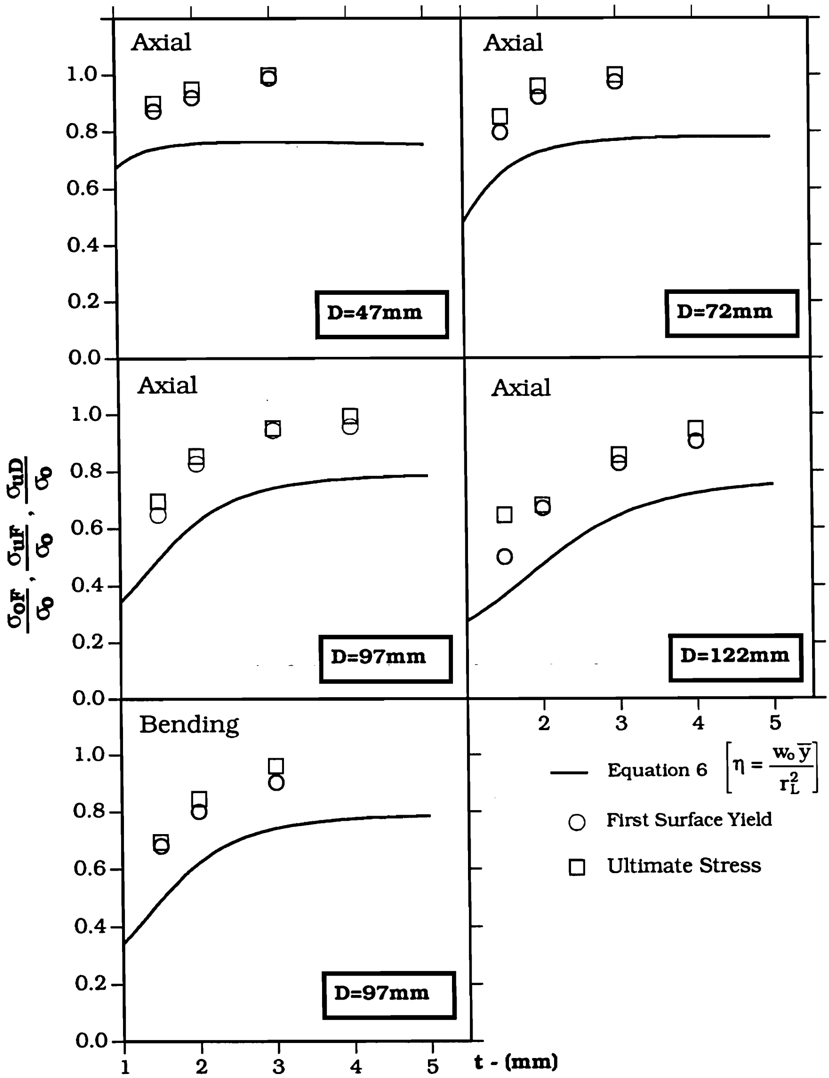


Figure 9 Comparison Equation 6 with Non-Linear Finite Element Analysis, Axial Compression and Bending

(B=122mm, B_L=17mm,D_L=18.5mm, L=1220mm, σ_o=390N/mm2, w_o=L/1000)

In Figure 9 the lip buckling resistance given by the non-linear, elasto-plastic finite element analysis is compared with the resistance given by the Perry equation (Equation 6) assuming an initial imperfection of $w_o = L/1000$, and an imperfection parameter

$$\eta = \frac{w_o \bar{y}}{r_L^2} \qquad \ldots(7)$$

It may be observed in Figure 9 that Equation 7 gives a conservative estimate of the lip buckling stress for the cross-section geometries and range of depths considered. In general, the lip deflected in the direction of the initial imperfection. However, in the case of the 122mm x 97mm x 1.5mm section, the deflection was initially outward but then changed direction, and failure occurred by inward buckling (Figure 10).

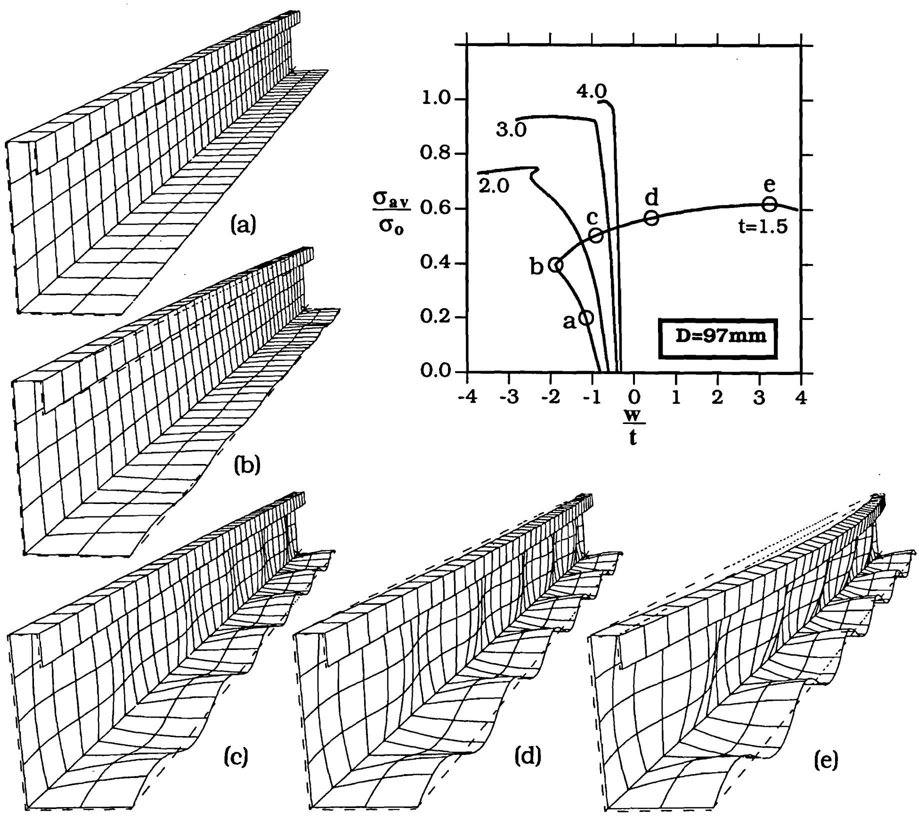


Figure 10 Lip Buckling Resistance v. Lateral Displacement w
(B=122mm, D=97mm, BL=17mm, DL=18.5mm, L=1220mm, so=390 N/mm2)

The reversal can be explained by the shift in actual vertical neutral axis of the effective lip which results from the diminishing effectiveness of the web as local buckling develops. The applied end force N_x is uniform, and initially the additional deflection w, is in the same direction as w_o. The shift in neutral axis results in a countervailing moment which causes the deflection to change direction. When w_o was increased to L/500, reversal did not occur. The rather large differences between the lip stress which causes first yield and the stress which causes failure, for the 122mm x 1.5mm section, as seen in Figure 9, is caused by the above reversal. Reversal of the lip displacement under load has also been reported by Desmond et al (1981) and Hancock (1985). TThe same members were analysed for w_o = L/500. Figure 11 shows that doubling the imperfection has a rather small effect on resistance. Equation 6 is more sensitive to w_o than are the FINASIC results.

A limited study on the effect of mode shape and magnitude of w_o, on the lip buckling resistance of a 122mm x 97mm x 3mm section 3metres long, was also carried out. The first and second eigenvectors for lip buckling obtained from the critical buckling analysis were scaled to obtain the required level of imperfection, such that w_o corresponded to η used in equation 6, and to $w_o = L_{cr}/1000$. The load-displacement history for a 3mm thick section can be seen in Figure 12. The lip buckling resistance for the alternative assumptions is shown in Table 2.

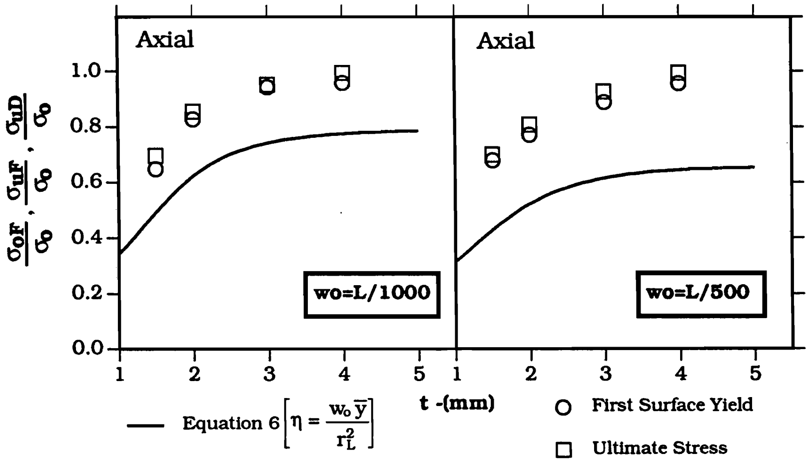


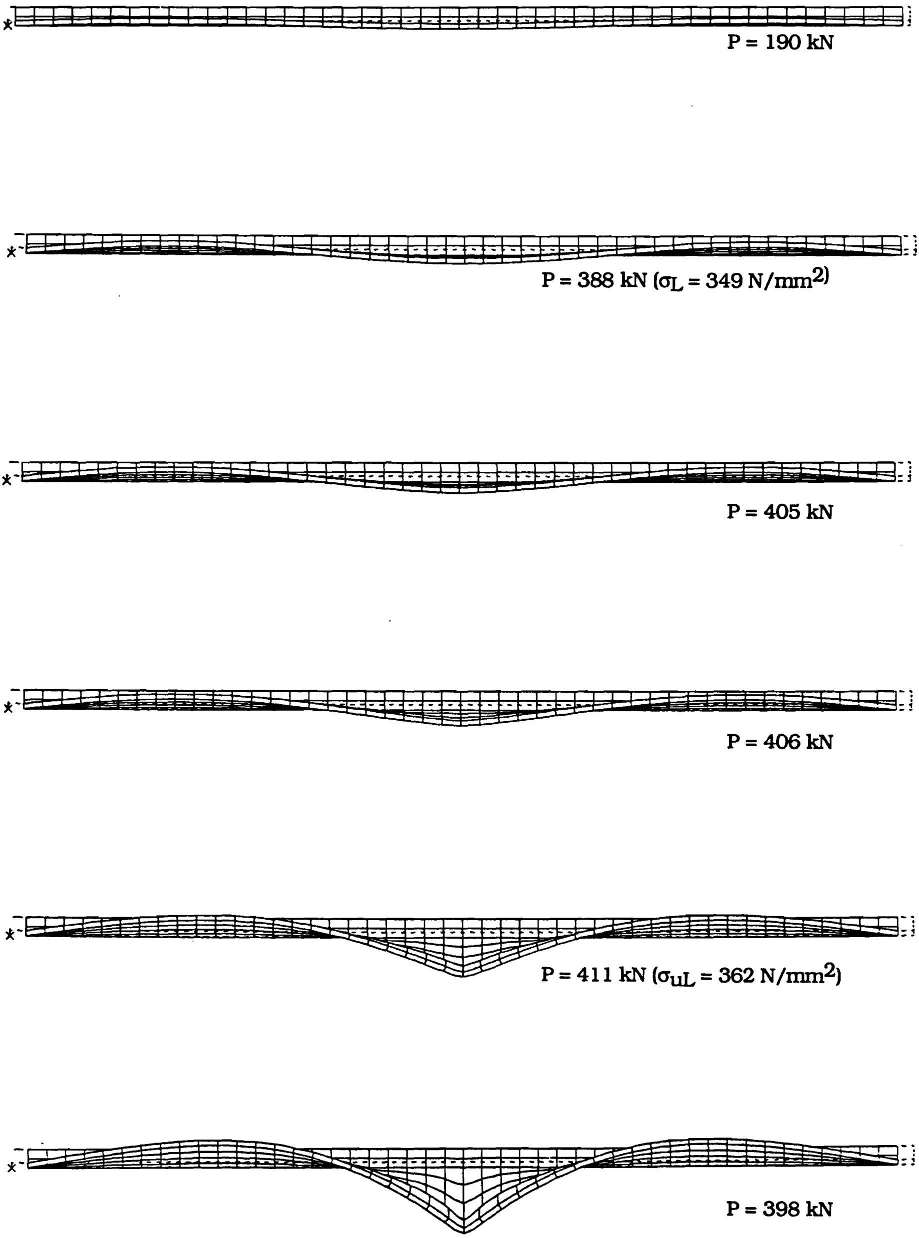
Figure 11 Imperfection Sensitivity of Lip Buckling Stress

B=122mm, D=97mm, B_L=17mm, D_L=18.5mm, L=1220mm, σ_o=390 N/mm^2

t (mm)	m	w_o (mm)	P_{oF} (kN)	P_{uF} (kN)	$\frac{P_{oF}}{P_{uD}}$
3.0	3	-1.0	389	402	1.22
	3	+1.0	**387**	411	1.21
	3	-0.6	**400**	418	1.16
	3	+0.6	409	421	1.18
	4	0.75	**386**	393	1.17
	4	0.2	422	430	1.14

** Equation 6 with η from Equation 7

Table 2 Sensitivity of Lip Buckling Resistance to Initial Imperfection
(B = 122mm, D = 97mm, B_L = 17mm, D_L = 18.5mm,L = 3000mm, σ_o = 390 N/mm^2)



B = 122mm, D = 97mm, B_L = 17mm, D_L=18.5mm, t=3.0mm
L=3000mm, σ_o=390 N/mm^2

Figure 12 Non-Linear Elasto-Plastic Lip Buckling Analysis, Axial Loading (displacement scale x 20)

5 EXPERIMENTS

Experiments on concentrically and eccentrically loaded cold-formed channel section columns were carried out to compare the buckling modes and lip buckling resistance with the prediction of the design model and finite element analysis.

Dimensions and material properties of the specimens tested are given in Table 3. All sections were strain gauged at mid length as shown in Figure 3. The ends of each section were inspected prior to testing to ensure that an even bearing surface had been obtained.

Test	B (mm)	D (mm)		B_L (mm)		D_L (mm)		t (mm)	σ_o (N/mm^2)	σ_u (N/mm^2)	e %
		D1	D2	BL1	BL2	DL1	DL2				
3 METRE BEAM/COLUMN (P at 65mm from table of section)											
BC1	126.3	101.4	102.4	20.2	20.7	19.8	20.2	1.00	295	377	25.2
BC2	124.4	100.4	100.5	20.3	20.5	19.8	20.2	1.86	360	390	22.0
BC3	125.0	99.0	99.6	22.6	22.7	19.0	17.8	3.00	346	425	23.0
3 METRE BEAM/COLUMN (P at neutral axis of effective section)											
SC1	125.7	99.0	99.0	20.5	20.5	18.5	20.5	1.5	364	494	26.1
SC2	125.5	100.2	100.7	20.6	20.5	18.3	18.2	3.0	489	539	20.8
9 METRE COLUMN (Restrained against flexural buckling)											
LC1	125.6	99.0	99.0	20.3	20.5	19.3	20.7	1.5	364	494	26.1
LC2	125.0	100.9	100.0	20.5	20.5	18.5	18.0	3.0	490	539	20.8

Table 3. Geometric and Material Properties

Two loading arrangements were used, the first arrangement was used to apply axial load to the ends of a 3 metre long channel section. It is well known that as the applied load is increased, the effective section reduces, and as a result a shift in neutral axis position of the section occurs. Consequently the knife-edges were located at the effective neutral axis position of each section tested under concentric loading. An alternative arrangement was used to simulated the eccentric moments found at the nodes of the full size test frame. The knife-edge supports were located 65mm from the outer surface of the table and allowed the channel to bend freely about the weak axis, but prevented strong axis bending, and also twisting about the longitudinal axis. The end plates were thick enough to restrain warping.

The second arrangement consisted of a 9 metre (3 x 3m) column, as shown in Figure 13. Channel sections 1.5 and 3.0mm thick were tested under axial load. Warping and lip rotation restraint existed at each end of the column but by using three spans the effect of restraint on the lip buckling behaviour of the central span is reduced. Flexure about both axes of the section and twisting about the longitudinal axis were restrained along the entire length. This was done to ensure that the lip buckling behaviour would not be affected by overall buckling. Test results are given in Tables 4 and 5, and Figure 14 and 15.

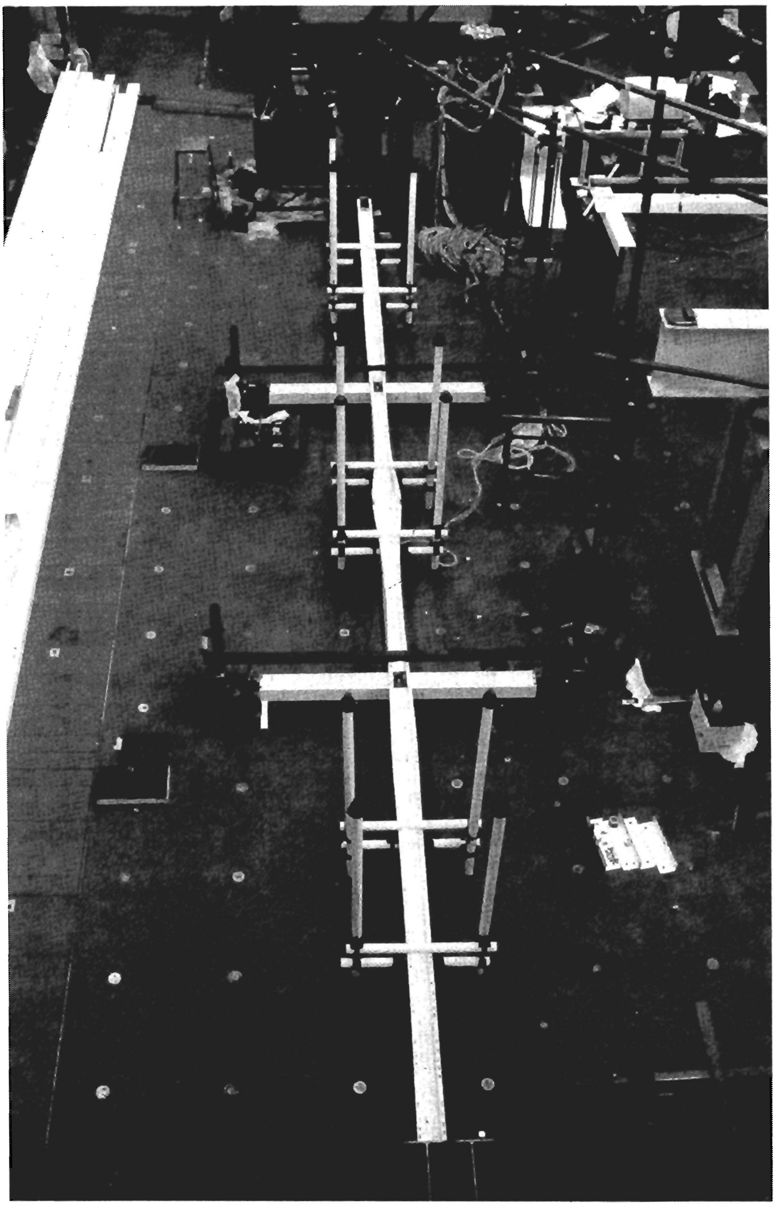


Figure 13 Lip Buckling Failure - 3 x 3 metre Chord Member

Experimental results are compared with the design model in Figure 16. BS5950 (1987) does not refer to lip buckling, but does stipulate that the sides of an open section should be stiffened by a simple lip having a width which is at least one fifth of the width of the adjoining element. For other types of edge stiffening a minimum allowable second moment of area of the lip about the middle surface of the element to be stiffened is given. The second moment of area of the lip and downturn for the channel sections considered is much greater than that required by BS5950 (1987) and EC3 (1989), but lip buckling still occurs for slender cross-sections.

t (mm)	P_{uT} (kN)	$\frac{P_{uT}}{P_{uD}}$	$\frac{P_{uT}}{P_{uBS}}$
3 METRE BEAM/COLUMN (P at 65mm from table of section)			
1.00	30.0	1.37	0.85
1.86	98.0	1.43	1.09
3.00	150.0	1.14	1.09
3 METRE COLUMN (P at neutral axis of effective section)			
1.50	80.0	1.14	0.813
3.00	275.0	1.06	0.98
9 METRE COLUMN (Restrained against flexural buckling)			
1.50	95.7	1.13	0.76
3.00	420.3 Failure of section by T.F.B.		

$C = 0.8(L_B/r_L)_0$

Table 4. Comparison of Test Results with Predicted Failure Loads

t (mm)	σ_{uT} (N/mm^2)		$\frac{\sigma_{uT}}{\sigma_{uD}}$	
	Gauge 4	**Gauge 6**	**Gauge 4**	**Gauge 6**
3 METRE BEAM/COLUMN (P at 65mm from table of section)				
1.00	151	163	1.14	1.23
1.86	338	335	1.40	1.39
3.00	436	345	1.33	1.06
3 METRE COLUMN (P at neutral axis of effective section)				
1.50	276	254	1.45	1.27
3.00	441	478	1.13	1.22
9 METRE COLUMN (Restrained against flexural buckling)				
1.50	233	247	1.17	1.24
3.00	361	364*	0.92	0.93

$C = 0.8(L_B/r_L)_0$

*Section failure by Torsional Flexural Buckling

Table 5 Comparison of Lip Buckling Stress (Equation 6) σ_{uL} with Measured Stresses (Figure 3)

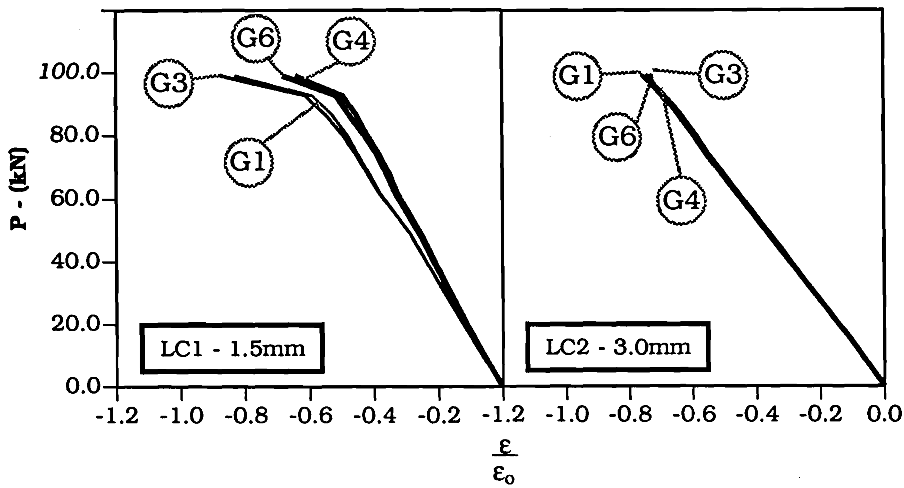


Figure 14 Load v. Strain - 9 metreColumn Tests

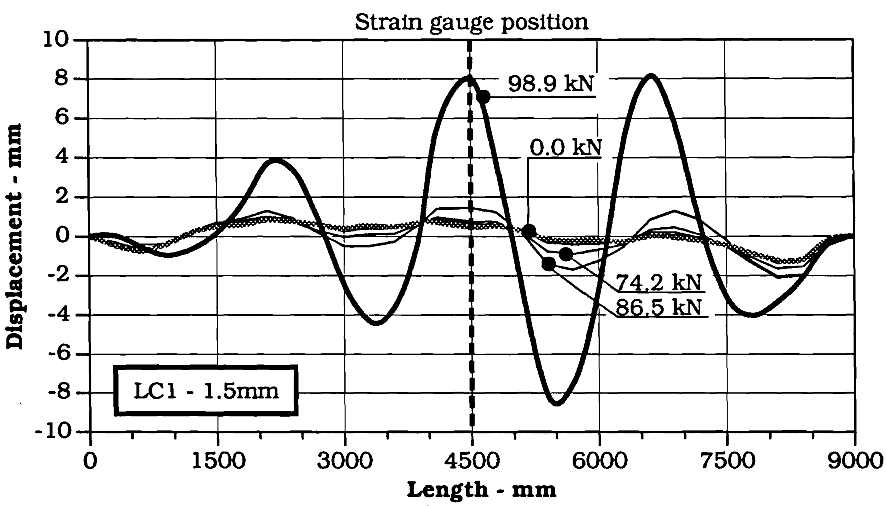


Figure 15 Load v. Lateral Displacement - 9 metre Column Tests

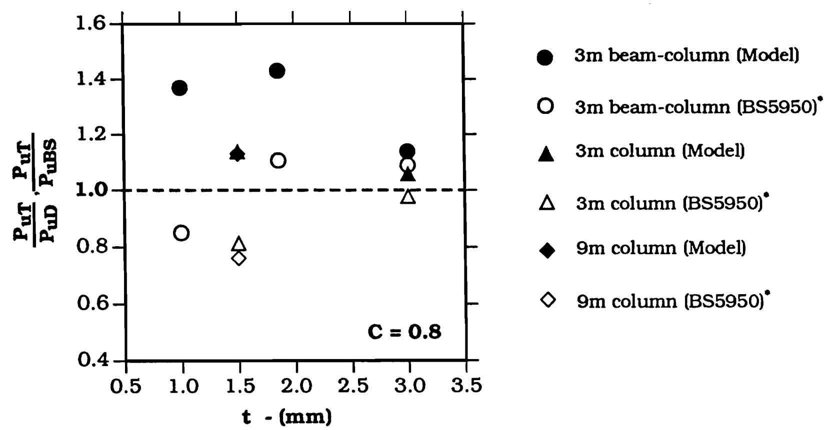


Figure 16. Comparison of Experimental results with Design Model

6 CONCLUSIONS

(1) The lip buckling phenomenon has been studied for a range of C-sections having lips with downturn. For the more slender sections, the lip buckling strength is considerably less than the yield stress. It is therefore essential to consider lip buckling when designing members in compression.

(2) The lip has been treated as a strut supported by an elastic foundation. The stiffness of the foundation depends on the deformational stiffness of the section. The stiffness is assumed to be that of uncoupled transverse strips. The critical buckling stresses so calculated, incorporating an assumed depth of lip and an assumed point of application of the disturbing force, accord satisfactorily with those calculated by finite element models in which the column deflection and rotation are prevented.

(3) Axial loading and pure bending have both been considered. If the critical lip buckling stress in bending is defined as the moment divided by the section modulus at the lip table, then the buckling stress for bending is about 33% greater than for axial loading. If the section modulus is assumed to be taken at the centroid of the lip section, the difference is reduced to about 10%.

(4) For a typical section and length of member, the number of lip buckling half waves in the length varies between two and four, depending on the thickness of the section.

(5) Lip buckling strength is estimated by introducing an assumed initial deflection and applying the Perry-Robertson formulation for column design to determine the average lip stress at which first yield occurs. The formulation shows a satisfactory agreement with experiments and with non-linear elasto-plastic finite element analysis.

(6) In the design method, it is assumed that local buckling of the table and/or webs of the section will not diminish the deformational stiffness of the section, provided that the wavelength for local buckling is small compared to the wavelength of lip buckling. For the sections considered, this assumption is found to be justified.

(7) In the current design procedure for the strength of chord members in the Conder Harley frame the yield stress of the material is replaced by the lip buckling strength.

(8) Lip buckling can be prevented by restraining deformation of the section at sufficiently close intervals

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APPENDIX- NOTATION

A_L	Effective area of lip
B	Breadth to mid thickness
B_L	Breadth of lip to mid thickness
C	Imperfection constant
D	Depth to mid thickness
D_L	Depth of lip to mid thickness
E	Modulus of elasticity (205 kN/mm^2)
H	Distance between the mid thickness of the table and the centroid of the lip
I_L	Second moment of area of lip about a vertical axis
L	Length of member
ℓ	Lip halfwave length of buckling
L_B	Minimum critical lip buckling half wave length
L_R	Is the distance between effective restraints
m	Number of half waves along the length of the member
F	Lip disturbing force
P_{cs}	Short strut resistance according to BS5950: Part V
P_{crF}	Critical buckling resistance obtained from finite element analysis
P_{oF}	Lip resistance at first surface yield obtained from finite element analysis
P_{uBS}	Ultimate resistance given by BS5950: Part V: 1987
P_{uD}	Ultimate axial load on member obtained from Equations 1 to 6
P_{uF}	Ultimate axial load on member obtained from finite element analysis
P_{uT}	Ultimate axial load on member obtained from tests
r_L	Radius of gyration of lip about a vertical axis
t	Thickness of section
$\bar{y}$	The greater distance from the vertical lip centroidal axis to the vertical surface of the lip
w	Lateral displacement of lip
w_o	Initial lip imperfection
e	Percentage elongation of material at ultimate load
β	Foundation modulus based on transverse stiffness of cross section
σ_{av}	Average stress on member
σ_{crF}	Elastic critical lip buckling stress obtained from finite element analysis
σ_{crL}	Elastic critical lip buckling stress obtained from equation 5
σ_{uL}	Ultimate stress of lip given by Equation 6
σ_{uD}	Ultimate stress in lip obtained from Equations 1 to 6
σ_{uT}	Ultimate stress in lip obtained from tests
σ_o	Yield stress of material
σ_{oF}	Stress at first surface yield obtained from finite element analysis
σ_u	Ultimate stress of material
σ_{uF}	Ultimate stress of lip obtained from finite element analysis
σ_d	Design strength (the smaller of σ_o or 0.84 σ_u)
η	Imperfection parameter
ν	Poisson's ratio