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Y. B. Kwon

Gregory J. Hancock

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Y.B. Kwon G.J. Hancock

Centre for Advanced Structural Engineering
School of Civil and Mining Engineering
University of Sydney, N. S. W., Australia

SYNOPSIS

Thin-walled lip-stiffened channel columns composed of high strength steel may fail in a distortional mode involving movement of the lip stiffener perpendicular to the flange plate it supports. In this report, test results for a simple lipped channel section(CH1) and an intermediate stiffened channel section (CH2) of thickness of approximately 1.1 mm (0.043 in) and 550 MPa (79.8 ksi) steel and undergoing distortional or mixed local-distortional buckling failure are compared with different design methods. The design methods compared are Australian Standard AS1538, EC3 Part1/Annexe A, the ECCS Recommendations and the AISI Specification. In addition, new methods based on a modified Winter formula for effective width are presented and compared with the tests.

1 INTRODUCTION

In recent years, thin-walled cold-formed steel structural members have been widely used in various applications including purlins and girts, steel framed housing, steel storage racks, lighting towers, sheeting and decking, and storage silos. Cold-formed sections have complicated deformation and failure modes, initial imperfections and residual stresses produced during the cold-forming process which are different from those of hot-rolled sections. Increased usage has led to further interest in the buckling and post-buckling behaviour and ultimate limit state of thin-walled cold-formed sections. Consequently, design specifications for cold-formed steel have been amended and continue to be amended based on recent theoretical and experimental research.

The design specifications for cold-formed steel structures such as AISI Specification (1986)/Addendum (1989), the ECCS Recommendations (1987) and the Australian Standard (AS1538-1988) have recently been revised and further revisions are planned. The Eurocode EC3/Annexe A for cold-formed members is also under development for the design of cold-formed members. Some of the main features of the changes in the design of compression members are the adoption of a single effective width formula for both stiffened and unstiffened elements and design provisions for partially stiffened elements. A partially stiffened edge-stiffened element is one for which one edge is connected to a web or similar element and the other edge is connected to an edge stiffener which is not of adequate size to prevent distortional buckling of the flange of the section. Distortional buckling is the mode where the stiffener moves normal to the element it stiffens. It can be contrasted with local buckling where the edge stiffener remains fixed and only the plate element buckles. The provisions in the AISI Specification (1986) for edge stiffeners are based on the research work of Desmond, Pekoz and Winter (1981) who studied various simple lipped channels. There are no such provisions in the Australian Standard AS1538 for partially stiffened elements although a rational elastic buckling analysis of the section is permitted to determine the plate buckling coefficient for use in the effective width equation. In EC3 Part1/Annexe A, provisions of partially stiffened elements have been prepared which adopt the effective area by reducing the thickness of the lip stiffener with part of the flat area depending on the slenderness of the stiffener.

There is no explicit provision for the distortional mode or the mixed mode of local and distortional buckling in the AISI, ECCS and AS1538. Distortional buckling may interact with local buckling, making it more complex to derive simple provisions. Lau and Hancock (1988) proposed two different design methods for the distortional mode. One method accounts for distortional buckling by adjusting the effective width of the flange element supported by the edge stiffener using the plate buckling coefficient based on the elastic critical stress for distortional buckling of the section. This is similar to the AISI (1986) provisions where a buckling coefficient, K, based on the adequacy of the lip stiffener is used in the calculation of the effective width. The method proposed by Lau and Hancock was compared with the test results of channel and hat sections of thickness 1.7-2.4 mm (0.067-0.094 in) and proved accurate. The alternative method proposed by Lau and Hancock used the elastic and inelastic distortional buckling stresses as a cutoff (limit state) for design to be checked in addition to other provisions for local and column buckling. It assumed no interaction between distortional buckling and either local or column buckling. It also proved accurate for the columns studied.

In an earlier paper (Kwon and Hancock 1992), tests on simple lipped channel sections (called CH1) and intermediate stiffened channel sections (called CH2) composed of high strength steel were reported where the channel sections buckled in a distortional mode or a mixed local-distortional mode. Design curves based on effective width formulae, and distortional buckling strengths were proposed and compared with the test results. This paper reviews the proposed design curves and compares them with the design curves of AS1538, EC3 Part1/Annexe A, ECCS and AISI.

2 SECTIONS AND RESULTS

The geometry and dimensions of the Kwon and Hancock (1992) test sections (CH1 and CH2) are shown in Fig. 1 and Tables 1(a) and (b) respectively. The experimentally determined yield stress and Young's modulus are used rather than nominal values to allow the direct assessment of the accuracy of strength predictions. The test strengths are given in Tables 2(a) and (b). Full details of the test results used are given in Kwon and Hancock (1992).

3 ULTIMATE STRENGTH AND EFFECTIVE WIDTH

3.1 Distortional Buckling Formulae

The formulae proposed by Kwon and Hancock (1992) for determining the strength of slender sections which are formed from thin steel of high yield strength and which may buckle in the distortional or mixed local-distortional modes in the elastic range of material properties are given by Eq. (1).

$$\sigma_{max} = F_y\left(1 - \frac{F_y}{4\sigma_d}\right) \qquad \sigma_d \geq \frac{F_y}{2} \tag{1a}$$

$$\sigma_{max} = F_y\left(0.055\left(\sqrt{\frac{F_y}{\sigma_d}} - 3.6\right)^2 + 0.237\right) \qquad \frac{F_y}{13} \leq \sigma_d \leq \frac{F_y}{2} \tag{1b}$$

where σ_d is the elastic distortional or mixed mode buckling stress. Unlike the earlier formulae described by Lau and Hancock (1988), these equations permit considerable post-buckling reserve of strength in the distortional and mixed buckling modes. Equation (1a) is a parabolic fit to the test results of Lau and Hancock (1988) and is the same as that proposed by Lau and Hancock in the inelastic range. Equation (1b) is an empirical fit to the test results of Kwon and Hancock (1992) in the post-buckling range. The design curves are shown in Fig. 2(a) along with both sets of test results. These curves are based on the idea that the distortional buckling strength or the mixed local-distortional buckling strength can be computed independently of local or overall buckling.

3.2 Effective Width Formulae for the Sections

The alternative approach described in the introduction is to use the effective width of the flange undergoing distortional buckling to predict its strength. The effective area of the section consists of the effective areas of the flange, web and stiffener calculated separately. The effective width of a plate element according to AISI, ECCS and AS1538 is given by the Winter formula as;

$$\frac{b_e}{b} = 1 \qquad \lambda \leq 0.673 \tag{2a}$$
$$\frac{b_e}{b} = \sqrt{\frac{\sigma_l}{f}}\left[1 - 0.22\sqrt{\frac{\sigma_l}{f}}\right] \qquad \lambda \geq 0.673 \tag{2b}$$

where

$$\sigma_l = K\frac{E\pi^2}{12\,(1-\nu^2)}\left(\frac{t}{b}\right)^2 \tag{2c}$$

$$\lambda = \sqrt{\frac{f}{\sigma_l}} = \frac{1.052}{\sqrt{K}}\left(\frac{b}{t}\right)\sqrt{\frac{f}{E}} \tag{2d}$$

and K is the buckling coefficient of the plate, b and b_e are the flat width and effective width of plate element respectively and σ_l is the elastic local buckling stress. In AS1538 and ECCS, f is taken as the yield stress F_y while it is taken as F_n in the AISI Specification. The value of F_n is determined from the column design formula (Eq. 8) and it approaches F_y for short columns. EC3/Annexe A provides for an effective thickness by reducing the thickness of an edge stiffener or intermediate stiffener depending on the stiffener slenderness. AISI and ECCS reduce the area of the partial stiffener by multiplying by the ratio of the second moment of area of the stiffener to that of an adequate stiffener.

An alternative effective width formula was proposed by Kwon and Hancock (1992) for design against distortional buckling. It is based on the idea that a single plate strength curve of a type similar to the Winter formula (Eqs. 2a and 2b) could be used to design against distortional buckling such that the local buckling stress (σ_l) is replaced by the distortional buckling stress (σ_d). The Winter formula based on the distortional buckling stress has been modified by raising the exponent of the (σ_d/F_y) term from 0.5 to 0.6 and increasing the 0.22 coefficient to 0.25 as given in Equation (3b).

$$\frac{b_e}{b} = 1 \qquad \lambda \leq 0.561 \tag{3a}$$
$$\frac{b_e}{b} = \left(\frac{\sigma_d}{F_y}\right)^{0.6}\left(1 - 0.25\left(\frac{\sigma_d}{F_y}\right)^{0.6}\right) \qquad \lambda \geq 0.561 \tag{3b}$$

where

$$\lambda = \sqrt{\frac{F_y}{\sigma_d}} \tag{3c}$$

The theoretical justification for increasing the exponent to 0.6 is that it moves the curve closer to that of a column design curve which would have an exponent of 1.0 from the plate strength curve which has an exponent of 0.5. The 0.22 coefficient is increased to 0.25 to provide a reasonable fit to the test results at low column slenderness. Comparison of test results with the formula is shown in Fig. 2(b). Notice how the specimens with the highest slenderness of each section type lie close to the original Winter formula (Eq. 2b) since they have a very small lip and fail mainly in a mode involving plate flexure whereas those with a large lip lie well below the Winter formula (Eq. 2b).

3.3 Buckling Stress Coefficients

The buckling coefficient K for a uniformly compressed stiffened element which has an adequate lip is taken as 4.0 in all standards and specifications. For uniformly compressed unstiffened elements, the K value is taken as 0.5 in AS1538 and 0.43 in ECCS, EC3 and the AISI specifications. AISI and ECCS have provisions for determining the K value for elements which are partially stiffened. Since AS1538 does not have explicit provisions, a rational elastic buckling analysis, such as a semi-analytical finite strip analysis of the type described in Hancock (1978) or formulae of the type described by Lau and Hancock (1987) are permitted to calculate K values for inadequately stiffened elements. The K values calculated using the ECCS and AISI equations with the values of F_n taken as F_y and using the second moments of area (I_{se}) in Table 3(b) are given in Table 3(a) for the test sections of Kwon and Hancock (1992). In addition, the K_l and K_d values based on finite strip buckling analyses (Hancock 1985) are also given in Table 3(a). In this case, K_l and K_d are calculated from the local (σ_l) and distortional (σ_d) buckling stresses using $K_l = \sigma_l \frac{12(1-\nu^2)}{E\pi^2}\left(\frac{b}{t}\right)^2$ and $K_d = \sigma_d \frac{12(1-\nu^2)}{E\pi^2}\left(\frac{b}{t}\right)^2$. The K_l and K_d values have been determined separately for the flanges and web.

The distortional buckling coefficient (K_d) for the flanges of the CH1 and CH2 sections are significantly less than 4.0 but greater than 0.5 since the flanges are partially stiffened elements. The distortional buckling coefficient (K_d) for the web of the CH1 sections is less than 4.0 since it buckles at a lower load than if it were a simple plate as a result of the distortional buckle in the flanges. The distortional buckling coefficient (K_d) for the web of the CH2 section is in the range 3.46-6.09 and varies with the distortional buckling stress in the flanges. The values of K determined for the flanges using the AISI formulae with $F_n = F_y$ and ECCS Recommendations are comparable with, but slightly lower than the K_d values determined using the finite strip analysis. The values of K determined for the web of the CH1 section using the AISI Specification and ECCS Provisions are 4.0 since the edge stiffener on the flange is assumed to have no effect on the web buckling. The values of K determined for the web of the CH2 section using the AISI Specification is 3.31 which is less than 4.0 since the intermediate stiffener in the web is not fully effective. The values of 3.31 is fairly accurate for the CH2-7 section but very conservative for the CH2-14 section.

For the CH1 channel section, the local buckling coefficient (K_l) for the web is slightly greater than 4.0 since it is restrained by the stokier flange in the local buckling mode. The local buckling coefficient of the flange is less than 4.0 since it buckles at a lower load than if it were a simple plate as a result of the local buckle in the web. For the CH2 channel section, the local buckling coefficient for the flange is slightly greater than 4.0 since it is now restrained by the web which contains an intermediate stiffener. The local buckling coefficient for the web of the CH2 section based on the full plate width is approximately 8.0 as a result of the intermediate stiffener.

Required second moments of area for the stiffeners of the test sections have also been compared in Table 3(b) with the AISI/ECCS and AS1538. The value of I_{req} is the second moment of area of the stiffener which is defined as adequate for the flange plate to behave as a stiffened element. The AISI values for the lip stiffener to be adequate are much greater than those of AS1538. However, they are similar for the intermediate stiffener. The second moments of area of the edge stiffener according to EC3/Annexe A for the edge section, which is composed of the stiffener and part of the flange of the section (Fig. 3) are shown in Table 3(b) for comparison. In all cases, the edge stiffeners are less than adequate, even when compared with AS1538.

3.4 Q-Factors for the Sections

The Q-factor design approach has been used in the column design curves of the Australian Standard AS1538, ECCS Recommendations and EC3 Part 1/ Annexe A to account for the effects of local buckling on the column strength. The Q-factor of a section is defined as the ratio of the effective section area at the maximum permissible design stress to the full area of the cross section so that the product of Q and F_y gives the stub column strength. The effective area of a section is obtained by summing the effective areas of all the individual elements forming the section. For the AISI Specification, Q has been replaced by Ae/A where Ae is calculated at the stress F_n. If $F_n = F_y$, as it would be for a stub column, then Ae/A can be compared directly with Q in other standards. According to the ECCS Recommendations and the AISI Specification, the effective area of a partial lip stiffener and intermediate stiffener have to be reduced by multiplying by the ratio I_{se}/I_{sa}. EC3 Part 1/ Annexe A has provisions to have the effective area reduced by multiplying by the ratio of effective thickness based on the slenderness ratio of the stiffener to the actual thickness.

To compute the Q-factors determined for the test sections, several different methods have been used in this paper. The K and I values given in Tables 3(a) and (b) respectively have been used to compute Q-factors. If the K values are greater than 4.0, they are taken as 4.0. The values are summarised for each of the test sections and design methods in Table 4. The value of test strength (σ_u) to test yield stress (σ_y) is also included in Table 4 for comparison.

(a) In calculating Q1 values in accordance with the Australian Standard AS1538, the lips and the flanges were treated as unstiffened elements (K=0.5) and the webs were assumed simply supported at both edges (K=4.0).

(b) In calculating Q2 in accordance with the Australian Standard AS1538 using a rational elastic buckling analysis to determine the K values, the K_d values for the web and the flange in Table 3(a) corresponding to *distortional mode* have been used. The K values for the stiffener as an unstiffened element were taken as 0.5.

(c) In calculating Q3 values in accordance with the AISI Specification, the K values of the flanges in Table 3(a) were determined according to AISI equations for edge stiffened elements. The K values of the webs of the CH2 sections given in Table 3(a) were determined according to the AISI equations for intermediate stiffened elements. The K values for the lip stiffeners were taken as 0.43. The values of Ae/A in the AISI Specification, where Ae is the effective area at the stress F_n taken equal to the yield stress F_y, is expressed as Q3.

(d) In calculating Q4 values in accordance with the ECCS Recommendations, the K values of the flanges in Table 3(a) were determined according to the ECCS equations for edge stiffened elements. The K values of the webs of the CH2 sections given in Table 3(a) were determined according to the ECCS equations for intermediate stiffened elements. The K values for the lip stiffeners were taken as 0.43. The differences between

Q3 and Q4 resulted from the different definitions for flat width of an element in the ECCS Recommendations and AISI Specification. The width of the flat elements for the ECCS is the distance between the centrelines of the supporting plates (mid-thickness width) but that for the AISI is the clear flat width which does not include the curved portion as shown in Fig. 4.

(e) In calculating Q5 in accordance with EC3/Annexe A, the EC3 equations, which are based on a different approach from the other specifications, were used. EC3 reduces the thickness of the edge section and intermediate stiffened sections depending on the stiffener slenderness $\bar{\lambda}_R = \sqrt{F_y/\sigma_{ER}}$ where σ_{ER} is derived according to the buckling of an infinitely long column on an elastic foundation. The Q5 values were obtained by assuming the actual compressive stress σ_c as the yield stress F_y.

(f) In calculating Q6 using the modified Winter formula (Eq. 3) and using a rational elastic buckling analysis to determine the K values, the K_d values of the flanges for the CH1 section in Tables 3(a) corresponding to the *distortional mode* were used. The K value of the web was taken as 4.0 when the value in Table 3(a) was greater than 4.0.

(g) In calculating Q7 values in accordance with the AISI Specification, the K values of the flanges and the webs in Table 3(a) determined according to the AISI equations were used. However the modified Winter formula (Eq. 3) rather than the usual Winter formula (Eq. 2) was used and the effective stiffener area was reduced by the ratio of I_{se}/I_{sa}.

It can be clearly seen that the Q1-Q5 values based on the Winter formula are greater than those Q6, Q7 based on the modified Winter formula (Eq. 3)

4 COLUMN DESIGN CURVES

4.1 AS1538-1988

The column curve in the Australian Standard (AS1538-1988) is based on the Perry curve (Ayrton and Perry 1886). The unfactored column design curve is given by

$$F_m = QF_y \left\{ \left[\frac{1 + (1+\eta)(F_{oc}/QF_y)}{2} \right] - \sqrt{\left[\frac{1 + (1+\eta)(F_{oc}/QF_y)}{2} \right]^2 - \frac{F_{oc}}{QF_y}} \right\} \quad (4a)$$

where the imperfection parameter η is given by

$$\eta = (1.25 - Q)\frac{QF_y}{F_{oc}} \quad (4b)$$

The allowable stress (F_a) is given by

$$F_a = \frac{F_m}{\Omega} \quad (5a)$$

where the load factor Ω is given by

$$\Omega = \frac{1}{0.6} \quad (5b)$$

and F_{oc} is the elastic buckling stress which is the lesser of the flexural or flexural-torsional buckling stress.

4.2 ECCS Recommendations-1987 and EC3/Annexe A-1989

The column curve in the ECCS Recommendations is also based on the Perry curve but a different imperfection parameter from that in the Australian Standard (AS1538-1988) is used, such that

$$\eta = \kappa \left[\sqrt{\frac{F_y}{F_{oc}}} - 0.2 \right] \tag{6a}$$

where

$$\kappa = \alpha (4 - 3Q) \leq 0.76 \tag{6b}$$

and the value of F_m in Eq. (4a) is taken equal to QF_y if it is greater than QF_y.

The column curve in the draft Eurocode EC3/Annexe A is given by

$$N_{rc} = \kappa F_y A_e / \gamma_m \tag{7a}$$

$$F_m = N_{rc}/A \tag{7b}$$

$$\kappa = \frac{1}{\phi + [\phi^2 - \lambda^2]^{\frac{1}{2}}} \leq 1 \tag{7c}$$

$$\phi = 0.5 \left[1 + \alpha (\lambda - 0.2) + \lambda^2 \right] \tag{7d}$$

$$\lambda = [F_y/F_{oc}]^{\frac{1}{2}} [Q]^{\frac{1}{2}} \tag{7e}$$

where F_{oc} is computed using the effective area for the flexural buckling stress and is computed using the total gross section for flexural-torsional buckling stress. The value of γ_m is a partial safety factor for the material and is generally 1.0 if it is not specified otherwise. The value of α is taken as 0.21 for box sections and I-sections buckling about the major axis and is taken as 0.34 for I-sections buckling about the minor axis, lipped channel sections and lipped Z-sections. For lipped or unlipped angles, unlipped channel sections and unlipped Z-sections, the value of α is taken as 0.49.

4.3 AISI-1986 and Addendum-1989

The column curve in the AISI Specification(1986) which has not been changed in Addendum(1989, 1990 for LRFD) is based on the parabolic formula similar to the one given by Eq. 1a. The design curve is given by

$$F_m = \frac{A_e}{A} F_n \tag{8a}$$

where

$$F_n = F_{oc} \qquad F_{oc} \leq \frac{F_y}{2} \tag{8b}$$

$$F_n = F_y \left[1 - \frac{F_y}{4F_{oc}} \right] \qquad F_{oc} \geq \frac{F_y}{2} \tag{8c}$$

and A_e is the effective area at the stress F_n. The allowable stress on a column is obtained by dividing the value of F_m by a safety factor. The value of the safety factor is generally taken as 1.92.

4.4 Proposed Design Method

Proposal 1a uses the column curve in the Australian Standard AS1538 with the short length column strength based on the modified Winter formula. The column curve for the proposed design method is based on Eq. 4(a) but with the value of the Q-factor taken equal to the Q6 value which corresponds to the distortional buckling mode and is based on the modified Winter formula. This design method was proposed firstly by Lau and Hancock (1988) and modified in the present research in calculating Q6 using the modified Winter formula. In computing the Q6 value corresponding to the distortional or mixed buckling modes, the effective width of the intermediate stiffened web is calculated based on the whole-width and the effective area of the intermediate stiffener is reduced by multiplying by the ratio I_{se}/I_{min} shown for the web in Table 3(b).

Proposal 1b uses the column curve in the AISI Specification with the short length column strength based on the modified Winter formula. The proposed column curve is based on Eq. 8 but the effective area in Eq. 8a should be computed using the modified Winter formula (Eq. 3) rather than Winter formula (Eq. 2). It is different from simply replacing Ae/A in Eq. 8a by Q7 in Table 4 since F_n is assumed equal to F_y to compute the Q7 values.

Proposal 2 is a modification of the Alternative II method proposed by Lau and Hancock (1988) where the distortional buckling strength is taken as a cut-off. The proposed design strength is given by the lesser of Eq. 9(a) and (b).

$$P_m = A_e F_n \tag{9a}$$

$$P_m = A F_m \tag{9b}$$

where A is the gross area of the section and

$$F_m = F_y\left(1 - \frac{F_y}{4\sigma_d}\right) \qquad \sigma_d \geq \frac{F_y}{2} \tag{9c}$$

$$F_m = F_y\left(0.055\left(\sqrt{\frac{F_y}{\sigma_d}} - 3.6\right)^2 + 0.237\right) \qquad \sigma_d \leq \frac{F_y}{2} \tag{9d}$$

The effective area A_e and stress F_n are those given for the AISI Specification in Section 4.3. For long columns, the final failure mode is assumed as the flexural or flexural-torsional buckling mode and the AISI column curve has been adopted for the design curve as given by Eq. 9a. For intermediate length columns which buckle in the distortional mode, the experimental design formulae described in Section 3.1 have been adopted and the gross section has been used to produce the ultimate column load as given by Eq. 9b.

5 Comparison of Tests with AS1538, AISI, ECCS, EC3/Annexe A and Proposed Design Methods

The ultimate strengths of all of the test sections are compared in Tables 5(a)-5(h) with the design strengths computed using the Q factors in Table 4 and the appropriate column design curves from Sections 4.1-4.4. Comparisons between the column design curves in different specifications are also made with the test results in Figs 5 and 6 for the CH1-7 and CH2-7 sections respectively. Since different safety factors are used in the AISI Specification, ECCS Recommendations, EC3/Annexe A and AS1538, the unfactored column curves are used in Figs 5 and 6. The flange flat-width to thickness ratio of the test sections are slightly beyond the maximum permissible flat-width ratio which is 60 for a flange stiffened by an edge stiffener in the specifications. Therefore, the direct application of the AISI Specification and ECCS Recommendations is not completely valid. However, the comparison can give useful clues to extension of the design procedures.

The AISI, AS1538 and EC3 design curves show higher values than the test results for the CH1 sections. The ECCS design curve provides a conservative estimate for short and intermediate length columns for the CH1 sections. However, The ECCS Recommendations provide very conservative values for long columns. For the CH2 sections, the AISI and EC3 show higher values than the test results. The ECCS Recommendations provide a conservative fit for short and intermediate columns.

The provisions for partial edge and intermediate stiffeners in EC3/Annexe A, which reduce the thickness of the edge and intermediate section depending on the stiffener slenderness $\bar{\lambda} = \sqrt{F_y/\sigma_{ER}}$, give unconservative column strengths due to overestimation of the spring coefficients calculated assuming fixed end boundary conditions at the centre of the web for the edge stiffener and at both edges of the web for the intermediate stiffener.

Comparisons between the design proposals (1a, 1b, 2) given in Section 4.4 and the test results are given in Figs 7 and 8 for the CH1-7 and CH2-7 sections respectively. Proposal 1a provides a slightly unconservative fit to the test results for the short columns of the CH1-7 channel section as shown in Fig. 7 and Table 5(f). However, it provides a conservative fit to the test results for the long column of the CH1-7 section. As the lip stiffener size is increased (CH1-5, CH1-6, CH1-7), the buckling mode changes from distortional to local through mixed local-distortional and the column strengths become more unconservative values for the CH1 sections as shown in Table 5(f). Proposal 1a provides a conservative fit for the CH2 sections as shown in Fig. 8 and Table 5(f). As the lip stiffener size is increased (CH2-7, CH2-8, CH2-10, CH2-12, CH2-14), the design values become less conservative for the CH2 sections as shown in Table 5(f).

Proposal 1b shows slightly lower values than the Proposal 1a for stub and intermediate columns of the CH1 section but higher values for long columns as shown in Fig. 7 and Table 5(g). For the CH2 section, it shows higher values than Proposal 1a as shown in Fig. 8 and Table 5(g). As the lip stiffener size is increased, the column strength becomes more unconservative for the CH1 section but does not change for the CH2 section.

Proposal 2 coincides with Proposal 1a for stub columns of the CH1 section but provides slightly higher values than Proposals 1a and 1b for intermediate and long columns of the CH1 section as shown Fig. 7 and Table 5(h). Proposal 2 also shows good agreement with Proposal 1a for intermediate length columns of the CH2 section but shows higher values for long columns as shown in Fig. 8 and Table 5(h). As the lip stiffener size is increased, the column strength changes from conservative to unconservative values.

6 CONCLUSIONS

Test results for cold-formed channel sections undergoing distortional buckling and mixed local-distortional buckling have been summarised. Detailed comparisons of the test results with the AISI Specification (1986), the ECCS Recommendations (1987), EC3/Annexe A (1989) and Australian Standard AS1538 (1988) showed that the column strengths predicted by all the specifications were fairly unconservative for stub and intermediate length columns except for the ECCS design curves which showed conservative values for intermediate columns.

Three different design methods for cold-formed sections undergoing local and distortional bucklings are proposed and compared with the test results. The first method proposed (Proposal 1a) is based on the Australian Standard (AS1538) column curve using the modified Winter formula and Q-factors corresponding to the distortional buckling stress rather than the local buckling stress. The second method proposed (Proposal 1b) is based on the column curve in the AISI Specification using the modified Winter formula to calculate the effective area of the section. The third method (Proposal 2) is a combination of the column design method for flexural or flexural-torsional buckling in the AISI Specification with the proposed design curves (Eqs. 1a, 1b) which consider the interaction between local and distortional buckling. The comparisons of all three methods with the test results show that the design methods proposed can be used for columns which may buckle mainly in the distortional buckling mode interacting with local buckling. The third method (Proposal 2) is probably the simplest to implement since it requires a simple additional check for distortional buckling in addition to the existing design rules in the AISI Specification.

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9 NOTATION

A	gross section area
A_e	effective section area
b	flat width of compression element
b_e	effective flat width of compression element
b_f	width of flange
b_w	width of web
CH1	simple lipped channel section
CH2	stiffened lipped channel section
d	depth of lip stiffener
E	Young's modulus
f	stress in element computed using effective width
F_a	allowable stress
F_m	unfactored column design stress
F_n	unfactored stress determined from AISI column design Formula
F_y	yield stress in design formula (taken as σ_y in Table 5)
F_{oc}	elastic buckling stress in axially loaded member
I_{req}	adequate second moment of area of stiffener (I_{sa}, I_{min})
I_{sa}, I_{min}	adequate second moment of area of stiffener determined according to AS1538 and AISI/ECCS respectively
I_{se}, I_r	second moment of area of stiffener about its centroidal axis parallel to flange plate according to AS1538 and EC3 respectively
K	plate buckling coefficient
L	length of column
N_{rc}	unfactored column design load determined from EC3
Q, Q1-Q6	Q-factors
P_m	unfactored column design load
r	inner radius of corner of test section
s1	depth of intermediate stiffener of web of test section
s2	width of intermediate stiffener of web of test section
t	thickness of section

α	coefficient used in ECCS/EC3 column design formula
γ_m	partial safety factor
η	imperfection parameter in column design formula
κ	reduction factor
$\lambda, \bar{\lambda}$	nondimensionalised slenderness
ν	Poisson's ratio
σ_d	elastic distortional buckling stress
σ_{ER}	elastic buckling stress determined from EC3
σ_l	local buckling stress
σ_m	maximum stress of columns
σ_y	measured yield stress
ϕ	ratio used in EC3 column curve (Eq. 7d)
Ω	load factor

Table 1(a) Measured Test Specimen Dimensions
Simple Lipped Channel (CH1)

Specimen	t* (mm)	L (mm)	bw (mm)	bf (mm)	d (mm)	r (mm)	A (mm^2)
CH1-5-800	1.085	800	119.55	89.65	4.80	1.30	326.45
CH1-6-800	1.085	800	119.80	89.75	6.00	1.30	329.54
CH1-7-400	1.095	400	120.80	89.70	7.00	1.30	335.76
CH1-7-600	1.095	600	120.40	89.55	7.00	1.30	334.99
CH1-7-800	1.100	800	120.50	89.50	7.00	1.30	336.52
CH1-7-1800	1.100	1800	119.10	90.10	7.04	1.30	336.38

* base metal thickness
(1 in = 25.4 mm)
(1 in^2 = 645.16 mm^2)

Table 1(b) Measured Test Specimen Dimensions
Intermediate Stiffened Lipped Channel (CH2)

Specimen	t* (mm)	L (mm)	bw (mm)	bf (mm)	d (mm)	r (mm)	s1 (mm)	s2 (mm)	A (mm^2)
CH2-7-800	1.100	800	120.50	90.15	7.00	1.30	10.00	20.00	348.31
CH2-7-1000	1.100	1000	120.50	89.80	7.20	1.30	10.30	19.50	348.62
CH2-7-1800	1.100	1800	120.00	90.00	7.00	1.30	10.30	20.00	348.07
CH2-8-1000	1.095	1000	119.95	89.95	8.00	1.30	10.15	20.00	348.10
CH2-10-1000	1.105	1000	116.00	89.95	10.00	1.30	10.30	20.00	351.58
CH2-12-1000	1.100	1000	120.50	89.95	12.00	1.30	10.00	19.50	359.03
CH2-14-1000	1.105	1000	116.60	89.85	14.00	1.30	10.30	20.00	360.86

* base metal thickness
(1 in = 25.4 mm)
(1 in^2 = 645.16 mm^2)

Table 2(a) Column Test Results for Simple Lipped Channel (CH1)

Test Section	σ_{dt} (MPa)	σ_m (MPa)	σ_{dt}/σ_y	σ_m/σ_y
CH1-5-800	45.0	147.8	0.08	0.25
CH1-6-800	55.5	147.3	0.09	0.25
CH1-7-800	68.6	149.5	0.12	0.25
CH1-7-600	75.8	155.7	0.13	0.26
CH1-7-400	88.8	160.0	0.15	0.27
CH1-7-1800	62.7	140.6	0.11	0.24

(1 ksi = 6.895 MPa)

Table 2(b) Column Test Results for Intermediate Stiffened Lipped Channel (CH2)

Test Section	σ_{dt} (MPa)	σ_m (MPa)	σ_{dt}/σ_y	σ_m/σ_y
CH2-7-800	81.2	198.5	0.14	0.34
CH2-7-1000	75.2	193.2	0.13	0.33
CH2-7-1800	70.5	163.5	0.12	0.28
CH2-8-1000	91.6	192.1	0.16	0.33
CH2-10-1000	134.3	202.2	0.23	0.34
CH2-12-1000	139.3	206.2	0.24	0.35
CH2-14-1000	159.6	214.4	0.27	0.36

σ_{dt} test values of distortional buckling stress or mixed local-distortional buckling stress
σ_y mean yield stress of flat tensile coupon
σ_m maximum stress

(1 ksi = 6.895 MPa)

Table 3(a) Buckling Stress and K Values

Test Section No.	Theoretical Buckling Stress (MPa)		Flange				Web			
	Local σ_l	Distortional σ_d	b/t	K_l	K_d	K *AISI (ECCS)	b/t	K_l	K_d	K *AISI (ECCS)
CH1-5	73.3	39.5	77.5	2.37	1.28	0.94 (0.93)	104.7	4.34	2.34	4.0(4.0)
CH1-6	76.7	46.2	77.5	2.48	1.50	1.14 (1.13)	104.7	4.54	2.74	4.0(4.0)
CH1-7	77.7	53.4	77.5	2.52	1.73	1.33 (1.32)	104.7	4.60	3.16	4.0(4.0)
CH2-7	131.9	58.4	77.5	4.27	1.89	1.33 (1.32)	104.7	7.81	3.46	3.31(3.26)
CH2-8	135.3	64.7	77.5	4.38	2.09	1.53 (1.52)	104.7	8.01	3.83	3.31(3.26)
CH2-10	138.6	77.4	77.5	4.49	2.50	1.93 (1.90)	104.7	8.21	4.58	3.31(3.26)
CH2-12	140.4	90.2	77.5	4.55	2.92	2.32 (2.29)	104.7	8.31	5.33	3.31(3.26)
CH2-14	141.5	102.9	77.5	4.58	3.33	2.71 (2.68)	104.7	8.38	6.09	3.31(3.26)

$^*F_n = F_y$

Table 3(b) I Values for Stiffener

Test	Flange				Web		
	AS1538	EC 3	$I_{req}(mm^4)$		AS1538	$I_{req}(mm^4)$	
			ECCS/			ECCS/	
Section	$I_{se}(mm)$	$I_r(mm)$	AISI(I_{sa})	AS1538(I_{min})	$I_{se}(mm)$	AISI(I_{sa})	AS1538(I_{min})
CH1-5	1.6	5.5					
CH1-6	4.3	13.5	571/547	207	*	*	*
CH1-7	8.9	27.4					
CH2-7	8.9	27.4					
CH2-8	16.1	49.0					
CH2-10	40.2	120.5	571/547	207	180.7	422/395	414
CH2-12	81.1	161.8					
CH2-14	143.1	195.5					

* not applicable
(1 in = 2.54 cm)
(1 in^4 = 41.62 cm^4)

Table 4 Form Factors (Q)

Test Section	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Test (σ_m/σ_y)
CH1-5	0.265	0.289	0.279	0.239	0.273	0.241	0.226	0.251
CH1-6	0.270	0.311	0.289	0.249	0.284	0.262	0.236	0.250
CH1-7	0.275	0.333	0.297	0.258	0.296	0.283	0.243	0.253
CH2-7	0.401	0.355	0.405	0.363	0.349	0.310	0.360	0.327
CH2-8	0.406	0.371	0.418	0.371	0.360	0.326	0.367	0.326
CH2-10	0.414	0.394	0.425	0.386	0.380	0.335	0.381	0.343
CH2-12	0.422	0.411	0.439	0.403	0.385	0.364	0.395	0.349
CH2-14	0.421	0.420	0.453	0.420	0.387	0.375	0.409	0.363

Column length: 800 mm (2.625 ft) for CH1 sections and
1000 mm (3.281 ft) for CH2 sections

Q1 AS1538, Ks=0.5, Kf=0.5, Kw=4.0
Q2 AS1538, Ks=0.5, Kf and Kw for the distortional mode
Q3 AISI, Ks=0.43, Kf and Kw values in Table 3(a)
F_n is assumed F_y
Q4 ECCS, Ks=0.43, Kf and Kw values in Table 3(a)
Q5 EC3/Annexe A, σ_s is assumed F_y
Q6 AS1538, Ks=0.5, Kf and Kw for the distortional mode
modified Winter formula
Q7 AISI, Ks=0.43, Kf and Kw values in Table 3(a)
modified Winter formula

Table 5(a) Column Strength based on Q1 and AS1538 Column Curve (Sec. 4.1)

Test Section	Q1	F_m / F_y	σ_m/σ_y	σ_m/F_m
CH1-5-800	0.265	0.254	0.251	0.99
CH1-6-800	0.270	0.259	0.250	0.97
CH1-7-400	0.275	0.272	0.271	1.00
CH1-7-600	0.275	0.268	0.264	0.99
CH1-7-800	0.275	0.263	0.253	0.96
CH1-7-1800	0.275	0.218	0.238	1.09
CH2-7-800	0.401	0.380	0.336	0.88
CH2-7-1000	0.401	0.368	0.327	0.89
CH2-7-1800	0.401	0.299	0.277	0.93
CH2-8-1000	0.406	0.373	0.326	0.87
CH2-10-1000	0.414	0.381	0.343	0.90
CH2-12-1000	0.422	0.389	0.349	0.90
CH2-14-1000	0.421	0.389	0.363	0.93
MEAN				0.95

Table 5(b) Column Strength based on Q2 and AS1538 Column Curve (Sec. 4.1)

Test Section	Q2	F_m / F_y	σ_m/σ_y	σ_m/F_m
CH1-5-800	0.289	0.276	0.251	0.91
CH1-6-800	0.311	0.297	0.250	0.84
CH1-7-400	0.333	0.329	0.271	0.82
CH1-7-600	0.333	0.324	0.264	0.81
CH1-7-800	0.333	0.317	0.253	0.80
CH1-7-1800	0.333	0.254	0.238	0.94
CH2-7-800	0.355	0.338	0.336	0.99
CH2-7-1000	0.355	0.328	0.327	1.00
CH2-7-1800	0.355	0.271	0.277	1.02
CH2-8-1000	0.371	0.342	0.326	0.95
CH2-10-1000	0.394	0.363	0.343	0.94
CH2-12-1000	0.411	0.379	0.349	0.92
CH2-14-1000	0.420	0.388	0.363	0.94
MEAN				0.91

Table 5(c) Column Strength based on Q3 and AISI Column Curve (Sec. 4.3)

Test Section	Q3	F_m / F_y	σ_m/σ_y	σ_m/F_m
CH1-5-800	0.279	0.267	0.251	0.94
CH1-6-800	0.289	0.278	0.250	0.90
CH1-7-400	0.297	0.294	0.271	0.92
CH1-7-600	0.297	0.289	0.264	0.91
CH1-7-800	0.297	0.283	0.253	0.89
CH1-7-1800	0.297	0.232	0.238	1.03
CH2-7-800	0.405	0.384	0.336	0.88
CH2-7-1000	0.405	0.372	0.327	0.88
CH2-7-1800	0.405	0.301	0.277	0.92
CH2-8-1000	0.418	0.383	0.326	0.85
CH2-10-1000	0.425	0.390	0.343	0.88
CH2-12-1000	0.439	0.404	0.349	0.86
CH2-14-1000	0.453	0.417	0.363	0.87
MEAN				0.90

Table 5(d) Column Strength based on Q4 and ECCS Column Curve (Sec. 4.2)

Test Section	Q4	F_m / F_y	σ_m/σ_y	σ_m/F_m
CH1-5-800	0.239	0.206	0.251	1.22
CH1-6-800	0.239	0.215	0.250	1.16
CH1-7-400	0.258	0.258	0.271	1.05
CH1-7-600	0.258	0.239	0.264	1.10
CH1-7-800	0.258	0.223	0.253	1.13
CH1-7-1800	0.258	0.160	0.238	1.48
CH2-7-800	0.363	0.315	0.336	1.07
CH2-7-1000	0.363	0.294	0.327	1.11
CH2-7-1800	0.363	0.224	0.277	1.24
CH2-8-1000	0.371	0.301	0.326	1.08
CH2-10-1000	0.386	0.314	0.343	1.09
CH2-12-1000	0.403	0.329	0.349	1.06
CH2-14-1000	0.420	0.344	0.363	1.06
MEAN				1.14

Table 5(e) Column Strength based on Q5 and EC3/Annexe A Column Curve (Sec. 4.2)

Test Section	Q5	F_m /F_y	σ_m/σ_y	σ_m/F_m
CH1-5-800	0.273	0.261	0.251	0.96
CH1-6-800	0.284	0.272	0.250	0.92
CH1-7-400	0.296	0.293	0.271	0.92
CH1-7-600	0.296	0.288	0.264	0.92
CH1-7-800	0.296	0.283	0.253	0.89
CH1-7-1800	0.296	0.231	0.238	1.03
CH2-7-800	0.349	0.332	0.336	1.01
CH2-7-1000	0.349	0.323	0.327	1.01
CH2-7-1800	0.349	0.267	0.277	1.04
CH2-8-1000	0.360	0.333	0.326	0.98
CH2-10-1000	0.380	0.351	0.343	0.98
CH2-12-1000	0.385	0.356	0.349	0.98
CH2-14-1000	0.387	0.359	0.363	1.01
MEAN				0.97

Table 5(f) Column Strength based on Q6 and AS1538 Column Curve (Sec. 4.1)

Test Section	Q6	F_m /F_y	σ_m/σ_y	σ_m/F_m
CH1-5-800	0.241	0.232	0.251	1.08
CH1-6-800	0.262	0.251	0.250	1.00
CH1-7-400	0.283	0.280	0.271	0.97
CH1-7-600	0.283	0.276	0.264	0.96
CH1-7-800	0.283	0.279	0.253	0.91
CH1-7-1800	0.283	0.223	0.238	1.07
CH2-7-800	0.310	0.296	0.336	1.14
CH2-7-1000	0.310	0.288	0.327	1.14
CH2-7-1800	0.310	0.243	0.277	1.14
CH2-8-1000	0.326	0.303	0.326	1.08
CH2-10-1000	0.335	0.311	0.343	1.10
CH2-12-1000	0.364	0.338	0.349	1.03
CH2-14-1000	0.375	0.348	0.363	1.04
MEAN				1.05

* Proposal 1a - AS1538

Table 5(g) Column Strength based on Proposal 1b

Test Section	Ae/A	F_n / F_y	σ_m/σ_y	σ_m/ F_n
CH1-5-800	0.231	0.222	0.251	1.13
CH1-6-800	0.240	0.231	0.250	1.08
CH1-7-400	0.245	0.242	0.271	1.12
CH1-7-600	0.246	0.240	0.264	1.10
CH1-7-800	0.248	0.238	0.253	1.06
CH1-7-1800	0.271	0.216	0.238	1.10
CH2-7-800	0.366	0.352	0.336	0.95
CH2-7-1000	0.369	0.347	0.327	0.94
CH2-7-1800	0.393	0.317	0.277	0.87
CH2-8-1000	0.377	0.354	0.326	0.92
CH2-10-1000	0.390	0.368	0.343	0.93
CH2-12-1000	0.404	0.381	0.349	0.92
CH2-14-1000	0.419	0.396	0.363	0.92
MEAN				1.00

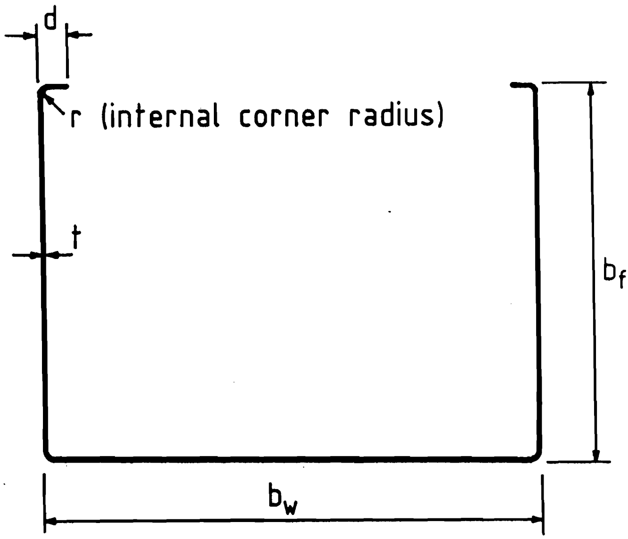
* Proposal 1b - AISI

Table 5(h) Column Strength based on Proposal 2

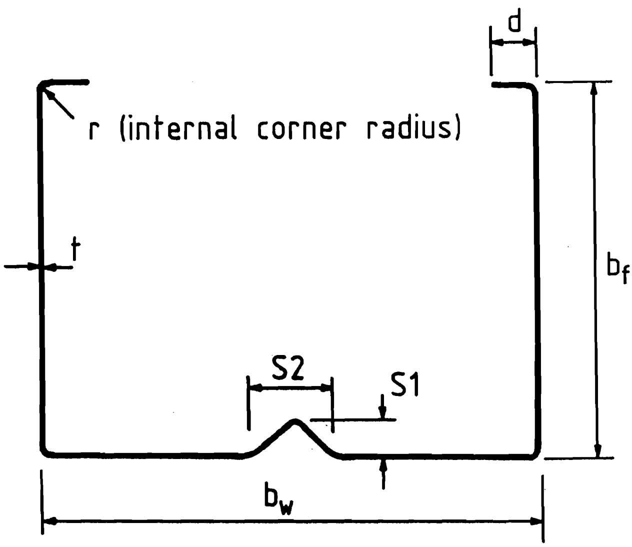
Test Section	*1Ae/A	F_n / F_y	σ_m/σ_y	σ_m/ F_n
CH1-5-800	0.139	0.237	0.251	1.06
CH1-6-800	0.143	0.252	0.250	0.99
CH1-7-400	0.093	0.286	0.271	0.95
CH1-7-600	0.120	0.282	0.264	0.94
CH1-7-800	0.147	0.274	0.253	0.92
CH1-7-1800	0.273	0.246	0.238	0.97
CH2-7-800	0.216	0.292	0.336	1.15
CH2-7-1000	0.248	0.277	0.327	1.18
CH2-7-1800	0.370	0.257	0.277	1.08
CH2-8-1000	0.251	0.304	0.326	1.07
CH2-10-1000	0.256	0.342	0.343	1.00
CH2-12-1000	0.260	0.374	0.349	0.93
CH2-14-1000	0.265	0.391	0.363	0.93
MEAN				1.01

*1 based on F_{oc}

* Proposal 2 - AISI



(a) Simple Lipped Channel (CH1)



(b) Stiffened Lipped Channel (CH2)

FIG.1 TEST SECTIONS

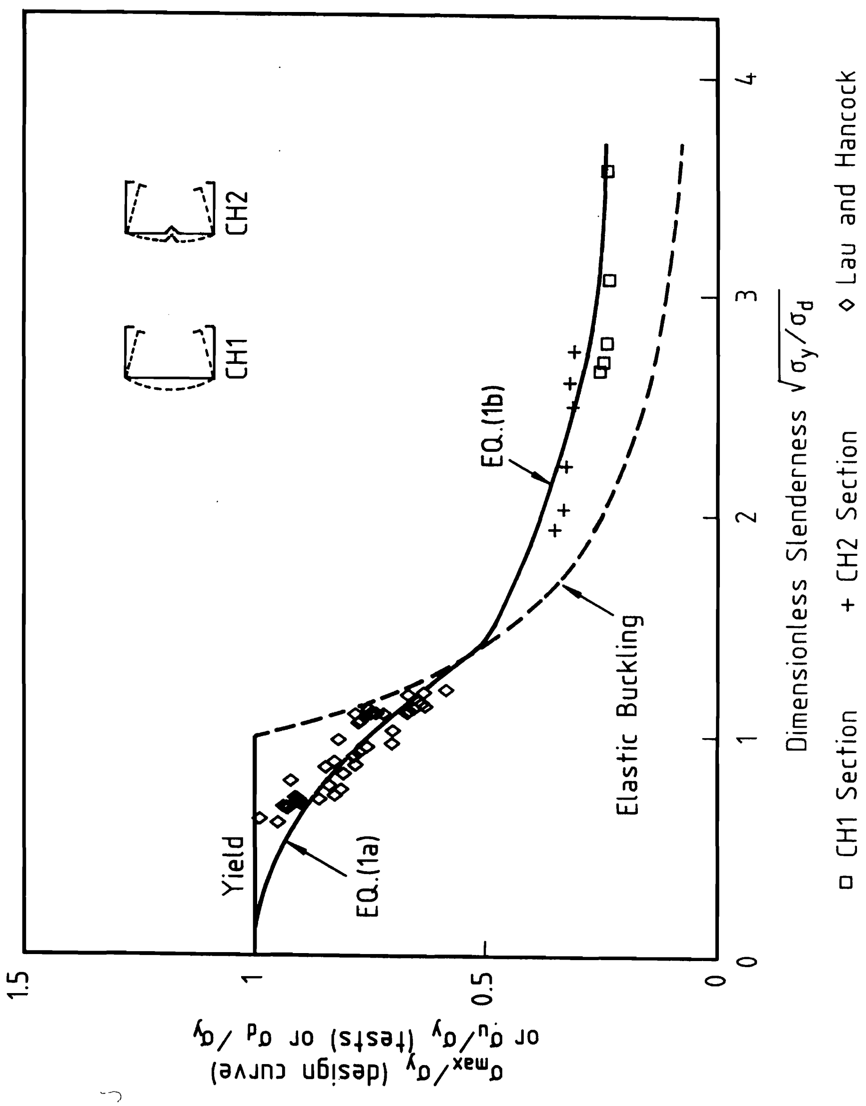


FIG.2(a) COMPARISON OF TEST RESULTS WITH DESIGN PROPOSAL 1

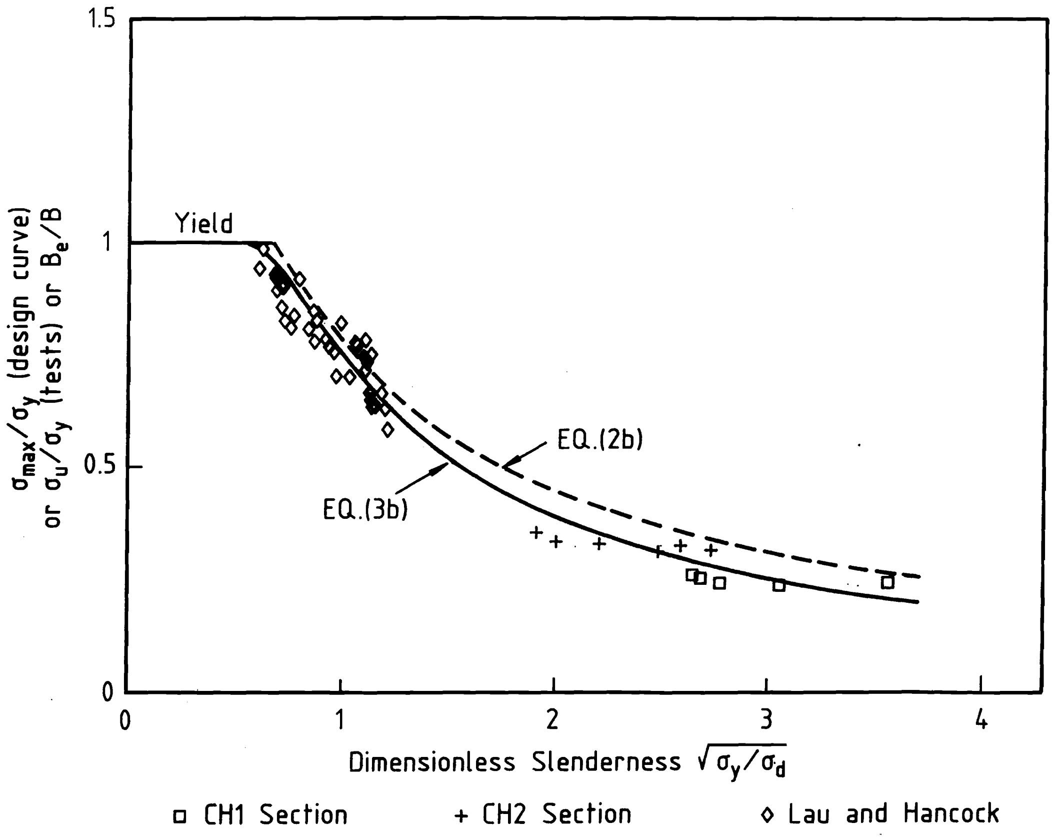


FIG.2(b) COMPARISON OF TEST RESULTS WITH DESIGN PROPOSAL 2 AND WINTER FORMULA

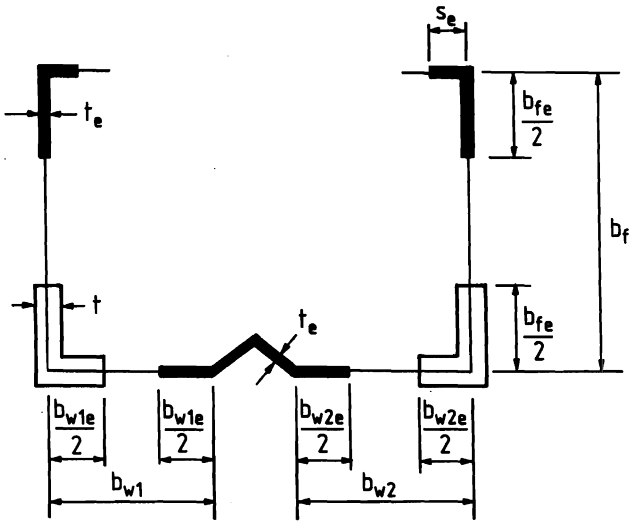


FIG.3 EFFECTIVE AREA OF STIFFENED LIPPED CHANNEL FOR EC3/ANNEXE A

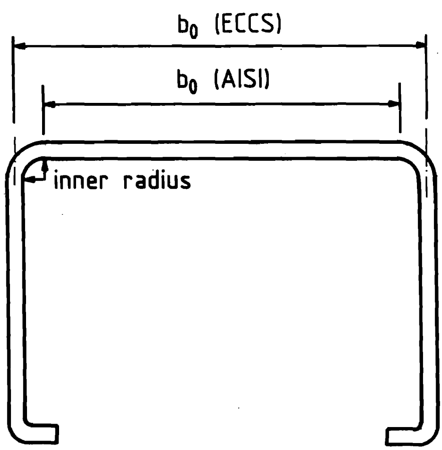


FIG.4 WIDTH OF SECTION DEFINED BY AISI AND ECCS

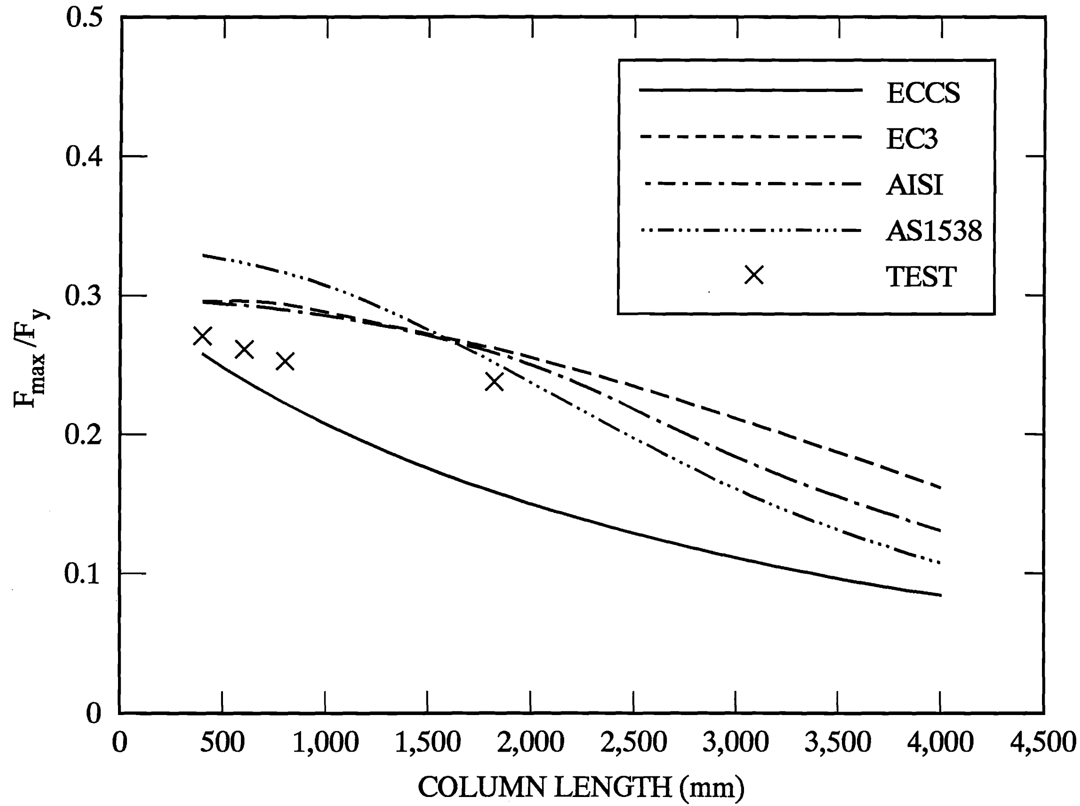


FIG.5 COMPARISON OF TEST RESULTS WITH EXISTING DESIGN CURVES FOR CHI-7 SECTION

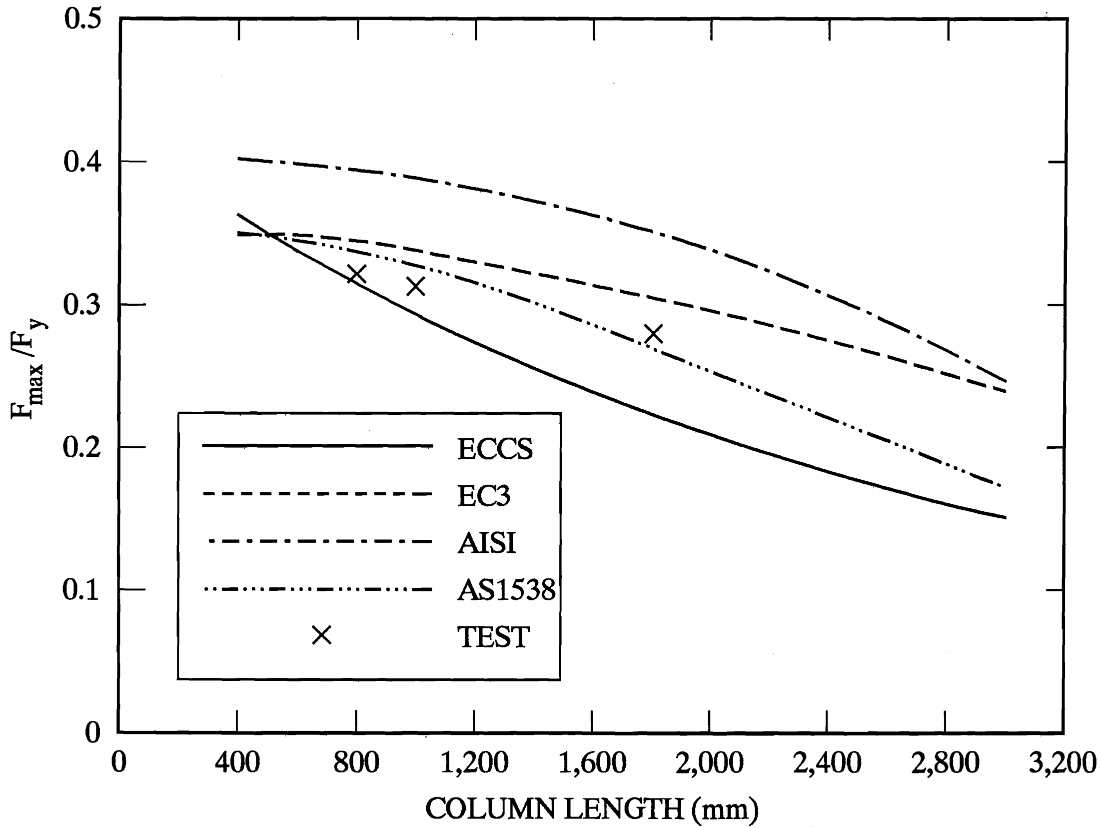


FIG. 6 COMPARISON OF TEST RESULTS WITH EXISTING DESIGN CURVES FOR CH2-7 SECTION

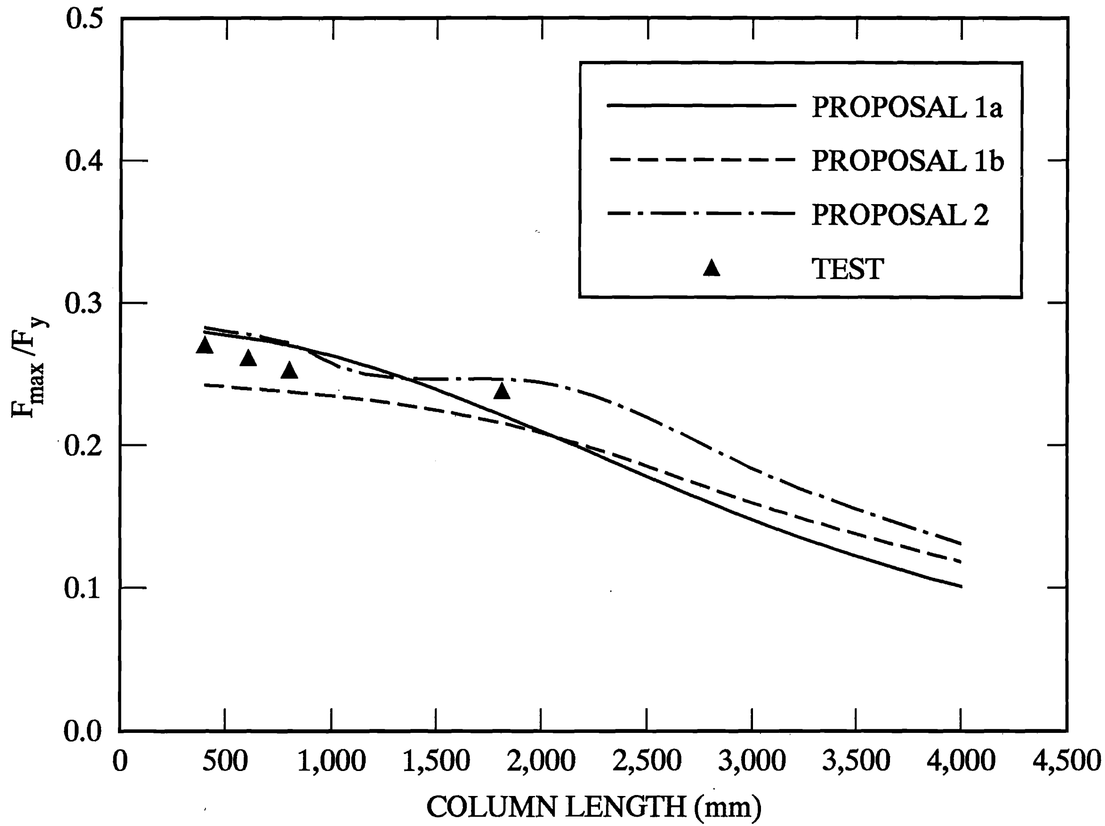


FIG. 7 COMPARISON OF TEST RESULTS WITH PROPOSED DESIGN CURVES FOR CHI-7 SECTION

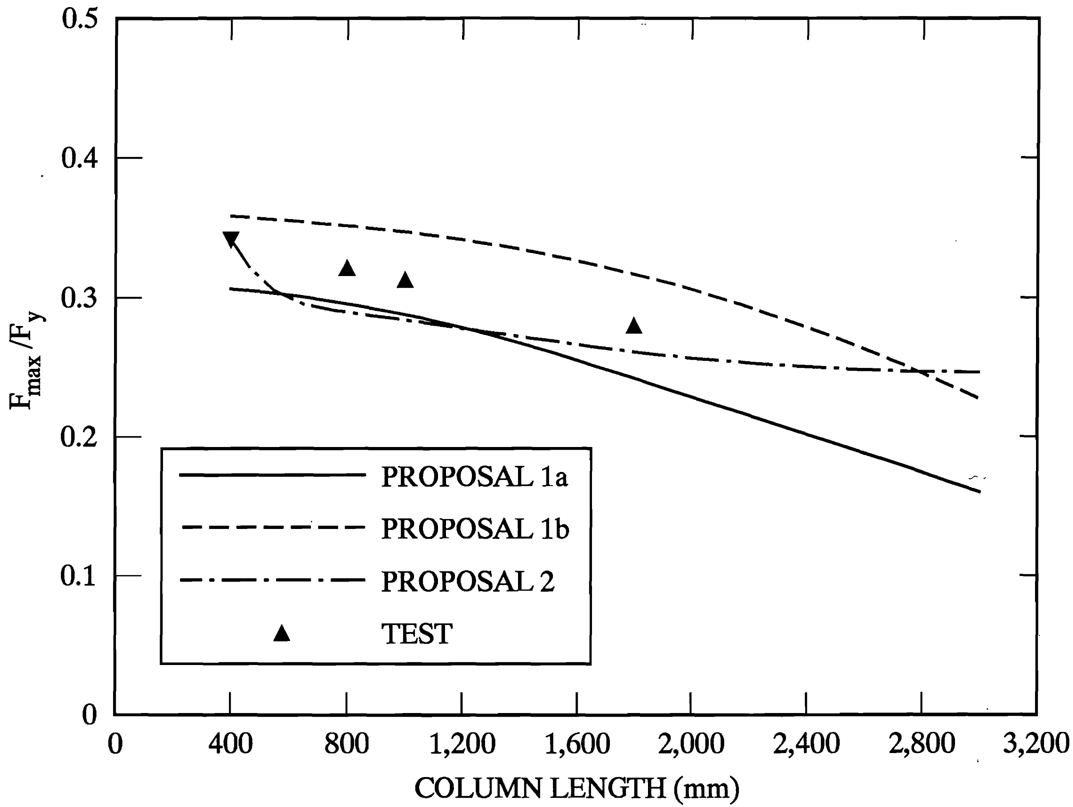


FIG. 8 COMPARISON OF TEST RESULTS WITH PROPSED DESIGN CURVES FOR CH2-7 SECTION