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Abstract

The innovative, rivet fastened Rectangular Hollow Flange Channel Beam (RHFCB) is a new type of cold-formed steel section, proposed as an extension to the widely researched hollow flange beams. The hollow flange beams have garnered much interest in the past due to the sections having capacities more typically associated with hot-rolled steel sections. Various researches have been carried out to investigate the behavior of continuously welded hollow flange beams but little is known on the behavior of RHFCBs. The structural behaviour of the RHFCB is unique compared to other conventional cold-formed steel sections and its moment capacity reduces with rivet spacing. The current cold-formed steel design standards do not provide a calculation method to include the effects of intermittent fastening. In this research an extensive parametric study was conducted using validated finite element models to investigate the section moment capacity of RHFCBs. This paper presents the findings from the parametric study and proposes new design equations for the section moment capacity of RHFCBs in the Direct Strength Method format. The parametric study considers various slenderness regions, section dimensions and rivet spacing. In the new design equations, a reduction factor parameter is included to calculate the section moment capacity of RHFCBs at any rivet spacing up to 200 mm.

Keywords: Cold-formed Steel Beams, Rivet Fastened Hollow Flange Channel Beams, Finite Element Analysis, Bending, Local Buckling, Design Equations.

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Introduction

The use of cold-formed steel in the construction industry today is becoming increasingly important and widespread. The benefits of cold-formed steel construction are lightweight, ease of transportation and reduced construction cost. In the past, traditional cold-formed steel sections such as the simple channels (Cs) and zeds (Zs), are used as purlins. Today, as fabrication technology improves, more unique cold-formed steel sections are introduced.

Significant to this development is the cold-formed and welded hollow flange beam, which has been shown by researchers to have capacities similar to those of hot-rolled steel beams. This superior quality of the section compared to other cold-formed steel sections, which are normally governed by local buckling due to free edges, has garnered much interest even after it was discontinued due to expensive dual-electric resistance welding used in its fabrication. In the past, the structural application of hollow flange beams is mainly as flexural members such as bearers and joists in the residential, industrial and commercial buildings. The first type of hollow flange beams is known as the Triangular Hollow Flange Beam shown in Figure 1 (a). With improved manufacturing process and capacity, the second type of hollow flange beam was developed, known as the LiteSteel beam (LSB) (Figure 1 (b)). Compared to the first triangular hollow flange beam, the rectangular flanges of the LSBs provide better connectivity to other members. Today, both hollow flange beams are discontinued due to expensive dual electric resistance welding used in the fabrication. However, there are still interests and demands in the industry for such sections.

(a) (b)

Figure 1: Hollow Flange Beams

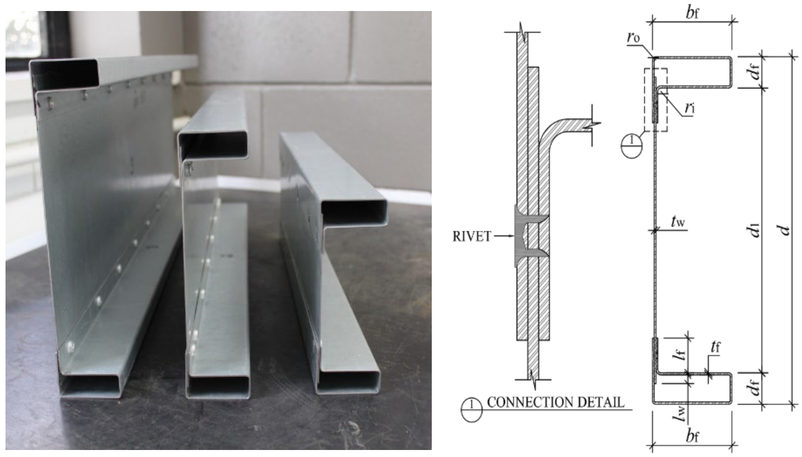


Figure 2: Rivet Fastened Rectangular Hollow Flange Channel Beam

As part of continuing research in this area, a new type of hollow flange beam known as the rivet fastened Rectangular Hollow Flange Channel Beam (RHFCB) was proposed (Figure 2) and investigated. Two cold-formed rectangular hollow flanges are connected to a web plate using self-pierce rivets at suitable spacings along the length to form the new hollow flange beam sections. Experimental and numerical investigations of the section moment capacity of RHFCBs subject to local buckling have been reported in Siahaan et al. (2016a and 2016b). The intermittently rivet fastened RHFCB serves as an inexpensive alternative by eliminating the electric resistance welding process, but still exhibits the torsionally rigid hollow flange characteristics of hollow flange beams.

The section moment capacities of the RHFCBs subject to local buckling effects have been investigated using four-point bending arrangement (Siahaan et al., 2016a). In the experimental investigation of its section moment capacity, the behaviour of 50 mm rivet fastened RHFCB has been shown to be comparable to welded hollow flange steel beam (Figure 1 (b)) investigated in Anapayan et al. (2011). Unlike other conventional cold-formed steel sections, the hollow flange beams have improved moment capacities due to the presence of torsionally rigid hollow flanges. Further the additional lips in the RHFCB (Figure 2) contribute to additional stiffening of the beam. However, the section moment capacity of RHFCBs reduced with increasing rivet spacing. Subsequently, finite element models were developed and validated by comparison with the test results (Siahaan et al., 2016b). However, they were limited to a few RHFCB sections and three rivet spacings, and the results are inadequate to develop accurate design rules for their section moment capacity as a function of RHFCB sizes and rivet spacing. In this paper, an extensive numerical parametric study of RHFCBs was conducted using the validated finite element model. The study considered various factors including RHFCB dimensions, rivet spacing and slenderness of the overall section.

A detailed numerical parametric study of intermittently fastened RHFCBs was conducted in this research to determine their section moment capacities including the inelastic capacity component. This paper describes the details of the parametric study and presents the results. Comparisons with current design standards were also made. New design equations were proposed for the section moment capacity of RHFCBs in the Direct Strength Method (DSM) format. In the new design equations, a reduction factor parameter was included to calculate the section moment capacity of RHFCBs at any rivet spacing up to 200 mm.

Parametric study

Finite element model (FEM) to simulate the behaviour of tested rivet fastened RHFCBs subject to local buckling was developed using MSC/Patran as pre- and post-processing facility, and analysed using ABAQUS. The RHFCBs were tested using a four-point bending arrangement and hence the FEM was a half-length model as shown in Figure 3. The details of the FEM are described in Siahaan et al. (2016b) where the model was validated by comparison with experimental results in terms of ultimate moment and failure mode as well as comparison with elastic local buckling moments from Thin-Wall software. The validated FEM was then used in an extensive parametric study of many RHFCB sections (Table 1). Figure 3 shows the simply supported boundary conditions used in the FEM where u_x, u_y and u_z denote translations and θ_x, θ_y and θ_z denote rotations in the x, y and z directions, respectively. Here, “0” denotes free while “1” denotes restrained. At the support, a Single Point Constraint (SPC) of “234” was applied where it is restrained against in-plane vertical deflection and out-of-plane horizontal deflection, as well as fixed against twist rotation (i.e. y- and z-axis translation; and x-axis rotation restrained).

$$u_x = 0 \; u_y = 1 \; u_z = 1 \; \theta_x = 1 \; \theta_y = 0 \; \theta_z = 0$$

At the loading point, SPC “34” was applied (Figure 3 (b)).

$$u_x = 0\ u_y = 0\ u_z = 1\ \theta_x = 1\ \theta_y = 0\ \theta_z = 0$$

A symmetrical boundary condition of SPC "156" was applied at the mid-span to simulate half span modelling used in the FEM.

$$u_x = 1\ u_y = 0\ u_z = 0\ \theta_x = 0\ \theta_y = 1\ \theta_z = 1$$

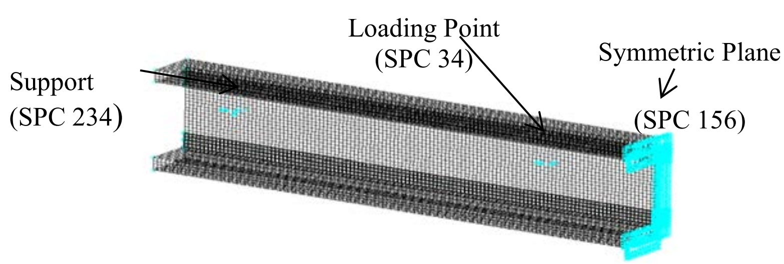
The FEM incorporated ABAQUS shell element S4R, with mesh sizes of 5 mm x 5mm. In order to simulate web stiffener plates, rigid body R3D4 was used. Nine integration points through the element thickness were used to model the distribution of stresses through the thickness of the shell elements. In order to model the surfaces that come in contact during the simulation at the lip-web-lip region, contact pair was modelled between the three surfaces. The details of this complicated contact model can be found in Siahaan et al. (2016) and are as shown in Figure 4.

Table 1: Nominal Dimensions and Section Properties of Rivet Fastened RHFCBs

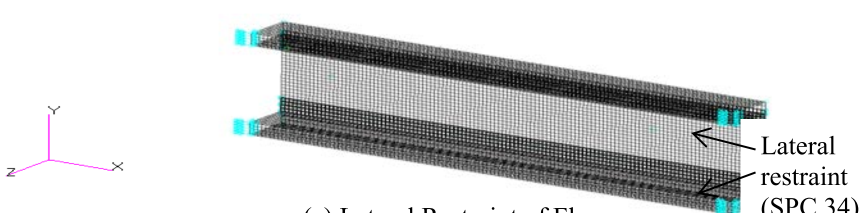
RHFCB Sections $d \times b_f \times d_f \times t_f \times t_w$ (mm)	d (mm)	b_f (mm)	d_f (mm)	t_f (mm)	t_w (mm)	Z (mm^3)
Group A						
200x75x20x3x3	200	75	20	3.0	3.0	115200
200x60x20x3x3	200	60	20	3.0	3.0	98700
200x45x20x3x3	200	45	20	3.0	3.0	83860
150x45x20x2x2	150	45	20	2.0	2.0	36830
200x45x20x2x2	200	45	20	2.0	2.0	56830
250x45x20x2x2	250	45	20	2.0	2.0	78790
250x75x20x2x3	250	75	20	2.0	3.0	111700
200x60x20x1.5x3	200	60	20	1.5	3.0	55990
150x45x20x2x3	150	45	20	2.0	3.0	38830
200x45x20x2x3	200	45	20	2.0	3.0	61070
125x45x20x2x2.5	125	45	20	2.0	2.5	28270
Group B						
152x62x19x1.1x1.9	152	62	19	1.1	1.9	28760
201x62x19x1.1x1.9	201	62	19	1.1	1.9	41820
250x62x19x1.1x1.9	250	62	19	1.1	1.9	58330
150x53x18x0.9x1.5	150	53	18	0.9	1.5	20120
150x53x18x1.1x1.5	150	53	18	1.1	1.5	23860
201x53x18x0.9x1.9	201	53	18	0.9	1.9	33380
201x53x18x1.1x1.9	201	53	18	1.1	1.9	38810
250x62x19x0.9x1.9	250	62	19	0.9	1.9	50090
250x62x19x1.1x1.5	250	62	19	1.1	1.5	55020

In this parametric study, an initial geometric imperfection of d/150 was considered for local imperfection where “d” is the section depth. Residual stresses are not considered in the FEM, assuming they are negligible (Siahaan et al., 2016b). In the analysis, two types of analyses were carried out: elastic buckling and nonlinear static analyses. Elastic buckling analysis was carried out first and was used to obtain governing eigenvector for the purpose of including geometric imperfection. Subsequently, nonlinear static analysis was carried out to investigate the behaviour of the RHFCB up to failure. Although the RIKS method is prevalent in obtaining the ultimate load in the analysis of cold-formed steel sections, general static analysis was employed for the FEM of the RHFCB due to localized instabilities. The method was incorporated to good success, with the addition of artificial damping, without affecting the behaviour of the beams significantly.

(a) Schematic Diagram of FE Model

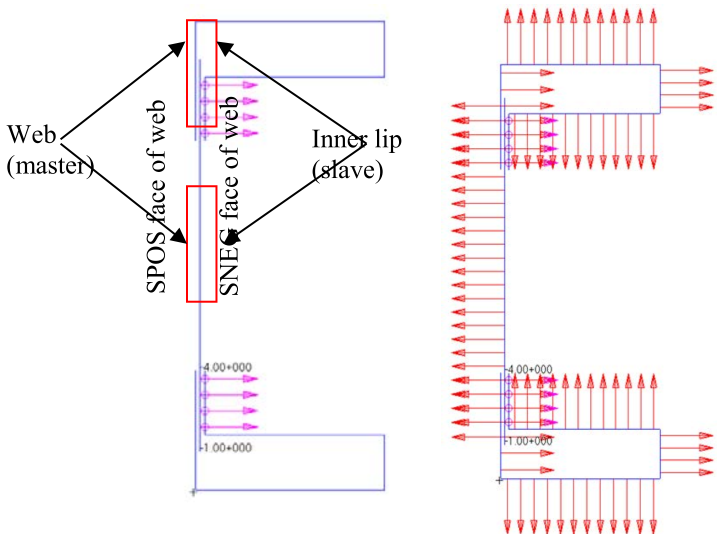


(b) Support, Loading Point and Symmetric Plane

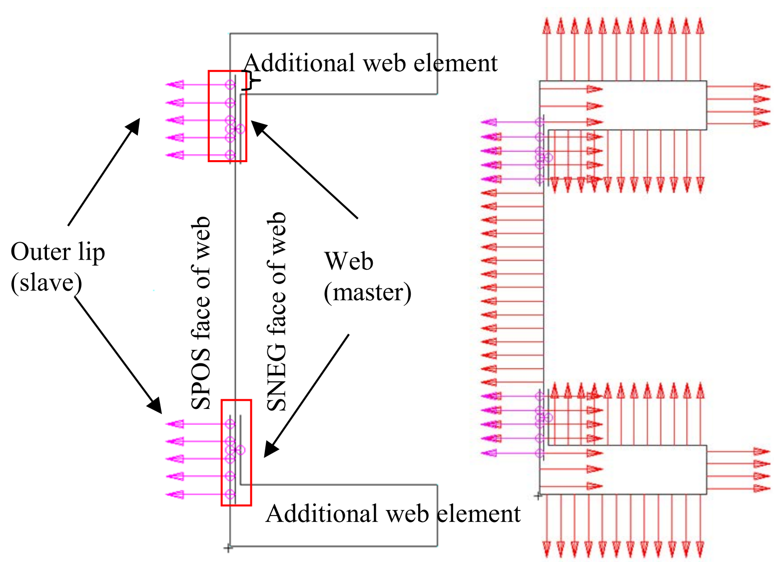


(c) Lateral Restraint of Flanges

Figure 3: Finite element model of RHFCB



(a) Contact Pair Simulation between Web and Inner Lip



(b) Contact Pair Simulation between Web and Outer Lip

Figure 4: Contact Modeling Details

Table 1 presents the nominal dimensions of the RHFCBs investigated in the parametric study. The lengths of the lips and the additional web elements (Figure 2) were 20 mm and 5 mm, respectively, to allow for assembly and fastening of the section, and were kept constants in this study. Also, the following mechanical properties are kept constant: Young's modulus of elasticity (E) = 200,000 MPa; Poisson's ratio (ν) = 0.3.

Since the RHFCB is not currently available in the market, there is no limitation on the section dimensions. Therefore, the RHFCBs investigated in this study were carefully selected based on parameters intended for investigation here: different combination of flange and web compactness (such as compact, non-compact and slender), fastener spacing (welded and rivet spacing of 50, 100 and 200 mm), combination of flange and web thicknesses ($t_f = t_w$, and $t_f < t_w$), and yield stresses. In this study, the welded RHFCB was considered as its moment capacity could be used as the benchmark in investigating the important effects of increasing rivet spacing on the moment capacity. In Table 1, Group A RHFCBs refer to thicker sections (mostly compact and non-compact according to AS 4100 (SA, 1998) classification while Group B refers to more slender RHFCBs which have been investigated earlier in the experiments and FEM validation (Siahaan et al., 2016a and 2016b). In this study, the numerical studies of slender, Group B RHFCBs, were extended by varying the yield stress. Note that AS 4100 hot-rolled steel classification was used here as the current AS/NZS 4600 (SA, 2005) cold-formed steel classification does not allow the inclusion of inelastic bending capacity for hollow flange beams. Table 1 presents the elastic section modulus (Z) values obtained from Thin-Wall. Further details of the parametric study and FEA results are reported in Siahaan (2016).

Comparison with current design rules

The numerical parametric study results are compared with the predicted section moment capacities from Effective Width Method (EWM) in AS/NZS 4600 and the Direct Strength Method (DSM).

Using the EWM provision in AS/NZS 4600, the section moment capacities (M_s) of Groups A and B RHFCBs were calculated and are presented in Siahaan (2016). It is noted that the current design standard does not have any provision for intermittent rivet spacing. Therefore, the predictions of M_s shown here refer to an assumed continuous welded connection along the web-flange junction and are compared with the ultimate moment capacities from FEA (M_u). For Group A

RHFCBs, the average M_u/M_s ratios for welded and 50 mm rivet fastened RHFCBs are 1.20 and 1.13 while they are 1.07 and 0.97, respectively, for RHFCBs rivet fastened at 100 mm and 200 mm.

Meanwhile for Group B RHFCBs, the average M_u/M_s ratios are 1.01, 0.90 and 0.81, respectively, for 50 mm, 100 mm and 200 mm rivet spacing. Previous experimental investigation (Siahaan et al., 2016) reported that the behaviour of 50 mm rivet fastened RHFCBs is comparable to that of welded hollow flange beams (such as the LiteSteel beam) where the AS/NZS 4600 is conservative in predicting the capacity of 50 mm rivet fastened RHFCBs. The results from this study show that the current design standard is able to predict the section moment capacities of 100 mm rivet fastened RHFCBs reasonably well. It is noted that the AISI S100 and AS/NZS 4600 have identical EWM design rules in relation to the section moment capacities of cold-formed steel beams.

The actual solution of the EWM for intermittently fastened beams is complicated. The current provisions in AS/NZS 4600 do not allow for the unrestrained edge conditions between the points of rivet fastening. Therefore, the calculation was based on an assumed continuous weld fastening. This study confirmed that the AS/NZS 4600 predictions are conservative for welded RHFCBs with a mean M_u/M_s ratio of 1.20, but this ratio reduces to 0.97 for Group A RHFCBs with 200 mm rivet spacing for the above reason (such as the lack of continuity along web to flange junction). Considering the M_u/M_s ratios, however, it is in general adequate to use the current AS/NZS 4600 design rules for RHFCBs with a maximum rivet spacing of 100 mm.

The Direct Strength Method (DSM) is an alternative design method, providing a more straightforward method to compute the section moment capacities of sections given that the elastic buckling (M_{ol}) and first yield (M_y) moments are known. The DSM can be found in the Australian/New Zealand Standard for cold-formed steel structures, AS/NZS 4600 (SA, 2005) as well as the AISI S100 Standard (AISI, 2012).

The nominal section moment capacity for local buckling (M_{nl}) of sections symmetric about the axis of bending can be calculated using Equations 1 and 2.

$$For\ \lambda_l \leq 0.776, M_{nl} = M_y \quad (1)$$

$$For\ \lambda_l > 0.776, M_{nl} = [1 - 0.15\left(\frac{M_{ol}}{M_y}\right)^{0.4}](\frac{M_{ol}}{M_y})^{0.4} M_y \quad (2)$$

where: $\lambda_l = \sqrt{M_y/M_{ol}}$; $M_y = Zf_y$; Z = elastic section modulus; f_y = yield stress, M_{ol} = elastic buckling moment.

In 2012, the AISI S100 standard included a new provision for inelastic reserve capacity in bending (i.e. where $M_{nl} > M_y$). For sections symmetric about the axis of bending or sections with first yield in compression, inelastic reserve bending capacity is given by Equation 3.

$$For\ \lambda_l \leq 0.776, M_{nl} = M_y + (1 - {}^{1}/{}_{C_{yl}{}^{2}})(M_p - M_y) \quad (3)$$

where: $\lambda_l = \sqrt{M_y/M_{ol}}$; $C_{yl} = \sqrt{{}^{0.776}/{}_{\lambda_l}} \leq 3$; $M_y = Zf_y$; $M_p = Sf_y$; Z = elastic section modulus; S = plastic section modulus; f_y = yield stress, M_{ol} = elastic buckling moment.

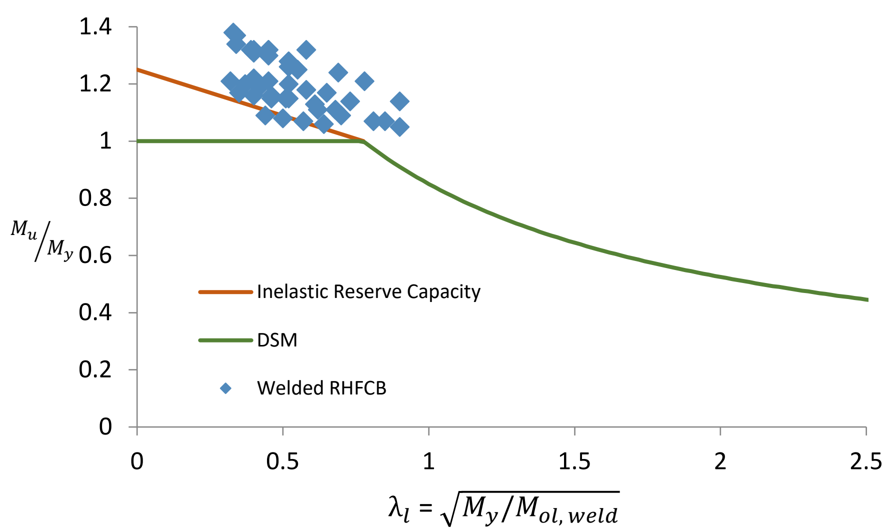


Figure 5: Comparison of Section Moment Capacities with DSM Predictions for Welded RHFCBs

The section moment capacity predictions using the current DSM based equations 1 to 3 are shown on a DSM plot for welded RHFCBs in Figure 5 using their elastic local buckling moment ($M_{ol,\ weld}$) from Thin-Wall software. The current DSM provision was found to be conservative for welded RHFCBs with most points scattered above the inelastic reserve capacity line. Then the results of RHFCBs with 200 mm rivet spacing were plotted on the DSM plot using their respective elastic local buckling moments ($M_{ol,\ rivet}$). In this plot (Figure 6), the results from experiments and Group A and B parametric study were included. For 200 mm rivet fastened RHFCBs, the current DSM provision in AS/NZS 4600 and AISI S100 was unable to predict their section moment capacities (unconservative). This can be attributed to the fact that for RHFCBs with the same dimensions, the variation in M_{ol} value with rivet spacing is small while M_y value remains constant. As a result, the DSM was not able to capture the reduction due to the loss of continuous connection along the web to flange junction. Therefore, there is a need to introduce a separate reduction factor in Equations 1 to 3 to account for the effect of intermittent rivet fastening (lack of continuity along the web to flange junction) on the section moment capacity of RHFCBs.

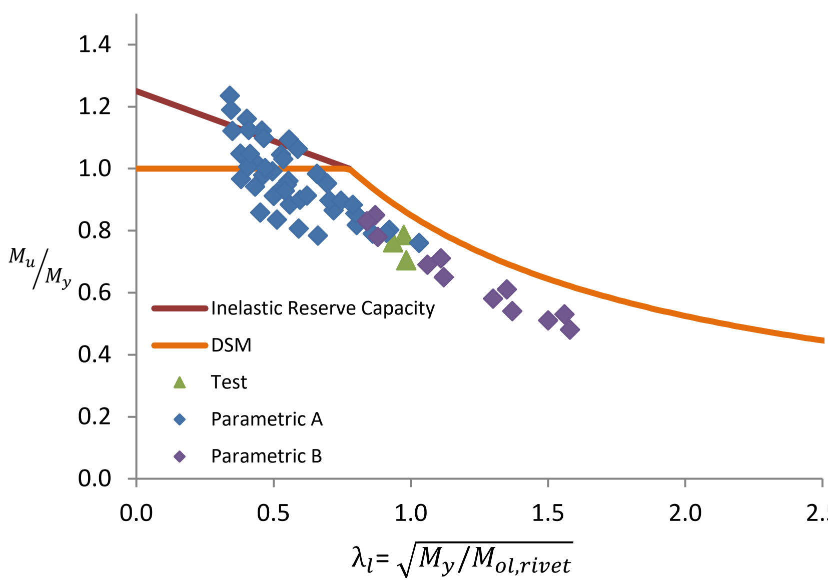


Figure 6: Comparison of Section Moment Capacities with DSM Predictions for Rivet Fastened RHFCBs at 200 mm Spacing

Proposed design rules for RHFCBs

In Siahaan et al. (2016a), the section moment capacity of rivet fastened RHFCBs was studied through experimental investigation of 15 rivet fastened RHFCBs. All tested RFHCBs were more in the slender region with λ_l values larger than 0.776 (DSM Eq. 2). Based on these test results, the section moment capacity of the rivet fastened RHFCBs was found to reduce by a factor of 0.0014 with increasing rivet spacing. Hence a reduction factor was proposed to Eq. 2, which took into consideration rivet spacing (s) and flange thickness (t_f).

In this parametric study, the section moment capacity investigation of the rivet fastened RHFCBs was significantly extended to beams in various slenderness regions. Hence, the appropriate design equation for rivet fastened RHFCBs is further refined here. The study looks into proposing modifications to Eqs. 2 and 3 as they currently do not account for intermittent rivet fastening. Therefore, it is proposed to introduce an accurate reduction factor q_s by considering the effects of all the potential influential parameters including the important parameter of rivet spacing.

As the first step into proposing the appropriate q_s, various parameters that influenced this reduction in the section moment capacity of rivet fastened RHFCBs were identified. These parameters are: rivet spacing (s), full web depth (d), clear web depth (d_1), additional web element (l_w), web thickness (t_w), flange width (b_f), flange thickness (t_f), flange depth (d_f), lip length (l_f), and the yield stress of the compression flange (f_y). In this parametric study, the additional web element (l_w), lip length (l_f), and flange depth (d_f) have been kept constant. Among the three parameters, flange depth (d_f) was taken to be more influential and so additional FEA was carried out by varying this parameter.

Using genetic algorithm (evolutionary) solver and all the numerical parametric study results, a suitable reduction factor (q_s) was developed and is shown in Equation 4. It was developed by including all elements which affect the deformation behaviour and the section moment capacities of the rivet fastened RHFCBs. In Equation 4, the first parameter (s/d) accounts for the effect of rivet spacing. The second and third parameters are in the form of the element's plate slenderness ratio. The second parameter was considered to account for web local buckling where the full web plate was considered ($(d_1 + 2l_w) / t_w$). Next, the horizontal flange element was considered to account for flange local buckling (b_f/t_f), followed by the adjacent vertical flange element which buckles sympathetically with the horizontal flange ($(d_f + l_f) / t_f$). Finally, the critical flange yield stress is considered.

$$q_s = 1 - 0.0135\left[{}^{s}/_{d}\right]^{0.669}\left[\frac{d_1 + 2l_w}{t_w}\right]^{0.444}\left[{}^{b_f}/_{t_f}\right]^{0.1}\left[\frac{d_f + l_f}{t_f}\right]^{0.1}\left[\frac{f_y}{250}\right]^{0.2} \quad (4)$$

The proposed reduction factor (q_s) can then be applied to DSM Equations 2 and 3, respectively, where they now become Equations 5 and 6. Based on the results of the parametric study also, it is proposed that the λ_l limit is extended from the initial value of 0.776 to 0.96. Equations 5 and 6 were proposed based on FEA results of welded RHFCBs (see Figure 7).

$$For\ \lambda_l > 0.96, M_{nl} = \left[\left[1 - 0.04\left(\frac{M_{ol,weld}}{M_y}\right)^{0.50}\right]\left(\frac{M_{ol,weld}}{M_y}\right)^{0.50} M_y\right] q_s \quad (5)$$

$$For\ \lambda_l \leq 0.96, M_{nl} = [M_y + (1 - \left[\frac{1}{{C_{yl}}^2}\right])(M_p - M_y)]q_s \quad (6)$$

where: $\lambda_l = \sqrt{M_y/M_{ol,weld}}$; $C_{yl} = \sqrt{{}^{0.96}/_{\lambda_l}} \leq 3$; M_y = first yield moment = Zf_y; M_p = plastic moment; $M_{ol,\,weld}$ = elastic buckling moment of welded RHFCB, q_s = reduction factor (Eq. 4).

Next, the reduction factors (q_s) calculated using Eq. (4) for all RHFCBs in this parametric study were compared with the values from FEA ($M_{u,\,rivet} / M_{u,\,weld}$). Taking the ratio of $q_{s\,(FEA)}$ to $q_{s\,(Eq.\,4)}$, the mean was 1.00 with a CoV of 0.047. This suggests good agreement between the proposed Eq. (4) and FEA values.

It can be seen that using Equation 6, the current plot is still conservative where many data points still remain above the inelastic reserve capacity line (Figure 7). Therefore, Eq. 6 was further refined to Eq. 7. The updated DSM plot using the proposed curved inelastic reserve capacity equation (Eq. (6)) is shown in Figure 7, which shows a better fit.

$$For\ \lambda_l \leq 0.96, M_{nl} = [M_y + (1 - \left[\frac{1}{{C_{yl}}^2}\right]^3)(M_p - M_y)]q_s \quad (7)$$

where: all the parameters are as defined for Eq. 6.

As a summary, the DSM provision in AISI S100 (Eqs. 1 to 3), AS/NZS 4600 (Eqs. 1 and 2) and the newly proposed Eqs. 5 and 6 and Eqs. 5 and 7 are compared in Siahaan (2016). In general, the AS/NZS 4600 was found to be over-conservative by 15% due to the exclusion of inelastic reserve capacity in RHFCBs. The current DSM in AISI S100, despite having a provision for inelastic reserve capacity for cold-formed steel beams, showed under-prediction by 11%. Meanwhile, the initially proposed Eqs. 5 and 6 showed good agreement with a mean value of 1.05. The finally proposed Eqs. 5 and 7 showed much better agreement with a mean value of 1.00 and a CoV of 0.074. Therefore proposed that Eqs. 5 and 7 are used in the design of RHFCBs subject to local buckling effects for rivet spacing of up to 200 mm.

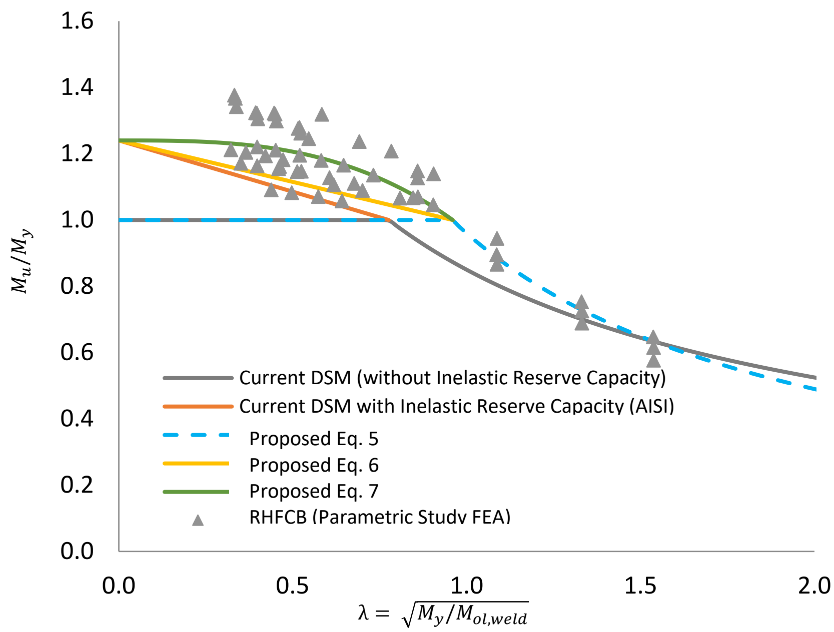


Figure 7: DSM Prediction using the Proposed DSM and Inelastic Reserve Capacity Equations 6 and 7 (Welded RHFCBs)

Conclusions

A numerical parametric study was conducted on the section moment capacities of rivet fastened RHFCBs, considering various aspects including: flange and web compactness, rivet fastener spacing, flange and web thicknesses and yield stresses. Comparison with the predictions from the effective width method based design equations in AS/NZS 4600 and AISI S100 showed that it is conservative for welded and 50 mm rivet fastened RHFCBs despite the assumption of continuity along the web to flange junction. A new proposal was made to the current DSM equations by introducing a reduction factor (q_s) to account for the loss of moment capacity due to intermittent rivet fastening. Suitable modifications were also made to include the available inelastic reserve bending capacity of RHFCBs accurately. Comparisons with the numerical parametric study results demonstrated the accuracy of the modified DSM equations.

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References

American Iron and Steel Institute (AISI) (2012), "Specifications for the cold-formed steel structural members, cold-formed steel design manual", AISI S100, Washington DC, USA.
Anapayan, T., Mahendran, M. & Mahaarachchi, D. 2011. Section moment capacity tests of LiteSteel beams. Thin-Walled Structures, 49, 502-512.
SA 2005. AS/NZS 4600:2005: Australian/New Zealand Standard Cold-formed steel structures. Sydney, Australia: SAI Global Limited Standards New Zealand.
Shifferaw, Y. 2008. Inelastic bending capacity in cold-formed steel members. Department of Civil Engineering, Research Report, John Hopkins University.
Siahaan, R. (2016), "Structural Behaviour and Design of Rivet Fastened Rectangular Hollow Flange Channel Beams", PhD Thesis, Queensland University of Technology, Brisbane, Australia.
Siahaan, R., Mahendran, M. & Keerthan, P. 2016. Section moment capacity tests of rivet fastened rectangular hollow flange channel beams. Journal of Constructional Steel Research, 125, 252-262.
Siahaan, R., Keerthan, P. & Mahendran, M. 2016. Finite element modeling of rivet fastened rectangular hollow flange channel beams subject to local buckling. Engineering Structures, 126, 311-327.