A General Design Rule for Bearing Failure of Bolted Connections Between Cold-formed Steel Strips

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Fifteenth International Specialty Conference on Cold-Formed Steel Structures
St. Louis, Missouri U.S.A., October 19-20, 2000

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SUMMARY

This paper presents the results of a finite element investigation[1,2,3] on the structural performance of cold-formed steel bolted connections. A parametric study on various connection configurations was performed to relate the bearing resistances of cold-formed steel bolted connections with steel strengths and thicknesses, and bolt diameters. A semi-empirical design rule for bearing resistances of bolted connections based on finite element results is proposed in which the bearing resistances are directly related with the design yield strength, and the design tensile strength of steel strips, steel thickness, and also with bolt diameters. Design expressions for resistance contributions due to both bearing and friction actions are given after calibration against finite element results.

1 INTRODUCTION

Due to recent advances in steel technology, cold-formed steel strips with high yield strength up to *550 N/mm^2*, or *G550* steel, becomes widely available for building products. However, the ductility of *G550* steel is found to be reduced with an elongation limit about *5%*; the elongation limit in low strength cold-formed steel such as *G300* (with yield strength *300* N/mm^2) is typical *15%*. With reduced ductility, there is concern about the structural adequacy of *G550* steels in term of deformation capacity, especially at connections where highly localized deformations are expected[1].

At present, many design rules[4,5,6,7] on the load carrying capacities of fasteners such as bolts, screws and rivets against bearing failure may be found in a number of design recommendations. However, they are empirical expressions[8,9,10] developed from test data of specific ranges of material properties and geometrical dimensions. It is important to recognize that the design rules in most design recommendations may not be adequate for high strength low ductility steels as they are originally developed from test data with low strength high ductility steels. Those design rules are unlikely to provide sufficient safety marginal in assessing the connection resistances of high strength low ductility cold-formed steels. Consequently[11,12,13,14,15], examinations on the resistance and also the associated failure modes of bolted connections with cold-formed steel strips of different grades were carried out and the applicability of existing design rules was also studied. A number of detailed finite element investigations on the structural behaviour of bolted connections in steel structures are reported in the literature[16,17,18].

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2 FINITE ELEMENT MODELLING

In the present project, the finite element package *ANSYS* (Version 5.3)[19] is used to predict the structural performance of bolted connections between cold-formed steel strips and hot rolled steel plates under shear. Three dimensional eight-node iso-parametric solid elements *SOLID45* are employed to model all the components of a typical bolted connection, namely, the cold-formed steel strips, the hot rolled steel plates, the bolt and also the washers, in order to capture material yielding across steel thickness. Furthermore, the normal stresses acting on the cold-formed steel strips due to the clamping forces in bolt shanks and also the tangential stresses due to frictional forces between contact interfaces may also be incorporated. Three material models are proposed as follows:

- multi-linear stress-strain curve with constant strength p_y at large strain, *FEA*-p_y ,
- multi-linear stress-strain curve with constant strength U_s at large strain, *FEA*-U_s , and
- multi-linear stress-strain curve with strength reduction at large strain, *FEA*-p_r.

All the three material models are based on the results of coupon tests and modified into true stress-strain curves; they are illustrated in Figure 1 for two different steel materials, namely, G300 and G550. While the material model *FEA*-p_r may be considered as physical impossible for materials in compression, it should be noted that the descending part of the curve represents a simplification on the effect of local buckling in thin steels or local cracking in thick steels to the finite element model.

Contact interfaces between the cold-formed steel strips and the bolt, the washer and the hot rolled steel plates are modelled by contact elements *CONTAC49* so that intuitive assumption on the position and the size of contact area are not required. Shear load is applied to the finite element model by imposing incremental displacements to the end of the cold-formed steel strip, along the longitudinal direction of the specimen while the hot rolled steel plate and the root of the bolt are fixed in space throughout the course of loading. As the finite element model incorporates material, geometrical and contact non-linearity, the full Newton-Raphson non-linear analysis procedure is employed to obtain the solution after each displacement increment. In a typical finite element model, there are over *2000* nodes, *1200* solid elements and *1000* contact elements, as shown in Figure 2. Typical deformed mesh of the finite element model together with a typical deformed bolt hole from a test specimen are also presented in Figure 2 for easy comparison.

3 RESULTS OF FINITE ELEMENT ANALYSES

Finite element models with different material models, namely, *FEA*-p_y , *FEA*-U_s and *FEA*-p_r , are employed to examine the load-extension curves of lap shear test specimens with cold-formed steel strips of different grades and thicknesses, and washers of different sizes. The load-extension curves of a number of bolted connections are successfully predicted and they are plotted onto the same graphs of relevant test data, i.e. in Figures 3 and 4, for direct comparison. It is shown that both the measured and the predicted load-extension curves follow each other very closely in terms of both the initial and the final slopes, and also the load carrying capacities at 3 mm extension, after allowing for variation in material properties and geometrical dimensions of the test specimens.

It is shown in Figure 3 that for G550 test specimens, the finite element models with material model *FEA*-p_r follows closely with the measured load-extension curves while the finite element models with material models *FEA*-p_y and *FEA*-U_s always give a resistance about *15 %* higher than that of

FEA-p_r at *3* mm extension. This confirms the suitability of the proposed stress-strain curves with strength degradation for cold-formed steel strips with high strength low ductility.

It is also shown in Figure 4 that for G300 test specimens, the material model *FEA-p_y* is very conservative due to low yield strength while the material models *FEA-U_s* and *FEA-p_r* tend to follow closely the measured load-extension curves, giving a resistance about *10 %* higher than that of *FEA-p_y* at *3* mm extension. As the material model *FEA-p_r* allows for strength degradation at large strain and achieves a model factor close to unity, it is thus suggested that the proposed stress-strain curve with strength degradation is also suitable for cold-formed steel strips with low strength high ductility.

It should also be noted that as observed in some lap shear tests, strip curling may occur at an extension of about *2* mm, and thus before the peak loads are reached. However, in the finite element models, curling of the ends of the cold-formed steel strips usually occurs at an extension larger than *4* mm. However, strip curling is unlikely to occur in typical connection arrangements in practice, and accurate modeling of strip curling is, thus, considered not to be critical.

Furthermore, it is also found[1,2] that the contact stiffness and the frictional coefficient between element interfaces, and the clamping force developed in bolt shanks are important parameters for accurate prediction of the load-extension curves of bolted connections. The patterns of yielding and strength degradation, and the strain distribution around the connections are also established in details. Typical strain levels in the cold-formed steel strips in the vicinity of bolt holes are found to be *40%*. Therefore, it is important to incorporate reduced strength at large strains for accurate prediction of the deformation characteristics of bolted connections. Typically, friction between the interfaces of washers and steel strips contributes *20 %* of the bearing resistance, depending on the clamping forces in bolts, the frictional coefficient between contact interfaces, and also the sizes of washers.

4 PARAMETRIC STUDY ON BEARING FAILURE

After calibration against test data, a parametric study using the finite element model is performed to provide design data for bearing failure in bolted connections over a range of steel strengths and thicknesses. The predicted bearing resistances, F_b , of the bolted connections based on different material models at *3* mm extension are presented in Table 1.

It should be noted that the bearing resistances based on material model *FEA-p_r* is *7%* higher than those obtained from material model *FEA-p_y* for low strength high ductility steels while it is about *6%* lower for high strength low ductility steels. Moreover, the frictional contribution of the bearing resistances, F_{bf}, is found to vary from 4.56 kN to 5.88 kN, i.e. within a range of 1.32 kN. Consequently, any error in predicting frictional forces of the connections will have little effect on the bearing resistance of bolted connections. For simplicity, a frictional force at 4.8 kN may be assumed for all bolted connections with a bolt diameter 12 mm and two washers tightened under a torque of 30 Nm; the corresponding clamping force in the bolts is estimated as 12 kN.

5 COMPARISON WITH DESIGN RULES

In order to assess the applicability of existing codified methods, the design rules for bearing resistances in *AISI*, *BS5950: Part 5* and *Eurocode 3: Part 1.3* are examined. For easy comparison, the design rules are re-presented in back analysis format with a strength coefficient α as follows:

$$F_{b,Rd} = \alpha\, d\, t\, f_u$$

where

$F_{b,Rd}$	=	bearing resistance of bolted connections	
α	=	*3.0*	for all steels according to *AISI*
	=	*1.65 + 0.45*t*	for all steels according to *BS5950: Part 5*
	or	*2.1* to *3.0*	for $t = 1$ mm to 3 mm
	=	*2.5*	for all steels according to *Eurocode 3: Part 1.3*

For direct comparison against finite element results, the partial safety factor ϕ in *AISI*, and γ_{M2} in *Eurocode 3: Part 1.3* are set to unity while the bearing resistance in *BS5950: Part 5* is evaluated using the tensile strength, U_s, rather than the yield strength, p_y, of the steel material. The predicted bearing resistances according to *AISI, BS5950: Part 5*, and *Eurocode 3: Part 1.3* are also presented in Table 2 for direct comparison with finite element results. In order to assess the adequacy of the design rules, a model factor for bearing resistances is established which is defined as follows:

$$\textit{Model factor} = \frac{F_{b,R} \ \textit{from finite element analysis}}{F_{b,R} \ \textit{from design rule}}$$

A model factor larger than unity represents a safe design resistance derived from the design rules when compared with the finite element results. The model factors for the three design rules are also presented in Table 2 for easy comparison. It should be noted that the bearing resistances predicted by the design rules differ significantly among themselves, with discrepancies between *5%* and *35%* even for low strength high ductility steels. Furthermore, as shown in Figure 5, the design rules do not give bearing resistances with consistent safety margin over the practical ranges of steel strengths and thicknesses. The design rules are only acceptable for connections with low strength high ductility steels, and for connections with high strength low ductility steels, over-prediction up to *10%* to *15%* is found.

6 PROPOSED DESIGN RULE

In order to predict safely the bearing resistance of bolted connections over a practical range of yield and tensile strengths, steel thicknesses, and bolt diameters at consistent extensions, a semi-empirical design rule for the bearing resistance of bolted connections, $F_{b.Rd}$, is proposed as follows after calibration against the finite element results using the material model *FEA-p_r* :

$$F_{b,Rd} = F_{bf.Rd} + F_{ff.Rd}$$

$$F_{bf.Rd} = \alpha\, t\, d\, f_u \,/\, \gamma_M \quad ; \quad \alpha = \frac{1}{\beta}\frac{f_u}{d} \quad ; \quad \beta = 15 + 35\gamma \quad ; \quad \gamma = \frac{f_y - 280}{1000}$$

$$F_{ff.Rd} = n\, \mu\, F_{BT.Rd} \,/\, \gamma_M$$

where

$F_{bf.Rd}$	=	resistance contribution due to bearing action (kN)
α	=	strength coefficient for bolted connections
t, d	=	thickness of steel strip (mm) and diameter of bolts (mm)
γ_M	=	*1.25* for connections
f_y , f_u	=	design yield and tensile strength of steel strips (N/mm^2)

$F_{ff.Rd}$ = resistance contribution due to frictional action (kN)
μ = coefficient of friction which is assigned at 0.2 for galvanized cold-formed steel strips
n = number of contact surfaces with a value of 2 for typical connections
$F_{BT.Rd}$ = clamping force at 12.0 kN.

The semi-empirical formula is calibrated with reference to bolted connections of yield and tensile strengths at 280 N/mm^2 and 390 N/mm^2 for 1.2 mm thick steels with 12 mm bolt diameter. It should be noted that both the yield and the tensile strengths of the steel strips are directly incorporated into the expression. It is regarded as a simple mean to allow for the effect of different yielding patterns associated in steel strips of different strengths and thicknesses.

A plot of the bearing resistances based on the proposed design rule against those obtained from the finite element model is presented in Figure 6. It is shown that the design bearing resistances are always conservative with a consistent safety margin over the entire range of steel strengths and thicknesses. Statistical analysis shows that the average model factor is *1.057* with a standard deviation of *0.036*. A linear regression is also performed and the regression constant is 1.053 while the regression factor is *0.990*, indicating the accuracy of the proposed design rule over the entire range of connection configurations covered in the parametric study.

7 CONCLUSIONS

A finite element model was established to investigate the structural behaviour of bolted connections between cold-formed steel strips and hot rolled steel plates under shear. By incorporating both solid and contact elements, the model is able to capture non-linearities associated with geometry, materials and boundary conditions. It is demonstrated that the finite element model is effective in predicting bearing failure in bolted connections over practical ranges of steel strengths and steel thicknesses.

After calibration against test data, a parametric study using the finite element model was carried out to investigate bolted connections with practical ranges of steel strengths and thicknesses. Design rules from *AISI*, *BS5950* and *Eurocode 3* are studied and comparison with finite element results shows that the design rules tend to give non-conservative bearing resistances for high strength low ductility steels with an over-prediction up to 15%.

Based on the finite element results, a semi-empirical design rule is proposed which relates the bearing resistance of bolted connections at *3* mm extension with a number of parameters, namely, the yield and the tensile strengths of steels, steel thicknesses, and also the bolt diameters. The proposed design rule is shown to give safe bearing resistances for cold-formed steel bolted connections with consistent safety margin over a wide range of connection configurations at consistent deformation limits. The proposed design rule is useful in predicting the moment resistances of bolted moment connections between cold-formed steel sections.

ACKNOWLEDGEMENT

The research project leading to the publication of this paper is supported by the Research Grants Council of the Hong Kong Government of the Special Administrative Region (Project No. PolyU5031/98E).

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Table 1
Bearing resistances of single bolted connections with different material models

	Material specification				F_b			Material model: *FEA*-p_r			Material model: *FEA*-p_y		
	t	d	p_y	U_s	FEA_p_r	FEA_p_y	Ratio	F_{bf}	F_{ff}	F_{bf}/F_b	F_{bf}	F_{ff}	F_{bf}/F_b
	(mm)	(mm)	(N/mm2)	(N/mm2)	(kN)	(kN)		(kN)	(kN)	(kN)	(kN)	(kN)	(kN)
B111	1.2	12	280	390	17.83	16.59	1.07	13.08	4.75	0.73	12.04	4.56	0.73
B211	1.6	12	280	390	22.79	21.24	1.07	17.91	4.88	0.79	16.32	4.92	0.77
B311	2.0	12	280	390	27.66	25.80	1.07	22.52	5.14	0.81	20.61	5.19	0.80
B411	2.5	12	280	390	33.65	31.50	1.07	28.15	5.50	0.84	26.06	5.45	0.83
B112	1.2	12	350	450	19.98	18.87	1.06	15.31	4.66	0.77	14.13	4.74	0.75
B212	1.6	12	350	450	25.65	24.24	1.06	20.55	5.09	0.80	19.18	5.06	0.79
B312	2.0	12	350	450	31.25	29.47	1.06	25.93	5.32	0.83	24.05	5.41	0.82
B412	2.5	12	350	450	37.74	35.63	1.06	32.18	5.55	0.85	30.05	5.58	0.84
B113	1.2	12	450	550	22.73	21.85	1.04	17.90	4.84	0.79	17.01	4.84	0.78
B213	1.6	12	450	550	29.07	27.98	1.04	23.91	5.16	0.82	22.78	5.20	0.81
B313	2.0	12	450	550	35.23	34.26	1.03	29.74	5.49	0.84	28.73	5.54	0.84
B413	2.5	12	450	550	42.46	41.07	1.03	36.83	5.62	0.87	35.43	5.64	0.86
B114	1.2	12	550	600	23.45	24.63	0.95	18.16	5.28	0.77	19.47	5.16	0.79
B214	1.6	12	550	600	29.51	31.54	0.94	24.16	5.35	0.82	26.22	5.32	0.83
B314	2.0	12	550	600	36.01	38.23	0.94	30.41	5.60	0.84	32.75	5.49	0.86
B414	2.5	12	550	600	44.15	46.39	0.95	38.32	5.83	0.87	40.51	5.88	0.87
B115	1.2	12	600	650	24.44	25.88	0.94	19.05	5.40	0.78	20.86	5.02	0.81
B215	1.6	12	600	650	30.64	33.00	0.93	25.31	5.33	0.83	27.67	5.33	0.84
B315	2.0	12	600	650	37.65	39.80	0.95	31.90	5.74	0.85	34.25	5.55	0.86
B415	2.5	12	600	650	45.97	48.85	0.94	40.13	5.84	0.87	43.11	5.74	0.88
					Average value		1.01		5.32	0.82		5.28	0.82
								maximum	5.84	0.87	maximum	5.88	0.88
								minimum	4.66	0.73	minimum	4.56	0.73

Table 2

Bearing resistances of single bolted connections with FEA_p_r models at $F_{BT} = 11.2$ kN

	Material specification				$F_{b,R}$				Model factor		
	t (mm)	d (mm)	p_y (N/mm2)	U_s (N/mm2)	BS5950 (kN)	EC3 (kN)	AISI (kN)	FEA (kN)	FEA BS5950	FEA EC3	FEA AISI
B111	1.2	12	280	390	12.30	14.04	16.85	17.83	1.45	1.27	1.06
B211	1.6	12	280	390	17.75	18.72	22.46	22.79	1.28	1.22	1.01
B311	2.0	12	280	390	23.87	23.40	28.08	27.66	1.16	1.18	0.99
B411	2.5	12	280	390	32.47	29.25	35.10	33.65	1.04	1.15	0.96
B112	1.2	12	350	450	14.19	16.20	19.44	19.98	1.41	1.23	1.03
B212	1.6	12	350	450	20.48	21.60	25.92	25.65	1.25	1.19	0.99
B312	2.0	12	350	450	27.54	27.00	32.40	31.25	1.13	1.16	0.96
B412	2.5	12	350	450	37.46	33.75	40.50	37.74	1.01	1.12	0.93
B113	1.2	12	450	550	17.34	19.80	23.76	22.73	1.31	1.15	0.96
B213	1.6	12	450	550	25.03	26.40	31.68	29.07	1.16	1.10	0.92
B313	2.0	12	450	550	33.66	33.00	39.60	35.23	1.05	1.07	0.89
B413	2.5	12	450	550	45.79	41.25	49.50	42.46	0.93	1.03	0.86
B114	1.2	12	550	600	18.92	21.60	25.92	23.45	1.24	1.09	0.90
B214	1.6	12	550	600	27.30	28.80	34.56	29.51	1.08	1.02	0.85
B314	2.0	12	550	600	36.72	36.00	43.20	36.01	0.98	1.00	0.83
B414	2.5	12	550	600	49.95	45.00	54.00	44.15	0.88	0.98	0.82
B115	1.2	12	600	650	20.50	23.40	28.08	24.44	1.19	1.04	0.87
B215	1.6	12	600	650	29.58	31.20	37.44	30.64	1.04	0.98	0.82
B315	2.0	12	600	650	39.78	39.00	46.80	37.65	0.95	0.97	0.80
B415	2.5	12	600	650	54.11	48.75	58.50	45.97	0.85	0.94	0.79

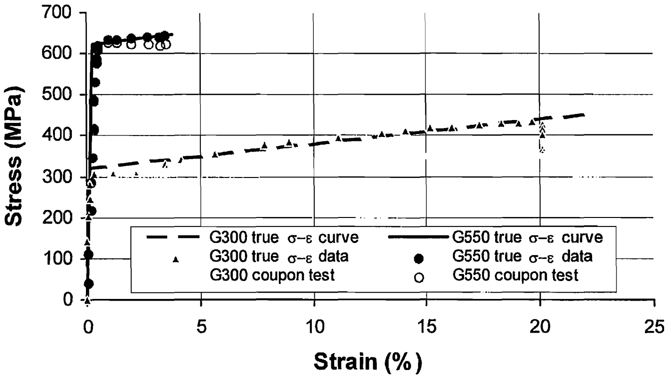


Figure 1a Stress-strain curves from coupon tests and true stress-strain curves of test specimens

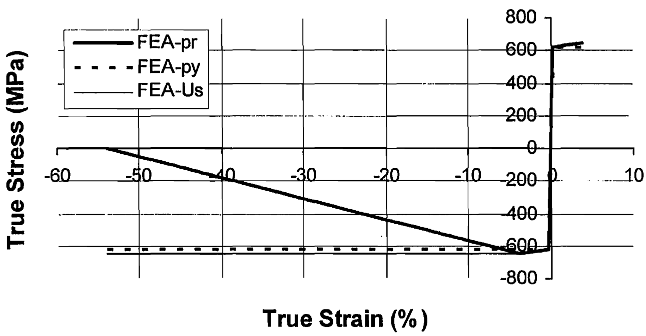


Figure 1b Proposed stress-strain curves for G550 cold-formed steel strips under tension and compression.

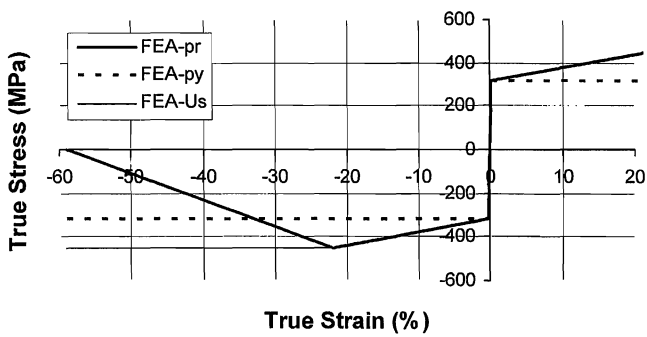
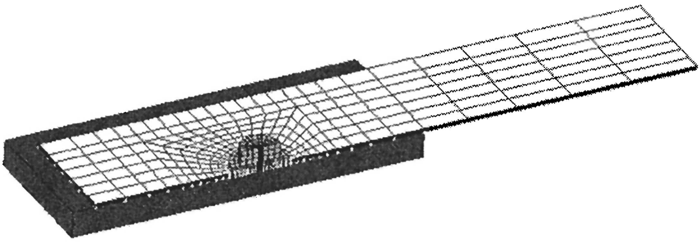
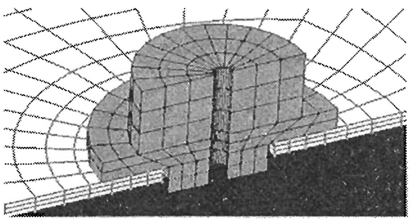


Figure 1c Proposed stress-strain curves for G300 cold-formed steel strips under tension and compression.

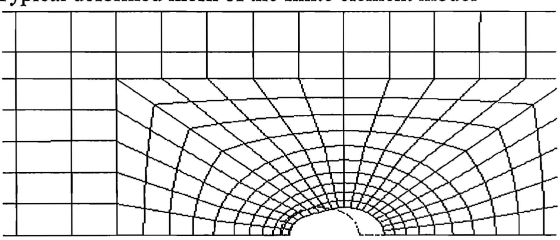
(a) Overall view of the finite element model



(b) An enlarged view of the bolt and the washer



(c) Typical deformed mesh of the finite element model



(d) Typical deformed bolt hole in test specimens after testing

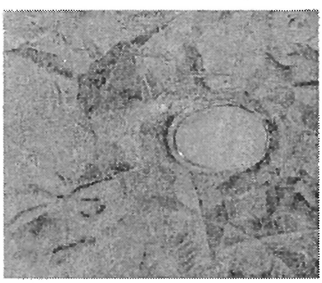
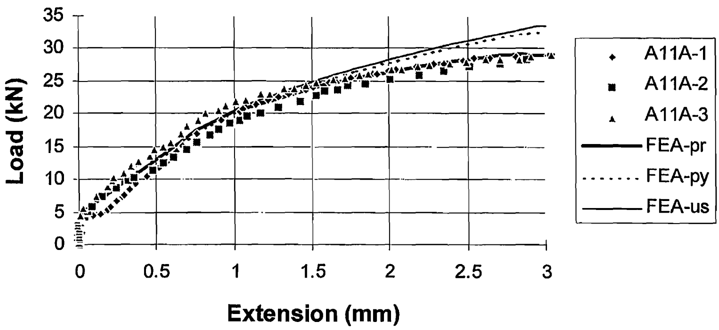
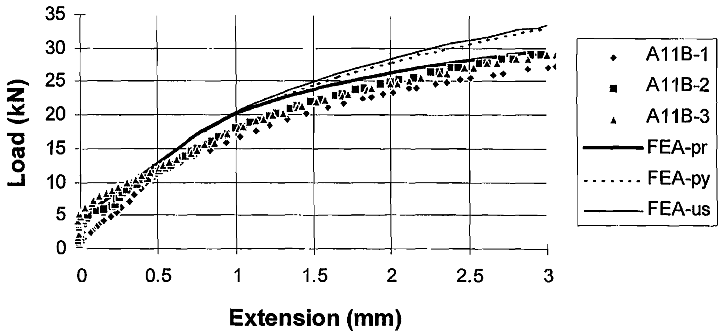


Figure 2 Finite element mesh for CFS-HRS connection (Specimen A11A)

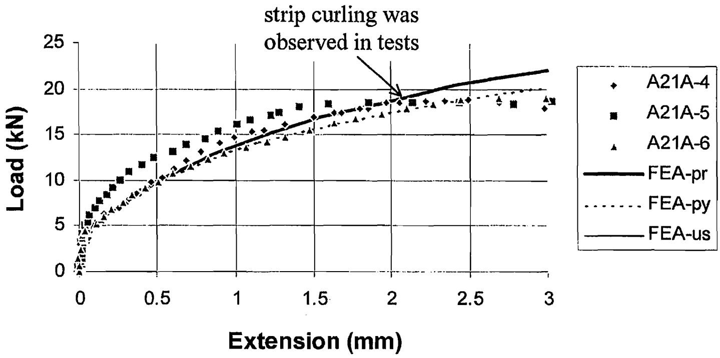


(a) Specimens with A11A configuration
Steel thickness = 1.6 mm, Bolt diameter = 12 mm
Washer diameters are 25.7 mm external and 13.0 mm internal; 2.3 mm thick.

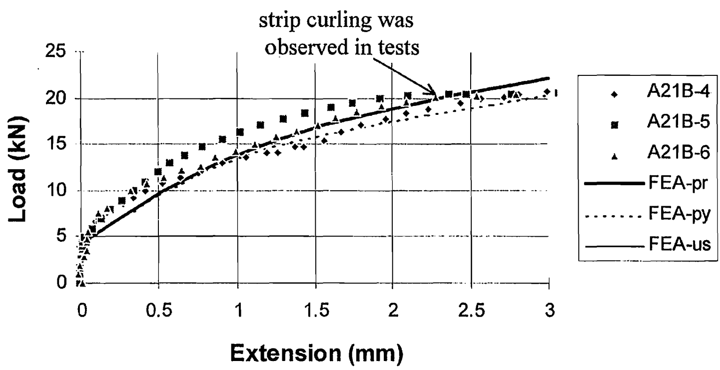


(b) Specimens with A11B configuration
Steel thickness = 1.6 mm, Bolt diameter = 12 mm
Washer diameters are 32.1 mm external and 14.6 mm internal; 3.0 mm thick

Figure 3 Theoretical and experimental load-deflection curves for bolted connections with G550 cold-formed steel strips



(a) Specimens with A21A configuration
Steel thickness = 1.5 mm, Bolt diameter = 12 mm
Washer diameters are 25.7 mm external and 13.0 mm internal; 2.3 mm thick.



(b) Specimens with A21B configuration
Steel thickness = 1.5 mm, Bolt diameter = 12 mm
Washer diameters are 32.1 mm external and 14.6 mm internal; 3.0 mm thick

Figure 4 Theoretical and experimental load-deflection curves for bolted connections with G300 cold-formed steel strips

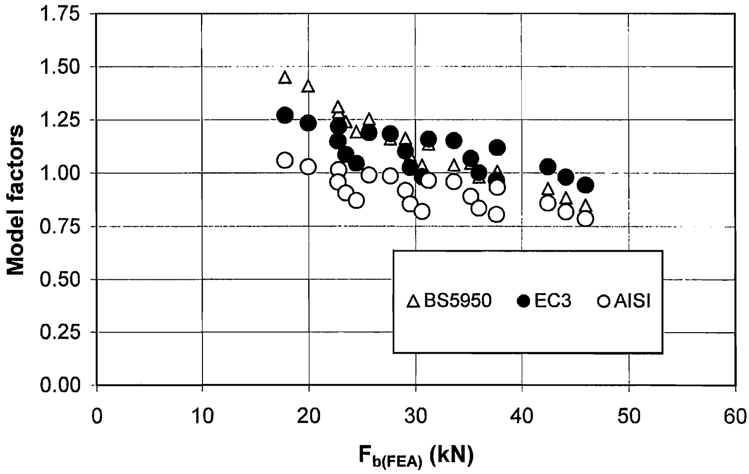


Figure 5 Comparison of bearing resistances among codified design rules

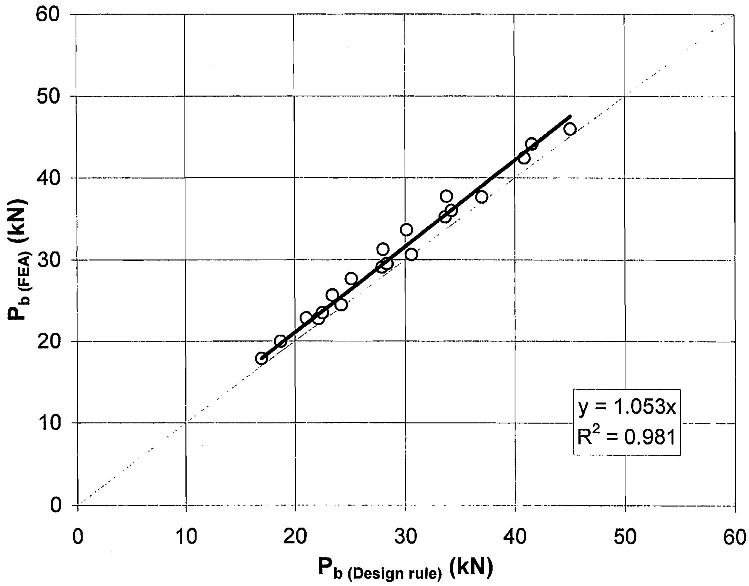


Figure 6 Comparison on bearing resistances between proposed design rules and FE analysis