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Application of a Finite Element Model to a Cold-Formed Steel C-Section with a Bearing Stiffener

S. R. Fox[1] and G.W. Brodland[2]

Abstract

Described in this paper is the application of a finite element model to a cold-formed steel C-section with a bearing stiffener installed between its flanges. This model has been used to determine both the web crippling capacity of the joist, and the forces that develop in the fasteners connecting the bearing stiffener to the joist. The finite element model was also used to carry out parametric studies of the stiffened joist assembly to determine the impact on the web crippling capacity and the fastener forces caused by variations in the assembly. Based on the results of these finite element studies, combined with available experimental work, a design expression has been proposed that can calculate the web crippling capacity of a cold formed steel C-section joist that has a bearing stiffener installed between the joist flanges. A second design expression has been proposed for predicting the forces in the fasteners that connect the joist to the stiffener. Predictions of both the web crippling capacity and the fastener forces are necessary for determining the ultimate strength of the stiffened joist assembly.

Introduction

Cold-formed steel structural members have been used extensively in building construction throughout the world. In recent years, the applications of these members have been increasing in the low-rise residential construction market. Cold-formed steel floor joists are typically C-sections ranging in depth from 150 to 355 mm (6 to 14 in.). The thin sheet steel used in these sections makes them prone to yielding and web buckling (or web crippling) when subjected to concentrated loads on the joist flanges. In an end-two-flange loading of a floor joist assembly like the one shown in Figure 1, the wall studs are transferring loads from above (i.e. roof loads and upper floor loads) and are bearing on top of the floor joist, which in turn bears on the foundation. To increase the strength of the floor joist at this location, bearing stiffeners are attached to the joist web. These stiffeners reinforce the joist web, but also like short columns that transfer axial load from the wall studs to the foundation.

The current design document in North America for cold-formed steel structural members is the "North American Specification for the Design of Cold-Formed Steel Structural Members". This specification is published in Canada by the Canadian Standards Association (CSA) as the CSA Standard S136-2002 [1], and in the United States by the American Iron and Steel Institute (AISI) as the AISI Specification [2]. The NA Specification includes design provisions for bearing stiffeners, although there is a limitation that requires the flat width of any element in the stiffener not to exceed the limit for local buckling. This limitation is not met by typical stud and track type bearing stiffeners in common use.

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A research program was initiated to study these more common types of cold-formed steel bearing stiffener assemblies, with the objective to develop design recommendations [3, 4, 5, 6]. This research has shown that the bearing stiffeners are subject to local buckling at moderate stress levels, eccentric axial loads and transverse loading from the fasteners connecting the stiffener to the joist. It was also concluded that the capacity of the stiffened joist assembly is a function of the web crippling capacity of the joist and the axial capacity of the bearing stiffener acting as a beam-column.

The design specifications [1, 2] have expressions for calculating the web crippling capacity of structural members. These expressions, however, do not apply to a joist with a bearing stiffener attached to the web. Web crippling involves a complicated interaction of elements and non-linear behavior that makes the development of an analytical model impractical. Consequently, experimental and finite element methods are typically used to derive empirical design expressions. Described in this paper is the development of predictor equations for the web crippling capacity of the stiffened joist based on the application of a finite element model developed for that purpose.

The bearing stiffener acts as a short beam-column subjected to eccentric axial load, but it is also subjected to lateral loads that develop in the fasteners connecting the stiffener to the joist. The deformation of the joist web during web crippling is restrained by the connection of the web to the stiffener. These restraining forces act on the bearing stiffener and affect its ultimate strength. As with the web crippling investigation, predictor equations for the fastener forces have been developed based on the application of the finite element model.

Deformation of a Stiffened Joist Subjected to Two-Flange Loading

The stiffened assembly considered in this study has the bearing stiffener located between the joist flanges. This location causes the applied load to be transferred to the stiffener through bearing on the underside of the joist flange. Illustrated in Figure 2 are the stages in the loading cycle. Initially the stiffener is not in contact with the joist flanges since the stiffener is cut shorter than the inside dimension of the joist to facilitate construction. As load is applied, the joist flanges rotate until they eventually contact the edge of the bearing stiffener. If the load continues to increase, the compressive force in the web will cause the web to buckle once the web crippling capacity of the joist has been reached. After web crippling, the assembly will not carry any significant additional load until the flanges come in full contact with the end of the stiffener. The buckled shape of the joist web after web crippling is shown in the photograph of a test specimen in Figure 3. This deformation behaviour has implications for the web crippling capacity of the joist and the forces that develop in the fasteners.

General Description of Finite Element Model

The numerical analysis was conducted using the finite element (FE) program ANSYS (version 5.6). Shown in Figures 4 and 5 are typical FE models of the end and intermediate stiffened joist configurations. The following element types were used in the models.
(a) *Shell Elements:* The basic behavior to be modeled was the deflected shape of thin sheet steel elements representing the joist. It was necessary to account for both the in-plane stresses and

bending behavior, as well as model the curvature of the deflected shape. Shell elements with mid-side nodes (8 node quadrilateral) were used to mesh all of the surface areas.
(b) *Contact Elements*: The FE program was able to model contact between designated target and contact areas utilizing additional elements that are overlaid on the meshed areas where contact is anticipated. The contact pairs use "target" elements for the areas that were taken to be stationary, and "contact" elements for the areas that change position and could come into contact with a portion of the target area. In the model developed, the target area represents the bearing stiffener and the contact area is the joist web.
(c) *Link Elements*: Link elements were used to represent the fasteners connecting the joist web to the stiffener. The three-dimensional spar element is a uniaxial tension-compression element with three degrees of freedom at each node: translations in the nodal x, y, and z-directions.

A typical model was comprise do approximately 500 elements and 1500 nodes. The model incorporated bi-linear material properties, with a modulus of elasticity of 300 MPa (2.9 ksi) after the yield point, and large displacement geometric non-linearity. A series of verification tests were carried out to confirm that the FE results were consistent with experimental results.

The stiffness of the link elements that were used to model the fasteners was varied to correspond to the behavior of the different stiffener types and fastener configurations. Thus the restraint provided to the joist web by the fasteners increased as the thickness or yield strength of the bearing stiffeners increased, or as the location of the fasteners moved closer to the joist flanges. An additional FE model of the stiffener was created and used to develop a predictor equation for this equivalent fastener stiffness. For the full details of the finite element modeling, consult Fox [3].

Parametric Studies using Finite Element Models

Finite element models were developed to investigate the effect of the following parameters:

- End and interior two-flange loading;
- Joist depths of 203, 254 and 305 mm (8, 10 and 12 in.);
- Joist thicknesses from 1.02 to 2.04 mm (0.040 to 0.080 in.);
- Web slenderness ratios from 100 to 300;
- Joist yield strengths from 230 to 450 MPa (33 to 65 ksi);
- 3-screw vertical and 4-screw horizontal fastener patterns;
- Variations in the location of the fastener(s) closest to the top flange (h/4, h/5, h/6, h/8 and h/12);
- Variations in the inside bend radius of the corner between the joist flange and web corresponding to ratios between 1 times the thickness (1t) to 3 times (3t); and,
- Different stiffnesses of the fasteners corresponding to different stiffener types.

In total, approximately 500 different FE models were developed and used to determine the web crippling capacity of the joist, the forcers in the fasteners and the joist web buckling mode.

It was determined that the web crippling capacity and fastener forces were influenced by the physical properties of the components (thickness, yield strength, fastener stiffness) as well as the geometric properties (web slenderness, fastener location). The degree of influence of each variable is reflected in the predictor equations, although not all of the variables are independent.

The joist exhibits distinct web crippling failure modes that depend on the joist web slenderness, stiffness of the fasteners and fastener locations. As the failure mode shifts from one type to another (e.g. as the fastener stiffness decreases), the web crippling capacity significantly changes, as do the forces in the fasteners.

Experimental Work

To validate the finite element model, and to provide additional data from which predictor equations could be generated, an experimental program was also carried out [3]. The basic test procedure involved conducting a series of end- and interior-two-flange loading tests on stiffened C-section joist specimens of different configurations. A typical set-up for an end location test is shown in the photograph in Figure 3. The range of assemblies tested is illustrated in Figure 6. For each assembly tested, the ultimate load, web crippling load and forces in the fasteners were measured.

Web Crippling Prediction Equation

The data from the FE parametric studies, combined with the experimental results, were used in a regression analysis to develop predictor equations for the web crippling capacity. The regression analysis was carried out using the MathCad^{TM} program. An iterative method was employed to determine the least squares of the residuals of the difference between the predicted capacity and the capacities determined in both test and finite element analyses. The equation for predicting the web crippling capacity of a C-section joist with a bearing stiffener is provided in Eqn. 1. The comparison of the predictions to the FE and test data is provided in Table 1.

$$P_n = CtF_y^{0.8}\left(1 - C_R\sqrt{R}\right)\left(1 - C_H\sqrt{H}\right)\left(1 - C_A\sqrt{A}\right) \text{ (in Newtons)} \qquad (1)$$

Where,

A = a/h
a = distance from top of joist to top fastener(s), mm
C = web crippling coefficient
C_A = fastener location coefficient
C_H = web slenderness coefficient
C_R = inside bend radius coefficient
F_y = yield strength of joist material, MPa
H = h/t
h = flat dimension of joist web measured in plane of web, mm
P_n = nominal web crippling capacity, N
R = r/t
r = inside bend radius of joist, mm
t = thickness of joist web, mm

The basic form of the equation was chosen because it matches the form used in the NA Specification [1,2]. Equation 1 differs from the standard web crippling expression in the substitution of the fastener location ratio term, *A*, in place of the bearing width ratio. In all of the tests and FE analyses, the bearing width was maintained at 100 mm (4 in.) to provide complete end bearing for the stiffener. Equation 1 is unit-dependent and only valid for metric units as shown.

A plot of the ratios of the FE and experimental web crippling capacities divided by the predicted capacities is provided in Figure 7. This plot illustrates the good correlation between the FE results and the predictor expression, but less agreement between the tests and the predicted. Logically there should be much better correlation with the FE results since they are determined numerically and there are no extraneous influences such as inconsistencies of material properties, imperfections, unsymmetrical loading and other factors that influence the repeatability of experimental work.

Fastener Force Regression Analysis

A regression analysis of the FE predictions of the fastener forces was also carried out. Predictor equations were determined for both the top fastener force, *F,* and the contact force, *C,* for each of the assembly configurations studied, and are listed in Table 2. The designation of the fastener forces are illustrated in Figure 8. For the configurations with 4 screws (Figure 6), the sum of the forces in the two screws were combined and considered as a single force.

A review of the coefficients of variation for the different configurations listed in Table 2 shows that the predictor equations are generally better for the fastener forces than for the contact forces. These equations are also unit-dependent and are only valid for metric units. A plot of the ratios of the FE fastener forces divided by the predicted capacities is provided in Figures 9 and 10.

Limitations of the Predictor Equations

The FE parametric studies revealed that there were assemblies where the buckling of the joist web during web crippling was localized under the bearing surface, while for other configurations the buckling occurred over the full depth of the web. These different failure modes are illustrated in Figure 11. The joists with high web slenderness ratios tend to have a more localized failure under the bearing surface (Figure 11(a)). As the web slenderness decreases (i.e. the thickness increases or the joist depth decreases), the full-web buckling failure mode starts to be predominant (Figure 11(c)). The majority of sections investigated failed in the partial-web buckling (web crippling) mode (Figure 11(b)).

The other parameters that influence the joist web buckling mode, in addition to web slenderness, are the location, $A=a/h$, and stiffness, E_s, of the fasteners connected to the joist web. At the one extreme, if there are no fasteners (i.e. $E_s = 0$) the joist will buckle in the full-web mode for all sections. As the fastener stiffness increases, a point is reached where the restraint created by the fastener causes the joist web to buckle in a partial-web mode, and at a higher web crippling load. The forces that develop in the fasteners are also affected by the buckled shape. For a 3-screw configuration, the fastener in the middle of the joist web will be in tension for the full-web buckling mode, but when the buckling mode changes to a partial-web mode the restraint to the web is provided by the contact of the web on the stiffener, and the middle fastener does not carry any load. The change in buckling mode also causes a change in the web crippling capacity.

The predictor equations presented in this paper are only valid for those assemblies that buckle in the partial-web mode. It is suggested that the minimum web slenderness ratios listed in Table 3 be used as a guide to ensure a partial-web buckling failure mode. For additional details, consult Fox [3].

To apply these predictor equations in practice, the appropriate safety factors or phi factors will be needed. These factors can be determined using the methods provided in the NA Specification and its commentary [1,2], which are dependent on the target reliability index and calibration parameters appropriate to the country of use.

Conclusions

The previous experimental work [3, 4, 5, 6] has shown that when the bearing stiffener is located between the joist flanges the capacity of the assembly depends on the web crippling capacity of the joist and the axial capacity of the stiffener. In order to predict the axial capacity of the stiffener, it is necessary to know the lateral forces transferred to the stiffener as a result of web crippling of the joist. In order to predict the web crippling capacity of the joist, an experimental program and finite element analysis was conducted.

Using the available experimental data and the results of the finite element parametric studies, a regression analysis was used to develop predictor equations for both the forces in the fasteners as well as the web crippling capacity of the joist. These equations are presented in this paper.

With the development of these predictor equations, the strength of the bearing stiffener can be predicted based on a beam-column model, but there are limitations on the applicability of the proposed method. The finite element study has shown that the forces in the fasteners and the web crippling capacity of the joist change significantly if the restraint provide by the fastener is not sufficient to prevent a full-web buckling mode. Consequently, limits on the joist web slenderness ratio have been proposed based on the bearing stiffener type.

In addition to its contribution to the strength of the stiffened joist assembly, the web crippling capacity of the joist could be considered as an additional design limit state. The web crippling could occur at service loads, and the subsequent deformations could possibly cause serviceability problems for the attached finishes.

Acknowledgements

This project was funded by the American Iron and Steel Institute and the Canadian Sheet Steel Building Institute. The continued support of these organizations is greatly appreciated.

APPENDIX - Notation

A = a/h
a = distance from top of joist to top fastener(s), mm
C = web crippling coefficient; contact force
C_A = fastener location coefficient
C_H = web slenderness coefficient
C_R = inside bend radius coefficient
E_s = fastener stiffness determined by FE analysis
F = fastener force
F_y = yield strength of joist material, MPa
H = h/t
h = flat dimension of joist web measured in plane of web, mm
P_n = nominal web crippling capacity, N
R = r/t
r = inside bend radius of joist, mm
t = thickness of joist web, mm

APPENDIX – References

1. Canadian Standards Association (CSA), CSA-S136-2002 "North American Specification for the Design of Cold-Formed Steel Structural Members", Rexdale (Toronto), Ontario, Canada, 2002

2. American Iron and Steel Institute (AISI), "North American Specification for the Design of Cold-Formed Steel Structural Members", Washington, D.C., 2001

3. Fox, S.R., "Bearing Stiffeners in Cold Formed Steel C-Sections", PhD Thesis, Department of Civil Engineering, University of Waterloo, Waterloo, Ontario, Canada, 2002

4. Fox, S.R and Schuster, R.M., "Tests of Cold Formed Steel Floor Joists With Bearing Stiffeners", Proceedings of the Fourteenth International Specialty Conference on Cold Formed Steel Structures, University of Missouri-Rolla, 1998

5. Fox, S.R and Schuster, R.M., "Strength of Bearing Stiffeners in Cold Formed Steel C-Sections", Proceedings of the Fifteenth International Specialty Conference on Cold Formed Steel Structures, University of Missouri-Rolla, 2000

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Table 1: Web Crippling Equation Coefficients and Comparisons to FE Results

Configuration	C	C_A	C_H	C_R	No. of Tests and FE Solutions	Average Test-to-Predicted Ratio	Coefficient of Variation
End, 3 Screw	396	0.624	0.031	0.351	121	1.00	0.075
End, 4 Screw	437	0.623	0.028	0.387	122	1.00	0.093
Intermediate, 3 Screw	395	0.531	0.024	0.350	123	1.00	0.059
Intermediate, 4 Screw	367	0.448	0.017	0.368	150	1.00	0.066

Table 2: Regression Equations for Fastener Forces and Comparisons to FE Results

Configuration		Predictor Equation	No. of FE Solutions	Average FE-to-Predicted Ratio	Coefficient of Variation
End, 3-Screw	Top Fastener	$F = (0.543)t^{0.96}F_y^{0.82}\frac{E_s^{0.28}}{R^{.22}H^{0.24}A^{0.60}}$	121	1.00	0.079
	Contact	$C = (0.00025)\frac{F_y^{1.1}E_s^{0.52}A^{0.50}H^{0.87}}{R^{0.69}}$	104	0.992	0.212
End, 4-Screw	Top Fastener	$F = (30.6)t^{0.70}F_y^{0.79}\frac{E_s^{0.16}}{R^{0.04}H^{0.74}A^{0.65}}$	106	0.998	0.077
	Contact	$C = (0.025)\frac{F_y^{1.23}E_s^{0.40}A^{0.28}H^{0.04}}{R^{0.33}}$	106	1.017	0.196
Intermediate, 3-Screw	Top Fastener	$F = (1.25)t^{0.76}F_y^{0.69}\frac{E_s^{0.35}}{R^{0.13}H^{0.46}A^{0.76}}$	77	0.994	0.073
	Contact	$C = (0.008)\frac{F_y^{0.48}E_s^{0.47}A^{0.06}H^{0.69}}{R^{0.59}}$	67	0.994	0.436
Intermediate, 4-Screw	Top Fastener	$F = (2.38)t^{0.91}F_y^{0.66}\frac{E_s^{0.32}}{R^{0.17}H^{0.36}A^{0.53}}$	99	0.982	0.107
	Contact	$C = (0.01)\frac{F_y^{0.60}E_s^{0.60}A^{0.37}H^{0.55}}{R^{0.85}}$	99	0.971	0.289

Note: See “Appendix – Notation” for definition of terms

Table 3: Minimum Web Slenderness Ratio (H) for Various Fastener and Stiffener Combinations

Stiffener Configuration		Stiffener Thickness (mm)			
		0.84	1.12	1.52	1.91
3-Screw	Stud	165	150	115	100
	Track	-	155	120	100
4-Screw	Stud	140	115	100	100
	Track	-	120	100	100

Note: 1 in. = 25.4 mm

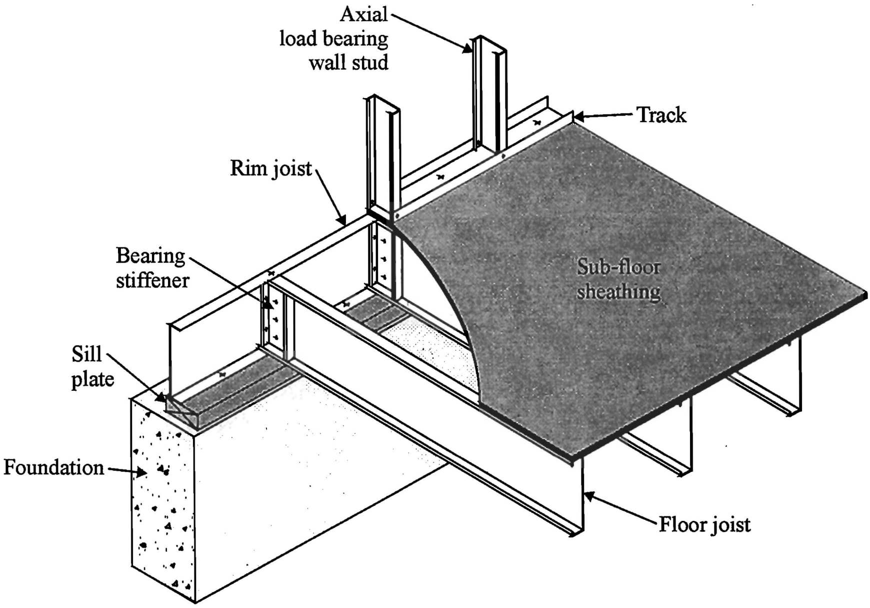
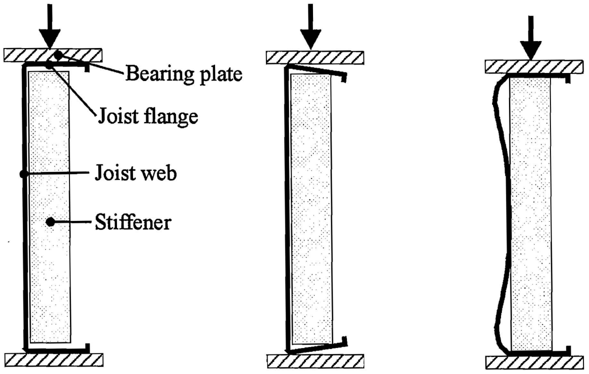


Figure 1: LSF Platform Construction Detail



(a) Prior to loading (b) Initial flange rotation (c) Web crippling

Figure 2: Stiffener Deformation Stages

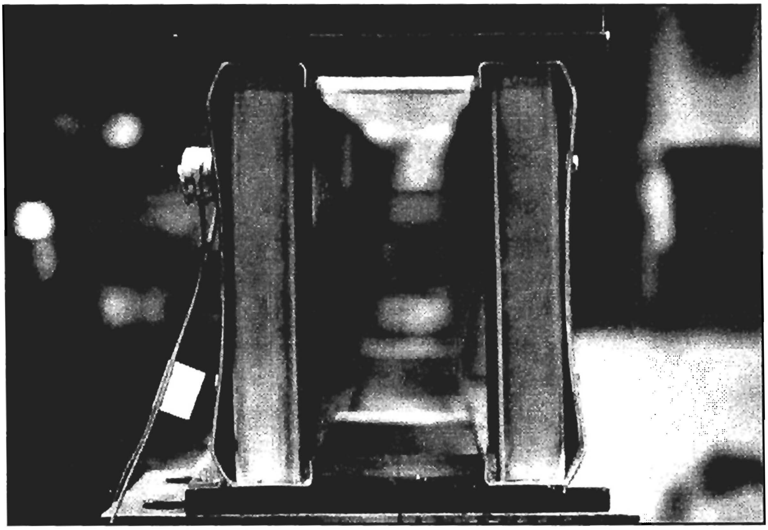


Figure 3: Photograph Showing Buckled Webs Prior to Failure of Stiffener

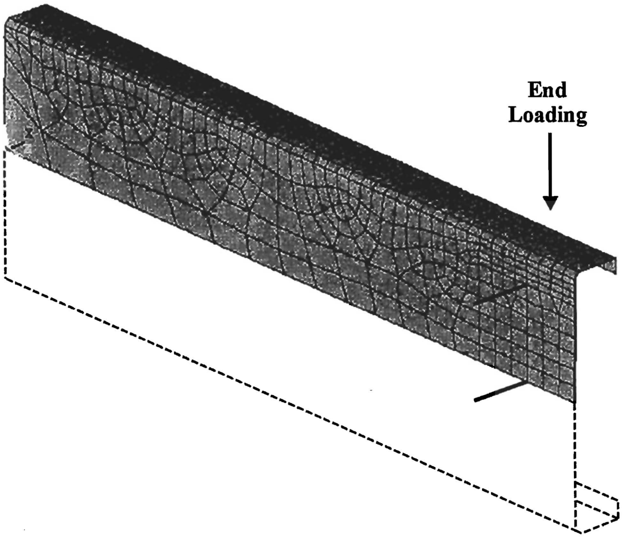


Figure 4: Typical FE Model of End Loading

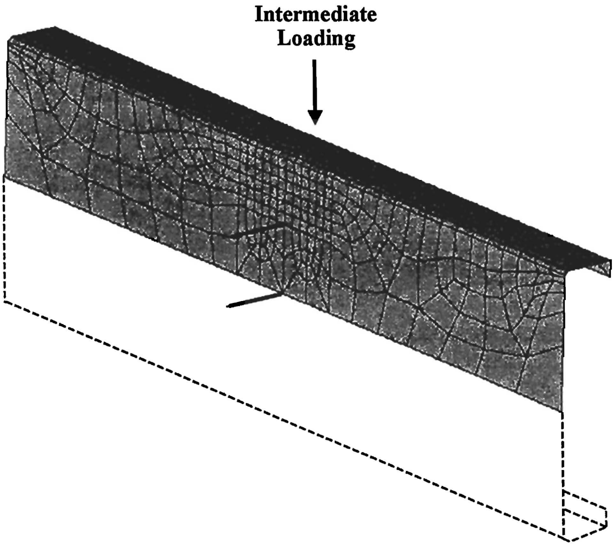
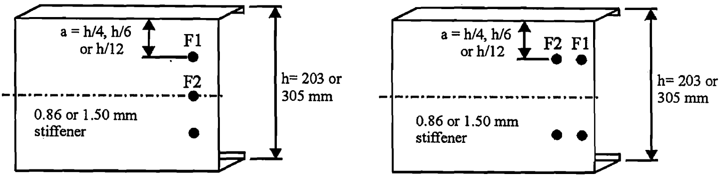
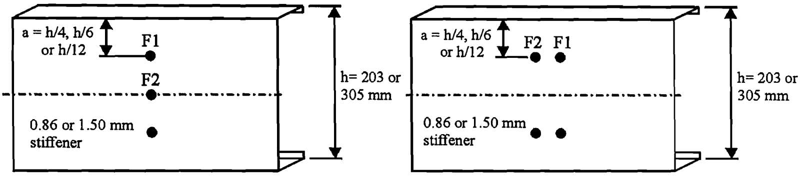


Figure 5: Typical FE Model of Intermediate Loading



3V Fastener Configuration - End **4H Fastener Configuration - End**



3V Fastener Configuration - Intermediate **4H Fastener Configuration - Intermediate**

Figure 6: Configurations of Assemblies Tested

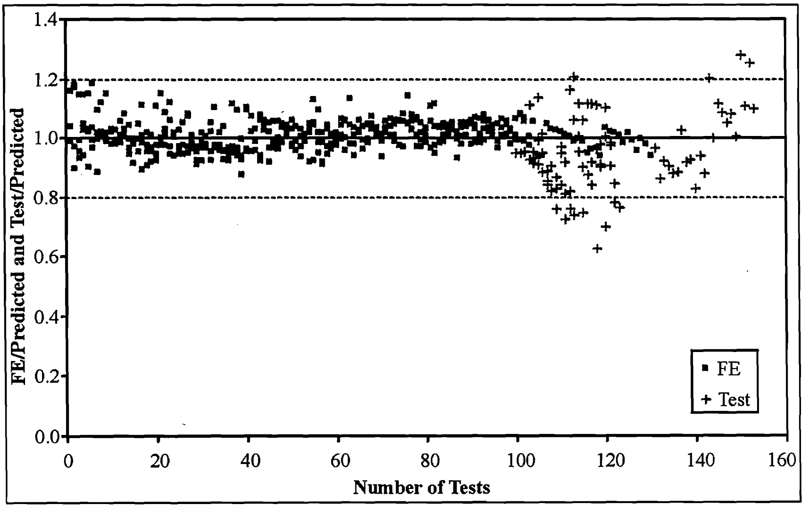


Figure 7: Web Crippling Test-to-Predicted Ratios

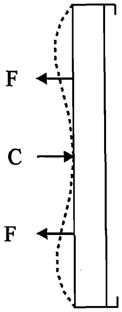


Figure 8: Fastener Force Designations

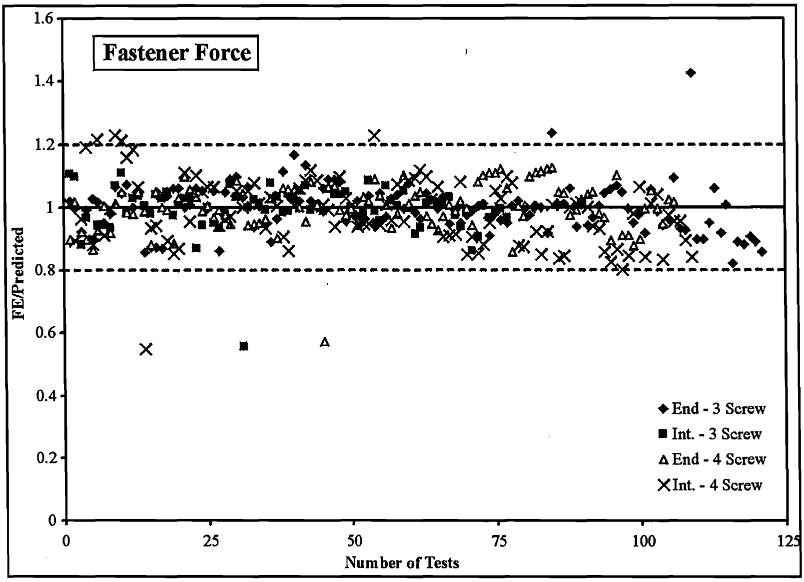


Figure 9: FE-to-Predicted Ratios for Fastener Forces

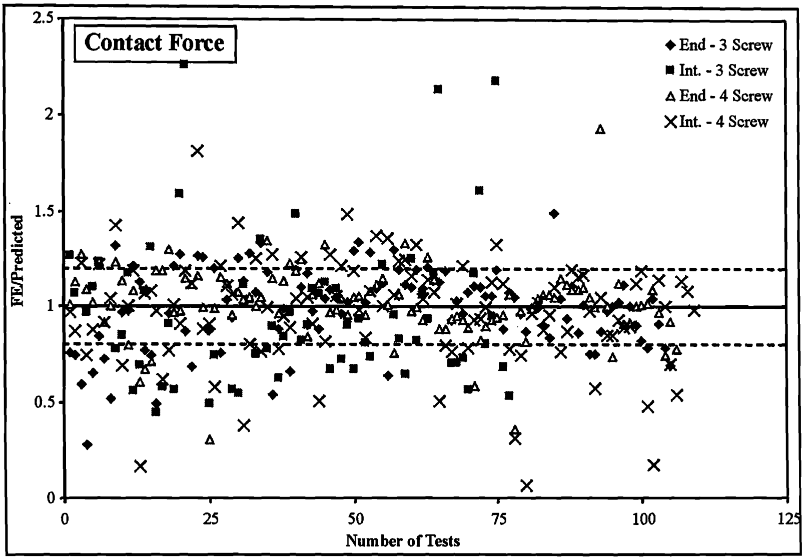


Figure 10: FE-to-Predicted Ratios for Contact Forces

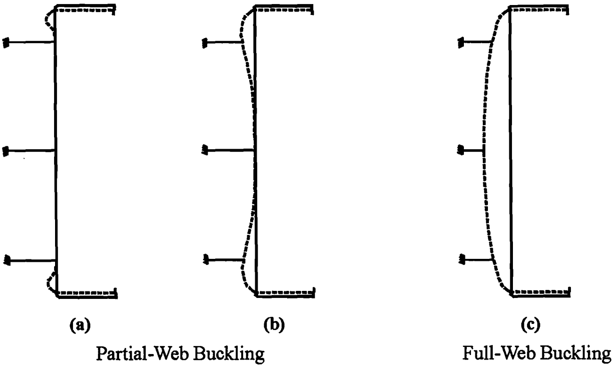


Figure 11: Web Buckling Failure Modes from FE Analysis