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BEHAVIOR OF NESTED Z-SHAPED PURLINS

By

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SUMMARY

This paper presents the results of an experimental study of 8 and 9 1/2 inch (203 and 241 mm) deep Z-purlins to determine the overlap length required for moment and stiffness continuity over a building frame. Influence of bolt installation techniques on ultimate purlin moment capacity and stiffness was evaluated. Bolt line forces were experimentally determined within the nested region.

INTRODUCTION

To provide the continuity required for continuous purlin design, adjacent purlins are nested over the building frame. This overlap must be of sufficient length to provide adequate strength and stiffness. Therefore, the overlap length and the load transfer mechanism in the overlap must be considered in the analysis and design of continuous purlins.

The primary objective of this investigation was to develop a test program to study the effects of overlap length, purlin size, and bolt installation procedures, on purlin strength and stiffness. A second objective was to develop an understanding of the load transfer mechanism in overlapped purlins. A computer model was developed to predict the bolt line forces in the overlap length of Z-purlins.

LITERATURE REVIEW

Research into the behavior of continuous Z-purlins without the interaction of roof panel systems and lateral bracing is limited. This absence has resulted in very little guidance in overlap length design requirements for continuous purlin systems.

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The behavior of bolted connections in conventional, hot rolled steel structures cannot be directly related to bolted connections in light-gage, cold-formed steel because the ratio of sheet thickness to bolt diameter in light-gage steel connections is small. In the 1950's, a test program was conducted at Cornell, by Winter (4,5), to study the behavior of bolted connections in light-gage steel . A total of 574 tests were conducted using unfinished bolts (A307) and high-strength (A325) bolts. A wide range of test parameters were evaluated. Two conclusions were drawn from this research: 1) A conservative value for the nominal bolt shear stress is 0.6 times the tensile strength of the bolts, based on the root area of the bolt; and 2) For oversize holes, slip into bearing at or below design loads cannot be prevented in A307 bolt 'handtight' connections.

Dhalla, Errera, and Winter (1,4), focused on the influence of ductility of steel sheets on the load carrying capacity of bolted connections. Three types of steel were chosen to give a wide range of ductility and strength values. Shear and bearing strength of low-ductility steel had a somewhat lower multiple of yield stress than for high-ductility steel. The tensile strength in the net section was found to be unaffected by the ductility (1). In a typical bolted connection, the load at which failure occurs is a function of the ultimate strength and the ductility of the base material. Therefore, based on strength, ductility should be as high as possible to prevent brittle fracture to occur under high loading conditions.

As the use of cold-formed Z-purlins increased, it was observed that under severe wind loads, purlins were not behaving in accordance with traditional beam-lateral buckling theory (3). A stiffening was provided to the top flange of the purlin by the roof panel or deck. In 1981, Needham (3) conducted a test program to study the state of stress in Z-purlins, and the magnitude of in-plane roof panel forces. The investigation concentrated on simple span beams using 9 1/2 inch (241 mm) deep purlins and a variety of roof panel systems. Test results indicated that simple bending stresses prevail in the purlin if the roof paneling can carry the primary unsymmetrical bending and torsional forces. The load buildup in the roof panel was lower than previously predicted by earlier test results.

In 1985, Dubowski (2), investigated the elastic behavior of bolted portal frame connections using finite element modeling. The objective was to isolate a mode of behavior called 'socket-action' which might be used to reduce bolting requirements. A second objective focused on determining the magnitude and distribution of bolt forces in a connection with several different bolting configurations. The results of the finite element analysis did not identify socket-action as a significant source of moment transfer for connections with large numbers of bolts and high connection depth to length ratios. However, nested purlins use only four bolts and connection lengths that may approach four times the connection depth.

EXPERIMENTAL TEST PLAN

Purlin depths of 8 and 9 1/2 inches (203 and 241 mm) with a web and flange thickness of 0.061 inches (1.5 mm) were tested. For each purlin depth, basic overlap tests were conducted on four specimens with varying overlap lengths (See Table 1). Each specimen is designated by two numbers separated by the letter B e.g. 9.5B36. Numbers before the B refer to the purlin depth, in inches, while the numbers after the B refer to twice the overlap length, in inches. The overlap length is the distance between the centerline of the overlapped purlin to the bolt line in the overlapped section (See Figure 1). Initially, single purlins, designated 8.0BS and 9.5BS, were tested to set a baseline for strength and stiffness properties.

The effect of bolt installation procedures was evaluated by placing tight and finger-tight bolts in the overlapped section. The tight bolt, or basic overlap, tests were conducted with the overlap bolts tightened, using the turn-of-the-nut method, to prevent any bolt slippage to occur. Finger-tight bolt tests were conducted with the overlap bolts tightened only finger-tight, to allow immediate slippage when the specimen was loaded. The overlap bolts for the 9.5B21 specimen, although tested as a basic overlap test, slipped when tested. The results of that test gave lower than expected values of both strength and stiffness. From those results, two additional tests, shown in Table 1, were conducted using finger-tight bolts to determine the influence of bolt installation procedures on strength and stiffness.

Bolt line shear tests were conducted to develop a better understanding of the load transfer mechanism in the overlapped section of Z-purlins. The results gave estimates of the actual bolt line forces in the overlapped section. The tests were conducted by placing small bolts in place of the normal 1/2 inch (12.7 mm) bolts in the overlapped section. As the purlin was loaded those bolts would fail in shear before the purlin failed. By changing the bolt size and material a small range of bolt line forces at purlin failure could be established. Brass and steel bolts with nominal bolt diameters of 1/4, 5/16, and 3/8 inch (6.35, 7.94, and 9.53 mm) were selected so a wide range of bolt shear strength capacities would be available. The shear strength of each bolt was determined experimentally.

The bolt line shear specimens tested are shown in Table 1. The addition to the normal specimen designation includes the material type (B-Brass and S-Steel) and the bolt size in inches. An 8 inch (203 mm) deep purlin with a 16 1/2 inch (419 mm) overlap was chosen for all bolt line shear tests.

Each purlin test specimen is made up of two purlins overlapped over a simulated building frame with a combined length of 12 feet (3.66 m). The purlin ends are attached to connections supported on rollers to simulate a simple support. See Figure 1 for a schematic of the purlin test specimen. At these supports, two small plates are attached to either side of the purlin web to prevent the purlin ends from twisting during tests. The rollers are supported on two 5 by 5 by 1/4 inch (127 x 127 x 6.35 mm) structural tubes spanning 13 feet (3.96 m). These tubes served as a support for the end connections and a base for the entire test fixture. The building frame was simulated with a W-section having a 5 1/4 inch (133 mm) flange width. Lateral support was provided by a brace attached to the simulated building frame and the bottom flange of the purlin.

Tests were conducted in a Baldwin hydraulic testing machine, located in the University of Kansas structural testing laboratory. See Figure 2 for the complete laboratory test setup. Deflections at each end were measured using LVDT's suspended from a channel placed above the upper crosshead of the testing machine.

RESULTS AND ANALYSIS OF EXPERIMENTAL DATA

A tabulation of the ultimate frame force and the effective purlin stiffnesses for each purlin test is presented in Table 2. The ultimate frame force corresponds to the frame load at which purlin failure occurred. The effective stiffness for each purlin, designated $I_{1\ eff}$ and $I_{2\ eff}$, will be discussed later.

The results of the basic overlap tests indicate that the ultimate frame force, or ultimate strength, of the 8 inch (203 mm) deep purlins is approximately equal to the ultimate strength of the 9 1/2 inch (241 mm) deep purlins. This result occurred for the following two reasons. First, the 9.5B specimens experienced additional distortions, or buckles, in the web areas, possibly reducing the ultimate strength of the purlin. Second, the ultimate tensile strength of the 8 inch (203 mm) deep purlins was found to be higher than the ultimate tensile strength of the 9 1/2 inch (241 mm) deep purlins. The coupon test results for the 8 inch (203 mm) deep purlins gave an average yield stress of 70.1 ksi (483 MPa) and an average ultimate stress of 89.2 ksi (615 MPa). The results for the 9 1/2 inch (241 mm) deep purlins gave an average yield stress of 57.7 ksi (398 MPa) and an average ultimate stress of 80.1 ksi (552 MPa).

The ultimate moment for each basic overlap test, (M_u), is nondimensionalized by dividing by the corresponding single purlin ultimate moment, (M_s). A plot of the ultimate moment ratio versus the overlap length to purlin depth ratio, L/d, is presented in Figure 3. The capacity of the nested purlins increased as the L/d ratio increased. At an L/d ratio of 2, the moment capacity of the nested purlin is approximately 1.5 times the capacity of a single purlin. The strength of nested purlins equals the strength of a single purlin when an L/d ratio of 0.5 is reached.

For each test purlin tabulated in Table 2, two effective stiffnesses were calculated, designated $I_{1\ eff}$ and $I_{2\ eff}$. The term,

$I_{1\ eff}$, refers to the effective moment of inertia of the single purlin. The term, $I_{2\ eff}$, refers to the effective moment of inertia of the purlin in the overlapped section.

The effective moment of inertia of each purlin, $I_{1\ eff}$, was found from the load-deflection curve data. The measured centerline deflection was calculated by averaging the two LVDT readings at each load. The effective moment of inertia in the overlapped section of the purlins, $I_{2\ eff}$, was determined by calculating the moment of inertia in the overlapped section that would cause the measured centerline test deflections. Because of the overlap, two moments of inertia were specified for the nested purlin; the single purlin areas with $I_{1\ eff}$, and the overlapped section with $I_{2\ eff}$. Based on the properties of the purlin test specimen, an equation was developed to determine the effective moment of inertia in the overlapped section. The equation is:

$$I_{2\ eff} = \frac{[0.125 - \beta^3]}{[6E\Delta_M/P\ell^3 - \beta^3/I_{1\ eff}]} \tag{1}$$

where

$I_{2\ eff}$ = Effective moment of inertia in the overlapped section (in^4, mm^4)
$I_{1\ eff}$ = Effective moment of inertia for single purlin (in^4, mm^4)
P = Frame load (lbs, kN)
Δ_M = Measured deflection at frame load P (in, mm)
ℓ = Total length of test purlin (in, mm)
L = Overlap length (in, mm)
λ = Overlap length to purlin length ratio (L/ℓ)
β = $(0.5 - \lambda)$
E = Modulus of elasticity (ksi, MPa).

A plot of the stiffness ratio, $I_{2\ eff}/I_{1\ eff}$, versus the overlap length to purlin depth ratio, L/d , is presented in Figure 4. The effective stiffness of the nested purlin increases as the L/d ratio increases and approaches two times the stiffness of a single purlin. The stiffness of a single purlin is reached when the L/d ratio is approximately 1.3.

A regression analysis was conducted to develop strength and stiffness prediction equations for nested Z-purlins. The best fit regression equation for the moment ratio-L/d ratio relationship was

$$M_u/M_s = 1.425\ (\ L/d - 0.374\ )^{0.08} \tag{2}$$

with a correlation coefficient of 0.966. For the stiffness ratio-L/d ratio relationship, the best fit regression equation was

$$I_{2\ eff}/I_{1\ eff} = 1.099\ (\ L/d - 0.374\ )^{0.4} \tag{3}$$

with a correlation coefficient of 0.998.

The prediction equations are based on both purlin sizes. The regression analysis curves calculated for the strength and stiffness data are shown in Figures 3 and 4, respectively.

A tabulation of the ultimate frame force and the effective purlin stiffnesses for each finger-tight bolt test is presented in Table 2. A plot of the tight and finger-tight strength data is presented in Figure 3. The results indicate a reduction in ultimate strength of approximately 15 percent for the two finger-tight bolt tests. The ultimate strength of the 9.5B21 specimen was reduced only 5 percent, but some friction was present in that test.

The reduction in ultimate strength was caused by the increased rotation that took place between the two overlapped purlins. This rotation caused the two compression flanges to bear immediately on each other. The load was therefore transferred through both the overlap bolts and the two compression flanges; whereas, in tight bolt tests, the load is transferred completely through the overlap bolts. This increased stress on the compression flanges caused premature buckling of the flanges, thus reducing the capacity of the nested purlins.

A plot of the tight and finger-tight stiffness data is presented in Figure 4. A reduction in effective stiffness of approximately 40 percent for the two 8 inch (203 mm) deep purlins was observed for finger-tight bolt tests. The effective stiffness of the 9.5B21 specimen was reduced almost 50 percent. Again, this reduction is caused by the increased rotation that occurs between the two purlins. Therefore, the overlap deflections increase significantly, thus reducing the effective stiffness of the overlapped section.

The bolt line shear tests were conducted to develop a better understanding of the load transfer mechanism in the overlapped section of Z-purlins. The shear test program was divided into two basic test steps. They were: 1) determine the average ultimate shear for each bolt size and material; and 2) conduct bolt line shear tests to determine the correlation between the bolt line force and the frame force.

To determine an average ultimate shear strength of the bolts, a series of bolt shear capacity tests were conducted for each bolt size and material. The results of these bolt tests are presented in Table

3. A total of six different bolts were tested, each bolt designated by the bolt material, brass or steel, and the bolt size, in inches. Each test was repeated four times.

To determine the correlation between the bolt line force and the frame force, bolt line shear tests were conducted on 8 inch (203 mm) deep purlins with a 16 1/2 inch (419 mm) overlap length. A tabulation of the results from the bolt line shear tests are presented in Table 4. Each test is designated by it's bolt type, material and size, followed by the bolt test number. The ultimate frame load in the second column refers to the frame load on the purlin at the time of either a beam failure or bolt failure. The third column is the total bolt shear capacity in each bolt line of the overlapped section. This quantity is twice the capacity of the single bolt since two bolts lie in each bolt line. The failure mode is designated as either a beam or bolt failure.

The results of the bolt line shear tests indicate that the ultimate frame load for the 8.0B33 specimen is approximately 2830 pounds (12.6 kN). From the results of the B312 tests, a range of bolt line forces at ultimate load was established. This range is between 2948 and 3122 pounds (13.1 and 13.9 kN). Thus, the load through each bolt line at purlin failure is approximately 3035 pounds (13.5 kN). Therefore, the bolt shear in each bolt line is equal to 3035/2830 (13.5/12.6), or 1.07, times the frame force.

Based on the experimental data from the bolt line shear tests, a simple computer model was developed that predicted the bolt line force. Simple planeframe elements were chosen to simulate the 8 inch (203 mm) deep purlin and the 16 1/2 inch (419 mm) overlap length used in the bolt line shear tests. A stiff link was chosen to approximate the centerline connection between the purlin and building frame. Two additional links were used to represent overlap bolt line. A schematic of the computer model is shown in Figure 5.

By varying the stiffnesses of each bolt line link, a relationship was established between the link force and the frame force (See Figure 6). The results indicate that the link force to frame force ratio increases as the stiffness of the bolt line increases. If the stiffness is high enough, the link force, or bolt line force, approaches 1.5 times the frame force.

The shaded area on Figure 6 represents actual stiffnesses measured from the purlins tested. The only significant source of deformations were the deflections due to local bearing failure. Therefore, for both B312 tests, measurements were taken of the hole deformations. The stiffnesses were determined for each purlin to establish upper and lower bounds of stiffness. Those stiffnesses were plotted using the planeframe solution curve, to predict the link force to frame force ratio. The resulting link force to frame force ratio matches the actual ratio found in the experimental results.

As stated earlier, the link force, or bolt line force, approaches 1.5 times the frame force as the stiffness of the connection increases. If larger bolts were placed in the overlapped section, the hole deformations due to bearing failure would tend to decrease. Therefore, the actual stiffness in the bolt line would increase significantly, and the computer model predicted the ultimate bolt line force would approach 1.5 times the frame force.

CONCLUSIONS

The results of the basic overlap tests indicated that the strength of nested purlins equals the strength of a single purlin when an overlap length to purlin depth ratio, L/d, of 0.5 is reached. The basic overlap test results also indicated that the stiffness of nested purlins equals the stiffness of a single purlin when an L/d ratio of approximately 1.3 is reached. Therefore, to reach both single purlin strength and stiffness, the overlap length must be approximately 10 1/2 inches (267 mm) for the 8 inch (203 mm) deep purlins and approximately 12 1/2 inches (318 mm) for the 9 1/2 inch (241 mm) deep purlins.

The use of finger-tight versus tight bolts in the overlapped section of Z-purlins had significant effect on purlin strength and stiffness. The strength, in terms of ultimate load, was reduced by as much as 20 percent. The stiffness was reduced approximately 40 percent, due to the increased deflections in the overlapped section.

The results of the bolt line shear tests indicated that the ultimate force through each bolt line was slightly higher than the ultimate frame force for the 8 inch (203 mm) deep purlin with a 16 1/2 inch (419 mm) overlap length. The computer model closely estimated the bolt line forces measured experimentally. The computer model also indicated that the bolt line forces may approach 1.5 times the frame force when larger diameter bolts are used.

The results of the basic overlap tests indicated that under high loading conditions, web buckling was more severe for the 9 1/2 inch (241 mm) deep purlins than for the 8 inch (203 mm) deep purlins. For purlins of higher depth to web thickness ratios, web buckling over the building frame could become more severe.

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APPENDIX - NOTATIONS

d = Purlin depth (in, mm)

E = Modulus of elasticity (ksi, MPa)

$I_{1\ eff}$ = Effective moment of inertia of the single purlin (in^4, mm^4)

$I_{2\ eff}$ = Effective moment of inertia in the overlapped section of the nested purlin (in^4, mm^4)

L = Overlap length measured from frame centerline to bolt line (in, mm)

L/d = Overlap length to purlin depth ratio

M_u = Ultimate moment for the nested purlin (kip-ft, kN-m)

M_s = Ultimate moment for the single purlin (kip-ft, kN-m)

P = Frame load (lbs, kN)

β = $(0.5 - \lambda)$

λ = Overlap length to purlin length ratio (L/ℓ)

ℓ = Total length of purlin test specimen (in, mm)

Δ = Total deformation between the nested purlins at the bolt line (in, mm)

Δ_M = Measured centerline deflection at frame load P (in, mm)

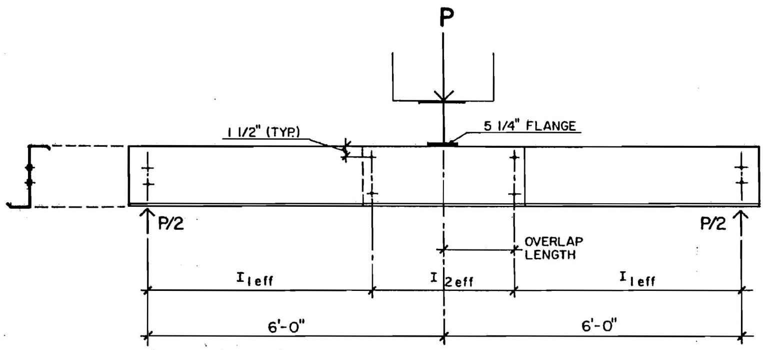

Figure 1 Purlin Test Specimen

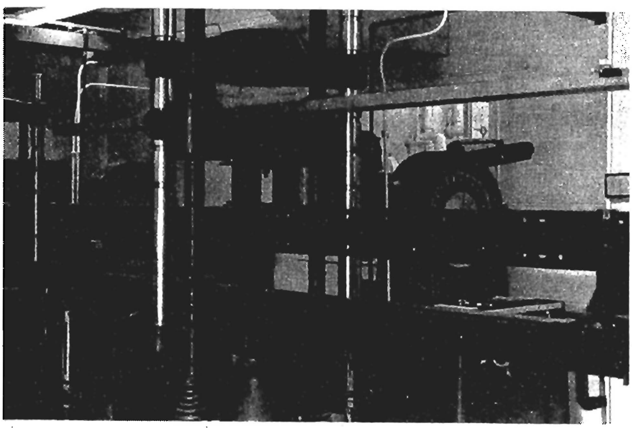

Figure 2 Laboratory Test Setup

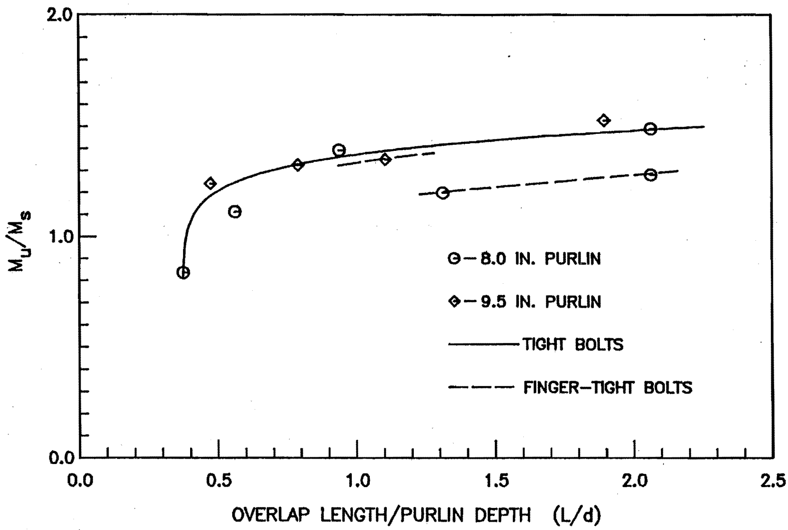

Figure 3 Strength Results for Tight and Finger-tight Bolt Tests

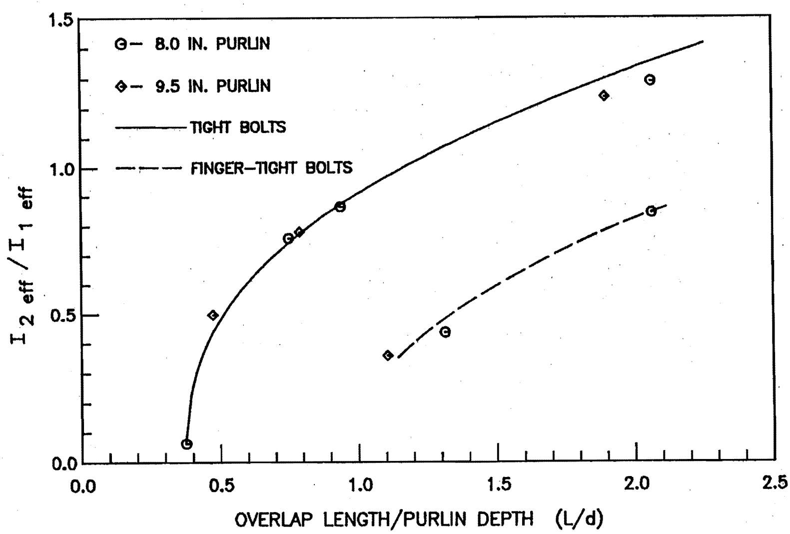

Figure 4 Stiffness Results for Tight and Finger-tight Bolt Tests

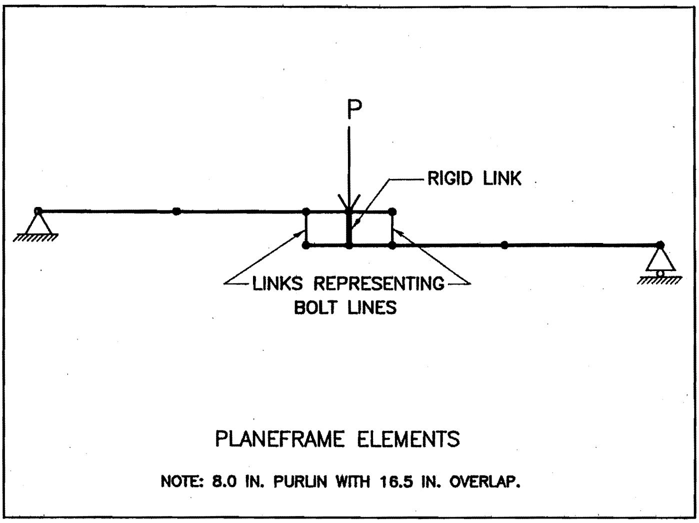

Figure 5 Computer Model

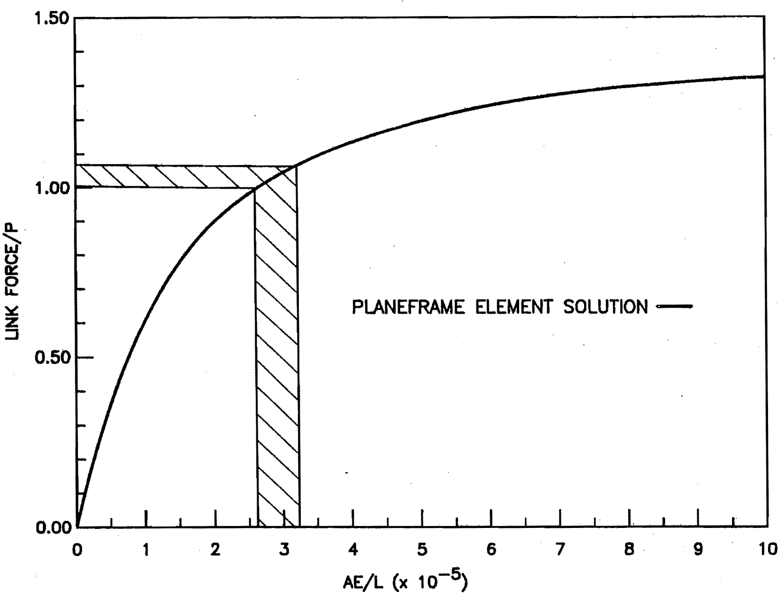

Figure 6 Planeframe Element Solution Curve

Table 1

TEST MATRIX

	Specimen Number	Purlin Depth (in.)	Overlap Length (in.)	Bolt Size (in.)	Bolt Type	Bolt Tightness
Basic Overlap	9.5BS	9.5	--	--	----	-----
	9.5B36	9.5	18.0	1/2	A307	T
	9.5B15	9.5	7.5	1/2	A307	T
	9.5B9	9.5	4.5	1/2	A307	T
	8.0BS	8.0	--	--	----	-----
	8.0B33	8.0	16.5	1/2	A307	T
	8.0B15	8.0	7.5	1/2	A307	T
	8.0B12	8.0	6.0	1/2	A307	T
	8.0B6	8.0	3.0	1/2	A307	T
Finger Tight	9.5B21	9.5	10.5	1/2	A307	FT
	8.0B33L	8.0	16.5	1/2	A307	FT
	8.0B21L	8.0	10.5	1/2	A307	FT
Bolt Line Shear	8.0B33B25-1	8.0	16.5	1/4	B	FT
	8.0B33S25-1	8.0	16.5	1/4	S	FT
	8.0B33S25-2	8.0	16.5	1/4	S	FT
	8.0B33B312-1	8.0	16.5	5/16	B	FT
	8.0B33B312-2	8.0	16.5	5/16	B	FT

T = TIGHT BOLTS
FT = FINGER-TIGHT BOLTS
B = BRASS BOLTS
S = STEEL BOLTS

Table 2

PURLIN TEST DATA

	Specimen Number	Ultimate Frame Force (lbs.)	Effective Stiffness (in.^{4})	
			$I_{2\ eff}$	$I_{1\ eff}$
Basic Overlap	9.5BS	2265	----	9.82
	9.5B36	3460	12.2	9.82
	9.5B15	3000	7.66	9.82
	9.5B9	2810	4.88	9.82
	8.0BS	2295	----	6.69
	8.0B33	3415	8.66	6.69
	8.0B15	3195	5.79	6.69
	8.0B12	2380	5.07	6.69
	8.0B6	1915	0.44	6.69
Finger Tight	9.5B21	3060	3.86	9.82
	8.0B33L	2940	5.64	6.69
	8.0B21L	2750	2.92	6.69

Table 3

BOLT CAPACITIES IN SHEAR

Bolt Number	Bolt Diameter (in.)	Bolt Material	Average Ultimate Shear (lbs.)
S25	1/4	Steel	1474
S25	1/4	Steel	1474
B312	5/16	Brass	1561
B375	3/8	Brass	2779
S312	5/16	Steel	2961
S375	3/8	Steel	3667

Table 4

BOLT LINE SHEAR TEST DATA

Bolt Type	Ultimate Frame Load (lbs.)	Total Bolt Shear Capacity (lbs.)	Failure Mode
B25-1	2980	2626	Bolts
S25-1	2850	2948	Beam*
B25-1	2800	2948	Bolts
B25-1	2675	3122	Beam
B25-1	2940	3122	Beam

* HOLE LOCATED 2.75 INCHES FROM TOP FLANGE.
NOTE: ALL TESTS ON 8.0 IN. PURLIN WITH 16.5 IN. OVERLAP.