International Specialty Conference on Cold-Formed Steel Structures

(1998) - 14th International Specialty Conference on Cold-Formed Steel Structures

Oct 15th, 12:00 AM

Spacing of Connections in Compression Flanges of Built-up Cold-formed Steel Beams

Roger A. LaBoube
Missouri University of Science and Technology, laboube@mst.edu

Wei-wen Yu
Missouri University of Science and Technology, wwy4@mst.edu

Michael L. Jones

Recommended Citation

LaBoube, Roger A.; Yu, Wei-wen; and Jones, Michael L., "Spacing of Connections in Compression Flanges of Built-up Cold-formed Steel Beams" (1998). *International Specialty Conference on Cold-Formed Steel Structures*. 4.
https://scholarsmine.mst.edu/isccss/14iccfsss/14iccfsss-session10/4

Fourteenth International Specialty Conference on Cold-Formed Steel Structures
St. Louis, Missouri U.S.A., October 15-16, 1998

Spacing of Connections in Compression Flanges of Built-up Cold-Formed Steel Beams

R. A. LaBoube[1], W. W. Yu[2], and M. L. Jones[3]

ABSTRACT

Built-up cold-formed steel sections may offer greater economy in building construction. Typical built-up sections are cellular decks or door and window header beams. A research project was initiated to determine if the current spacing criteria outlined in Section D1.2 of the AISI Specification accurately predicted the capacity of built-up sections with the cover plate in compression. This study showed that criteria No. 2 of the AISI Design Specification spacing criteria is restrictive when applied to built-up cross sections in bending. All test sections continued to carry additional load after the cover plate buckled. The tests showed that as the spacing of connectors increased the moment capacity of the section decreased. An analytical procedure was developed to compute the nominal moment capacity for a range of connector spacings.

INTRODUCTION

Today both residential and commercial buildings employ a wide variety of cold-formed steel members. The use of built-up steel sections may offer greater economy in building construction, for example, the use of cellular decks or door and window header beams.

Provisions of the 1996 AISI Specification (Specification, 1996) use a restrictive design approach which limits the spacing of connections in compression elements to a value that does not allow column-like buckling of the cover sheet between the connectors, or buckling of the unstiffened outside edge of a flat cover sheet. However, it is well known that buckling of the sheet does not immediately cause failure of the deck section. This increased strength occurs because of a redistribution of stress (postbuckling strength).

A recently completed study at the University of Missouri-Rolla (UMR) investigated the influence of the spacing of connectors in compression elements of built-up members. The study focused on hat shaped cross-sections with the cover plate in compression. This study investigated the behavior of both cover plate compression elements with and without edge stiffeners (Jones, 1997). This paper will summarize the study of the cover plate compression element without edge stiffeners.

---

[1] Distinguished Teaching Professor of Civil Engineering, Dept. of Civil Engineering, University of MO-Rolla, Rolla, MO 65409

[2] Curators' Professor Emeritus of Civil Engineering, Dept. of Civil Engineering, University of MO-Rolla, Rolla, MO 65409

[3] Structural Engineer, Black & Veatch Consulting Engineers, Kansas City, MO, former research assistant, Dept. of Civil Engineering, Univ. Of MO-Rolla, Rolla, MO 65409

LITERATURE REVIEW

AISI Design Specification. Provisions in Section D1.2 of the AISI Specification (1996) provide connector spacing requirements that attempt to make the flat sheet act monolithically with the cross section. The spacing is limited to: (1) that which is needed to develop the required shear strength, (2) limit column-like buckling behavior between fasteners, and (3) buckling of the unstiffened edge of the cover plate (Yu, 1991; Yu, 1996). When these provisions are met, the cover plate between fasteners can be assumed to be a fully stiffened element of width, w, between connection lines (Fig. 1).

The AISI Specification provisions are as follows: The spacing, s, in the line of stress, of welds, rivets, or bolts connecting a cover plate, sheet, or a non-integral stiffener in compression to another element shall not exceed:

(a.) that which is required to transmit the shear between the connected parts based on the design strength per connection; nor

(b.) $1.16t\sqrt{E/f_c}$, where t is the thickness of the cover plate or sheet, and f_c is the stress at service load in the cover plate or sheet; nor

(c.) three times the flat width, w, of the narrowest unstiffened compression element tributary to the connections, but need not be less than $1.11t\sqrt{E/F_y}$ if $w/t < 0.50\sqrt{E/F_y}$, or $1.33t\sqrt{E/F_y}$ if $w/t \geq 0.50\sqrt{E/F_y}$, unless closer spacing is required by (a) or (b).

Yener's Study. Yener studied the AISI requirements for connection spacing on cellular panels under load (Yener, 1984). The testing involved single lap joint tests, and one, two, and three-span beam tests. Thirteen simple span beam tests were performed (four with the cover sheet in compression). Four panels were tested in a three-span uniform load situation and four panels were tested in a uniform load two-span situation. Yener developed the following spacing criterion which is less conservative than the current AISI criteria (Specification, 1996):

Spacing of the connections shall be limited to the smallest of the following requirements:

(a.) Spacing shall not exceed that required to transmit the force induced by the applied loads and based on the allowable design strength of the connectors.

(b.) Spacing shall not exceed that required to prevent buckling of the cover plate between the connection lines such that $s = 0.6w$, but not less than $133t/(F_y)^{1/2}$, where w is the width of the flat plate between the connection lines.

(c.) Spacing shall not exceed that as to prevent the separation of the unstiffened compression plate element such that $s = 8w_u$, but not less than $507t/(F_y)^{1/2}$, where w_u is the width of the smallest unstiffened edge of the flat plate.

Luttrell and Balaji's Study. The research efforts of Luttrell and Balaji (1992) focused on cellular decks with cover plates in compression. Luttrell and Balaji developed a modified effective width approach assuming that if connections are spaced close enough, buckling between connectors is prevented, allowing the use of the AISI effective width equations. When spacing increases between connectors the possibility of column-like buckling between connectors is increased. If column-like buckling between connectors occurs, the AISI effective width equations are invalidated because the connection lines can not create edge supports required for the stiffened plate.

A summary of the modified effective width equations are as follows:

When $f_c < \sigma_{cr}$ the AISI effective width equations are valid for the flat sheet between the connection lines.

When $f_c = \sigma_{cr}$ the flat sheet between the connection lines is at a transition stress and the transition effective width factor ρ_t is found as follows:

Where

$$\lambda_t = \left(\frac{1.052}{\sqrt{k}}\right)\left(\frac{w}{t}\right)\sqrt{\frac{\sigma_{cr}}{E}} \tag{2}$$

$$\sigma_{cr} = \frac{\pi^2 E}{\left(\frac{k_c s}{r}\right)^2} \quad where,\ r^2 = \frac{t^2}{12},\quad k_c = 0.5 \tag{3}$$

$\rho_t = 1.0$ when $\lambda_t < 0.673$

$$\rho_t = \frac{\left(1.0 - \frac{0.22}{\lambda_t}\right)}{\lambda_t} \quad when\ \lambda_t \geq 0.673 \tag{4}$$

When f_c increases above the critical in the flat sheet the effective width will decrease and the final value of ρ is found as follows:

When $f_c > \sigma_{cr}$

$$\rho_m = \left(\frac{F_y}{f_c}\right)\sqrt{\frac{\sigma_{cr}}{D\,f_c}} \tag{5}$$

$$\rho = \rho_m \rho_t$$

Where:

λ_t = transition stress slenderness factor
σ_{cr} = Euler elastic column buckling stress
w = flat width between connection lines (Figure 1)
t = thickness of flat sheet
k = plate buckling coefficient
k_c = column buckling effective length factor
s = fastener spacing
r = radius of gyration of cover plate
ρ_t = transition stress reduction factor
ρ_m = reduction factor
f_c = stress at service load in the cover plat or sheet
D = Overall depth of section including the cover plate
E = Modulus of elasticity of steel, 29,500 ksi

UMR EXPERIMENTAL STUDY

A study of connections in a built-up section compression element was initiated at the University of Missouri-Rolla. The purpose of this study was to gain a better understanding of the structural behavior, and the parameters that effect the behavior of compression elements in built-up sections. A total of 60 full-scale beam tests were conducted.

Test Specimens. The sections used in this study were hat sections with flat cover sheets without edge stiffeners (Fig. 2). The specimens were divided into two groups: h-type material without edge stiffened cover plate, gsh-type material without edge stiffened cover plate. All connections were made with 3/4 inch, No.10, self-drilling screws. The mechanical properties of the materials were determined by performing tensile tests on coupons cut from the flat sheets. The specimens were tested following the guidelines outlined in ASTM A370 (American 1994). Table I lists the mechanical properties.

Specimens used in the study were designed to determine the effects of the following parameters:

yield strength, F_y, thickness, t, spacing of connectors, s, flat-width ratio of the flat sheet between the connection lines, w/t, depth of the section, D, and width of the flange on the hat section, d. Table II lists the dimensions of the sections used in the test program.

Specimen Fabrication. The fabrication process involved the placement of strain gages on selected specimens and the attachment of the flat sheet to the hat section using self-drilling screws. Figure 3 shows the typical placement of the strain gages.

Test Setup. The test program considered two test setups. Test setup #1, shown in Figure 4, was used on all but four specimens. The length of each specimen was 60 inches. Three inch wide bearing plates were used at all loading points. The actual distance between bearing plates for the two-point load varied depending on the spacing used on the specimen (Table III). Connector spacing was adjusted such that the bearing plate and screw connection would not coincide, as shown in Figure 5.

EXPERIMENTAL PROCEDURE

The data collected in the experimental study consisted of the ultimate load capacity of the beam section and the strain versus load readings when strain gages were employed. The ultimate load capacity was defined as the maximum load the cross section was capable of supporting.

EVALUATION OF TEST RESULTS

A total of 60 full-scale beam tests were completed at the University of Missouri-Rolla for evaluation of built-up sections without edge stiffened cover plates in compression. The tests included 16 sections with strain gages.

Evaluation of the test results consisted of a comparison of the predicted moment capacity using the AISI Specification, Yener's Spacing Criteria, Luttrell and Balaji's modified effective width equation, and a UMR model.

Behavior of Test Specimens. The behavior of the test sections varied based on connector spacing, material thickness, and cross-section geometry. Two buckling behavior categories, column-like buckling of the cover plate and plate like bucking behavior of the cover plate, were observed. The buckling behavior was column-like for all sections in which the tested spacing, s_t, exceeded that required by the AISI Specification, s_m, and plate-like buckling occurred for tested spacings having s_t less than s_m. The main differences in behavior can be attributed to the edge conditions of the cover plate and the thickness of the cover plate. When the spacing of the connectors was less than, s_m, the behavior of the cover plate was that of plate-buckling. Plate buckling behavior of the h-type and gsh-type material was basically identical except for buckling along the unstiffened edge of the cover plate. Because of the thinner gsh-type material, severe buckling of the outside edge of the cover plate and the hat section flange occurred. When the tested spacing of the section was increased beyond that required by the AISI Specification, the buckling behavior of the cover plate simulated a column of length, s, as depicted in Figure 1.

Strain Gage Results. Strain gages were used to determine the effective length factor and plate buckling coefficient for buckling of the flat plate between the connectors. Two gages were used at each location as shown in Fig. 3. Jones (1997) presents a detailed discussion of the strain gage study and findings.

Hat Section Bending Capacity. Ideally, in the design of built-up sections, each component contributes to carrying the applied load. To ensure that built-up cross section behavior was being achieved, the experimentally determined moment capacity was compared to the fully braced moment capacity for the hat shape alone. If the experimentally obtained moment capacity is less than the fully braced hat shape capacity alone, built-up action between the flat sheet and hat shape was not obtained. Figure 6 show the average percent increase in capacity over the fully braced hat capacity alone for the sections.

As shown by Figure 6, there was an increase in capacity due to the presence of a cover plate. The cover plate served two purposes: (1) the cover plate laterally braced the compression flange and webs of the hat section, and (2) the cover plate added additional capacity as a compression element between connectors.

Built-up Section Bending Capacity. The AISI Specification requires that spacing of connectors meet requirements in Section D1.2, Spacing of Connections in Compression Elements. When this spacing requirement is met, the nominal moment, M_n ($M_n = S_eF_y$), is based on initiation of yielding. In the calculation of the effective section modulus, the portion of the plate between the connection lines, w, was considered to be a uniformly compressed stiffened element with $k = 4.0$. The area outside the connection line was considered to be unstiffened cover plate.

Comparisons with the AISI Specification included two parts. First, a comparison was made with the sections in the test program that met the requirements of Section D1.2, Spacing of Connections in Compression. Second, a comparison was made with all test specimens which included spacings, s_t, that exceeded the maximum spacing required, s_m. For the test data of this study, the ratio s_t/s_m ranged from 1 to 12.

Figure 7 shows the ratio of the tested moment capacity, M_t, to the computed moment capacity M_c, $M_c = S_eF_y$, versus the connector spacing for all of the tested sections. For the h-type material, spacings greater that 1.5 inches did not satisfy the spacing requirements in Section D1.2. Figure 7 shows that the AISI Specification can accurately predict the moment capacity of the h-type material when the required spacing of Section D1.2 is not exceeded. The AISI Specification did not accurately predict the capacity of the sections when the spacing was increased beyond that required by Section D1.2 for the h-type or gsh-type material. However, the test results show that increasing the spacing of connectors beyond that required by Section D1.2 did not significantly diminish the capacity of the section.

Yener Spacing Criteria. Figure 8 shows M_t/M_c, when M_c is computed based on Yener's spacing criteria. Only the tests specimens having spacings less than or equal to Yener's criteria are given.

Based on the data given on Figure 8, the spacing recommendations proposed by Yener are too liberal for the specimens used in this test program, yielding computed moment capacities as much as 40% higher than the tested moment capacity. This inadequacy may be attributed to two factors: (1) Yener's spacing criteria was developed from tests on deck sections which consist of multiple flutes, and (2) the criteria was developed for a small number of tested sections with the cover plates in compression.

Luttrell and Balaji Modified Effective Width Model. Luttrell and Balaji's modified effective width model was developed from the results of 82 deck tests. The decks used in the study were industry standard deck sections with multiple flutes and edge stiffened cover plates.

Using Luttrell and Balaji's model, M_t/M_c versus connector spacing is shown by Figure 9. This shows that Luttrell and Balaji's model is adequate for the h-type material with a mean value of 1.03 and a Coefficient of Variation of 10 percent. The model, however, overestimates the capacity of the gsh-type material by as much as 30%.

UMR MODEL

Both Yener and Luttrell models failed to reasonably predict the capacity of the sections tested in this study.

The present AISI computation model considered the cover plate between the connections as a stiffened element and the section outside the connection line as an unstiffened element. This assumption is incorrect for cover plates without edge stiffeners when the flat plate buckles from edge to edge across the width in a column-like buckling pattern. There is no edge restraint provided at the connection line along the length of the specimen.

The following observations were also found to have had a definite effect on the moment capacity of the section: (1) As the spacing of the connectors increased beyond s_m, the buckling behavior changed from plate buckling to column buckling; (2) The tested capacity decreased as the spacing increased (Fig. 10); (3) As the width of the section increased the likelihood increased that sinusoidal plate buckling waves occurred; and (4) When the plate buckled, the specimen did not fail, meaning that postbuckling strength was provided by the cover plate.

Based on the UMR test data, a moment computation model for sections without edge stiffened cover plates was developed. It as determined that the significant parameter that influenced the moment capacity was the ratio of the actual spacing, s_t, divided by the minimum spacing, s_m, required by the AISI Specification. As the ratio of s_t/s_m increased the postbuckling strength provided by the cover plate decreased. The following is a summarizes the UMR model:

When $s/s_m \leq 3.0$, and $k\,s/r < 328$

$$M_n = S_x \sigma_{cr} (\alpha_1) \tag{7}$$

$3.0 < s/s_m < 6.0$, and $k\,s/r < 328$

$$M_n = S_x \sigma_{cr} (\alpha_2)(\alpha_3) \tag{8}$$

Where:

$\alpha_1 = 0.849 + 0.253(s/s_m)$
$\alpha_2 = -9.11 + 4.683(s/s_m) - 0.363(s/s_m)^2$
$\alpha_3 = 1.634 - 0.464(w/s)$
$k = 0.6$
s = Desired Spacing
$s_m = 1.16t\sqrt{(E/f_c)}$
t = Thickness of cover plate
f_c = Stress in the cover plate
w = Flat width of cover plate (Figure 1)
S_x = Full section modulus of section about x-axis.
r = Radius of gyration of cover plate
σ_{cr} = Euler column buckling stress with $k = 0.6$

Figure 11 shows a comparison of the tested to computed moment capacity for the UMR test specimens.

The data (Fig. 11) shows good correlation between M_t and M_n for the range of connector spacings studied. The M_t/M_n ratio had a mean of 1.00 with a coefficient of variation of 11%. The range of the parameters used to develop this model are as follows:

$F_y \leq 53$ ksi
$88 \leq w/t \leq 287$
$t \geq 0.017$ in.
$1.0 \leq s/s_m \leq 12.0$
$69.0 \leq k_c\,s/r \leq 328$
$1.0 \leq \alpha_1 \leq 1.7$
$3.8 \leq \alpha_2 \leq 6.0$
$0.75 \leq \alpha_3 \leq 1.3$

CONCLUSION

This research project was initiated to determine if the current spacing criteria outlined in Section D1.2 of the AISI Specification accurately predicted the capacity of built-up sections with the cover plate in compression. This study showed that criteria No. 2 of the AISI Design Specification spacing criteria is restrictive when applied to built-up cross sections in bending.

All test sections continued to carry additional load after the cover plate buckled. The results of the tests showed that the buckling behavior of the cover plate as a simple column can be prevented when adhering to the second criterion of Section D1.2 of the AISI Design Specification. Therefore the criterion is adequate for prevention of column-like buckling of the cover plate between connectors. The tests showed that as the spacing of connectors increased the moment capacity of the section decreased. An analytical procedure was developed to compute the nominal moment capacity for a range of connector spacings.

ACKNOWLEDGMENTS

This investigation was sponsored by the American Iron and Steel Institute. The financial assistance provided by the Institute and technical guidance provided by the AISI Connections Subcommittee (M. Golovin, chairman), is gratefully acknowledged.

APPENDIX - REFERENCES

American Society for Testing and Materials (1994), "Standard Methods and Definitions for Mechanical Testing of Steel Products," ASTM 370 1994.

Jones, M. L. (1997), "Spacing of Connections in Compression Elements for Cold-Formed Steel Members," Thesis submitted to the faculty of the University of Missouri-Rolla for partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering.

Luttrell, L. D. and Balaji, K. (1992), "Properties for Cellular Decks in Negative Bending," Proceedings of the 11th International Specialty Conference on Cold-Formed Steel Structures, University of Missouri-Rolla, Rolla, MO.

Specification for the Design of Cold-Formed Steel Structural Members (1996 Edition). American Iron and Steel Institute, Washington, D.C.

Yu, W. W., Cold Formed Steel Design, Second Edition, Wiley-Interscience, New York, 1991.

Yu, W. W. (1996), Commentary on the 1996 Edition of the Specification for the Design of Cold-Formed Steel Structural Members," American Iron and Steel Institute, Washington, D.C.

Yener, M. (1984), "Criteria for Connection Spacing in Cold-Formed Steel", ASCE, Journal of Structural Engineering, Vol. 110, No. 9, September. 1984, and Author's Closure, Journal of Structural Engineering, Vol. 112, No. 12, December. 1986.

Winter, G., Commentary on the 1968 Edition of the Specification for the Design of Cold-Formed Steel Structural Members, American Iron and Steel Institute, New York, NY, 1970.

Table I. Mechanical Properties of the Tested Steel

Section Type	Gage #	t (in.)	F_y (ksi)	F_u (ksi)	% elongation in two inch gage length
h*-type	18	0.0452	33	52	45
gsh*-type	26	0.0174	53	66	24

Table II. Cross Section Dimensions.

Section Type	Sheet Gage #	F_y (ksi)	D (in.)	B (in.)	t (in.)	w_h (in.)	R (in.)	d (in.)
h1	18	33	2.0	3.1	0.045	4.0	0.0625	0.5
h2	18	33	2.0	2.6	0.045	4.6	0.0625	1.0
h3	18	33	3.0	5.8	0.045	5.0	0.0625	0.5
h4	18	33	3.0	8.5	0.045	9.4	0.0625	0.5
h5	18	33	3.0	8.0	0.045	9.9	0.0625	1.0
gsh1	26	53	1.5	2.5	0.019	3.5	0.0625	0.5
gsh2	26	53	1.5	2.0	0.019	4.0	0.0625	1.0
gsh3	26	53	2.0	4.0	0.019	5.0	0.0625	0.5
gsh4	26	53	2.0	3.5	0.019	5.5	0.0625	1.0

Table III. Distances a & b on Figure 4

s (inches)	a (inches)	b (inches)
1.5	17.0	23
3.0	17.0	23
3.5	16.0	25
4.0	16.5	24
6.0	14.5	28

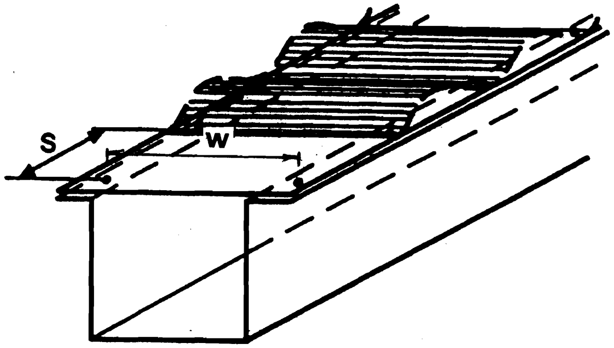

Figure 1. Spacing of Connectors in Composite Sections.

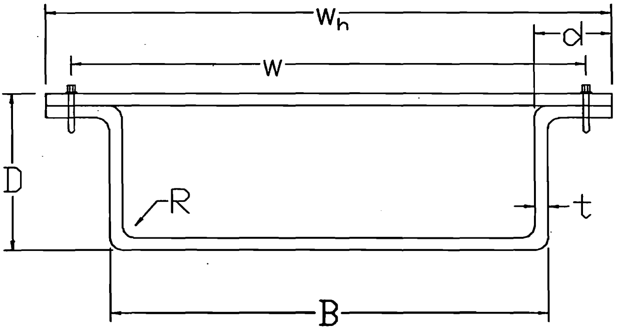

Figure 2. Section with Cover Plate.

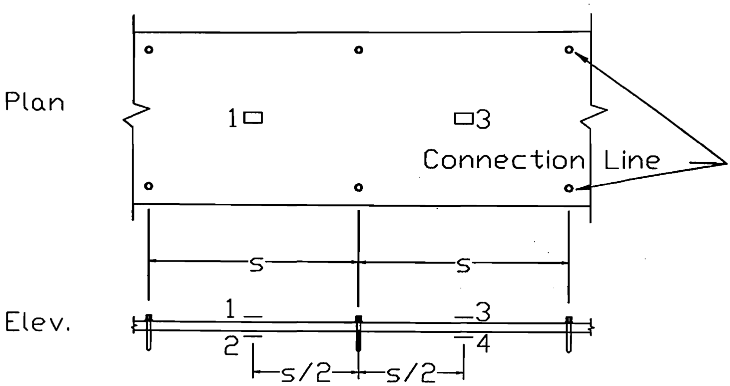

Figure 3. Location of Strain Gages.

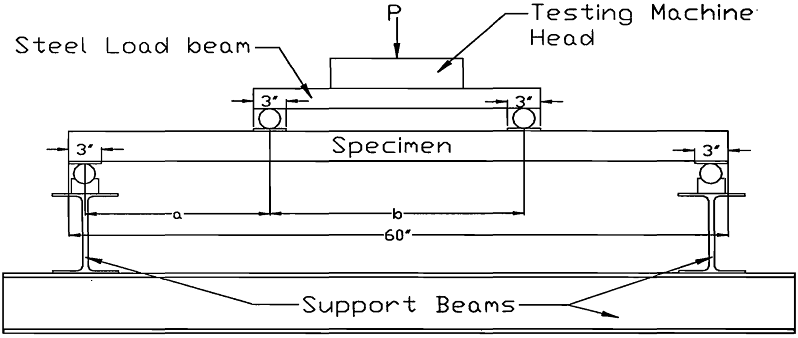

Figure 4. Test Setup for Two-Point Loading.

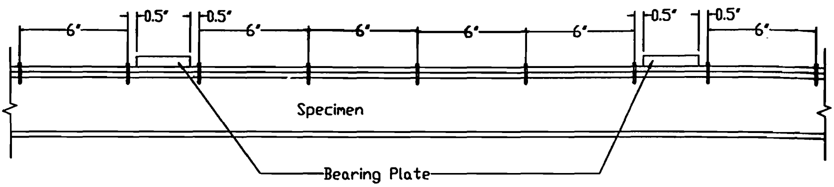

Figure 5. Spacing of Connections near the Bearing Plate.

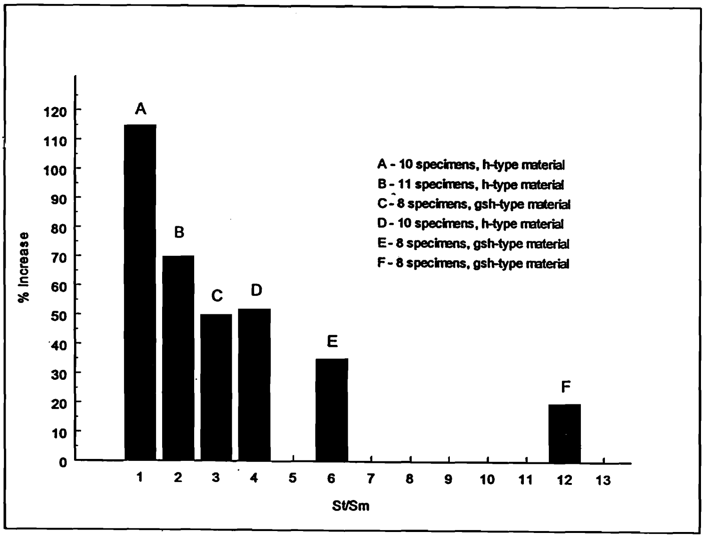

Figure 6. Percent Increase in Moment Capacity above Fully Braced Hat.

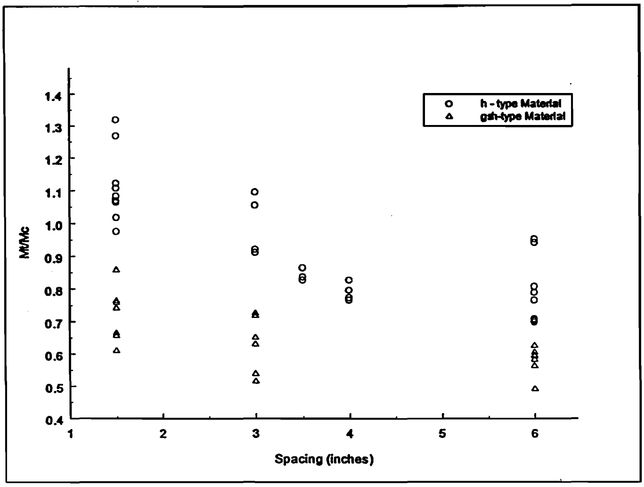

Figure 7. Moment Capacity vs Spacing.

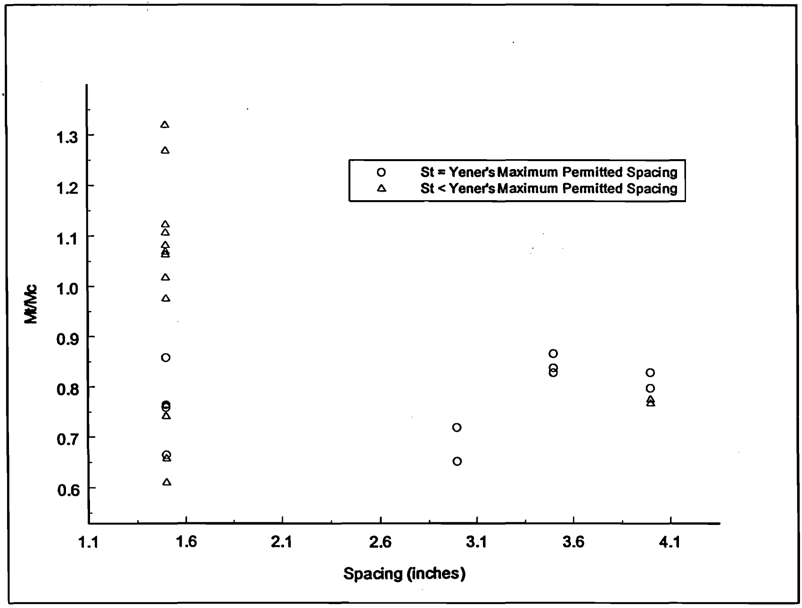

Figure 8. Comparison of Yener's Spacing Criteria to Experimental Data.

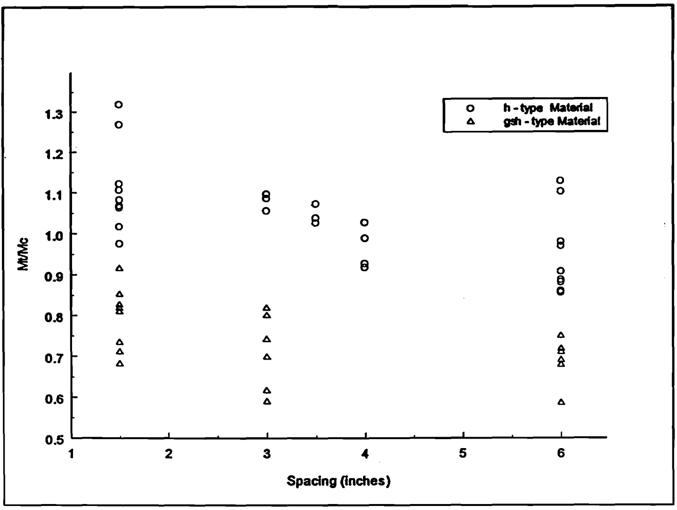

Figure 9. Comparison of Computed and Tested Moment Capacity using Luttrell and Balaji's Model

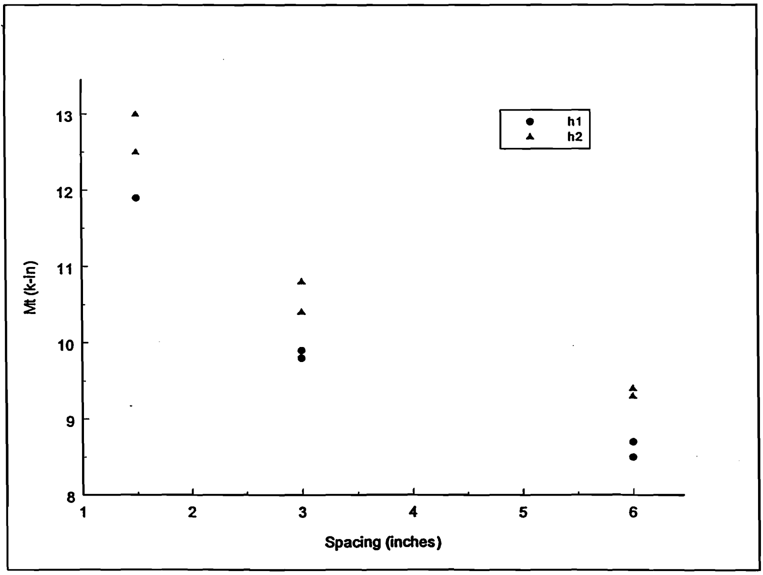

Figure 10. Tested Moment Capacity vs Tested Spacing

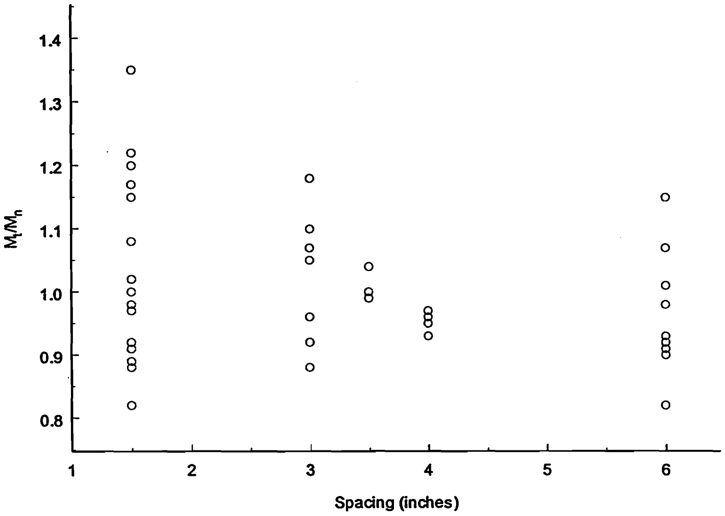

Figure 11. Comparison of Tested and Computed Capacities for UMR Model.