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COLD-FORMED STEEL Z-SECTIONS UNDER AXIAL LOAD

by

D. Polyzois[1] and A. Sudharmapal[2]

SUMMARY

The 1986 Edition of the AISI Specification has adopted the Unified Approach for evaluating the post-buckling capacity of stiffened, partially stiffened, and unstiffened plate elements in cold-formed sections. The criteria for design of sections with partially stiffened flanges, however, have been based mostly on research dealing with stiffeners located perpendicular to the flanges - a situation which is not representative of a large number of cross-sections in use today.

In the present paper, the current design criteria for cold-formed sections with sloping edge stiffeners are reviewed and evaluated through comparison with experimental data obtained in a test program involving 46 Z sections loaded in direct compression. The Z-sections varied in length from 18 in. (457 mm) to 96 in.(2438 mm). An important parametric variation in these tests was the angle between the edge stiffeners and the flanges which varied from 0 to 80 degrees.

INTRODUCTION

Cold-formed steel members, such as channels and Z-sections, provide substantial savings due to their high strength-to-weight ratio. As a result, they have become very popular in the construction of metal wall and roof systems in industrial, commercial, and agricultural buildings. The cross-section configuration of cold-formed sections, however, gives rise to behavioral phenomena, such as local and distortional buckling, which can lead to a substantial reduction in their load bearing capacity of such members. For typical sections, such as that shown in Fig. 1(a), there are three elements which are prone to failure by local bucking:

a) the flange
b) the web, and
c) the longitudinal lip stiffener

The majority of the experimental and theoretical studies to date have focused on the performance of cold-formed sections with lip stiffeners located transversely to the compression flanges (2,3,4,8). These studies have shown that the buckling and post-buckling behavior of edge stiffened elements depend on the bending rigidity of the edge stiffeners. Lau and Hancock (3) distinguish between two types of local buckling: the traditionally recognized local plate bukling, shown in Fig. 1(b), and distortional buckling, shown in Fig. 1(c). They point out that adequate stiffener rigidity prevents distortional buckling and leads to local plate buckling mode which usually occurs at a higher load. The post-buckling capacity of edge stiffened elements in

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this case, can be developed. Inadequate stiffener rigidity on the other hand, results in distortional buckling at a lower load and the development of any post-buckling capacity is questionable.

Before the 1986 Edition of the American Iron and Steel Institute (AISI) Specification (1), the design capacity of an edge-stiffened element was a function of the moment of inertia of the edge stiffener about the centroidal axis-parallel to the edge stiffened element. It was stated that in order for a compression element to be considered stiffened, the minimum moment of inertia of the stiffener, I_{min}, about the centroidal axis parallel to the edge stiffened element had to be:

$$I_{min} = (2W-13)t^4, \text{ but not less than } 9t^4 \qquad (1)$$

where W is the flat width-to-thickness ratio of the stiffened element. If the lip stiffener was bent at right angles to the stiffened element, the required overall depth, d_1, of the lip stiffener had to be at least:

$$d_1 = t(24W-156)^{1/3}, \text{ but not less than } 4.8t \qquad (2)$$

These requirements are sufficient to ensure yielding at the edges of the compression flanges stiffened by lips at 90 degrees. They are not, however, adequate for the case where sloping lip stiffeners are used.

In an experimental investigation conducted between 1976 and 1981 (6) involving Z-section girts, it was observed that the main mode of failure was distortional buckling at loads considerably lower than those corresponding to yielding. Although the sections were braced and the compression flanges were considered stiffened according to the criteria stated above, the sloping edge stiffeners were apparently inadequate in providing complete restraint to the compression flanges.

The analysis of stiffened and partially stiffened compression flanges was the subject of an extensive research project conducted at Cornell University by Desmond (2) who developed a series of empirical equations for computing the buckling coefficient of fully- and partially-stiffened compression flanges. The buckling coefficients, which range from 0.43 to 4.0, depend on the relative dimensions of the lip stiffeners and their orientation to the compression flanges. Knowing the buckling coefficient, the effective width approach can then be used to compute the ultimate capacity of the cold-formed section. Desmond's work formed the basis of the current AISI specification design criteria for partially stiffened flanges. Although his work involved mainly sections with lip stiffeners located transversely to the flanges, his recommendations were extended to cover sections with sloping edge stiffeners.

An experimental program involving cold-formed channel sections with sloping edge stiffeners was conducted in 1984 (5) to establish a relationship between the buckling coefficient of the compression flanges and the orientation of the lip stiffeners. Twenty-six stub columns consisting of two channels connected back-to-back were fabricated and tested. The angle between the lip stiffeners and the flanges varied between 0 and 90 degrees. Specimens whose lip stiffeners were transversely located to the compression flanges failed at loads corresponding to full yielding of the section. However, when the lip stiffeners were located at an angle smaller than 90 degrees to the flanges, the ultimate load was reduced. The reduction became increasingly larger as the angle between the lip stiffeners and the flanges decreased from 90 to 0 degrees. The mode of failure in these specimens was one of distortional buckling.

An evaluation of Desmond's empirical equations through comparison with this experimental data indicated a lack of agreement. Based on the new experimental data, the following equation for the buckling coefficient of the compression flanges was developed.

$$k = k_0 + k_1 - k_0)\sin\theta \tag{3}$$

where θ is the angle between the lip stiffener and the flange; $k_0 = 0.425$ and corresponds to the buckling coefficient of the flange when it is unstiffened; k_1 is a buckling coefficient determined from the following expression:

$$f_{cr} = k_1 \frac{\pi^2 E}{12(1-\nu^2)W^2} = F_y \tag{4}$$

Therefore,

$$k_1 = \frac{12(1-\nu^2}{\pi^2} [W^2 \frac{F_r}{E}] \tag{5}$$

where ν is the Poisson's ratio, F_y, is the yield stress of the section and E is the modulus of elasticity.

Equation 5 implies that when the lip stiffeners are at 90 degrees to the compression flanges, local buckling of the compression flanges takes place when the section reaches the yield stress. It thus assumes elastic behaviour up to the point of failure.

Equivalent buckling coefficients k were also computed from Eq. 5 except that f_{ave}, the average stress defined as P_{ult}/A was used. P_{ult} is the ultimate load of the specimens tested and A is their cross sectional area. As it was indicated in Reference 5, satisfactory agreement was obtained between the results from Eq. 5 and the test results. The specimens tested in that experimental program were designed to fail by local buckling of the compression flanges. Neither local buckling of the web nor lateral buckling of the specimens was allowed. To evaluate the performance of cold-formed sections with sloping lip stiffeners and webs subject to local buckling, a more extensive experimental program was undertaken (7). The length of the specimens was varied in order to examine the interaction between local and lateral buckling. The experimental program was divided into two phases: the first phase involved the testing of Z-sections under concentric loading and the second phase involved the testing of similar sections under eccentric loading. Forty-six specimens were tested in each phase. This paper deals with the results form phase 1 only. The discussion of the results, which follows a short description of the experimental program, focuses on the evaluation of the current AISI Specification (1) criteria for cold-formed Z-sections through comparison with this experimental data.

EXPERIMENTAL PROGRAM

The test specimens consisted of Z-sections varying in length from 18 in. (457 mm) to 96 in. (2438 mm). The angle between the flanges and the lip stiffeners varied from 0 degrees (no stiffeners) to 80 degrees. All specimens were cold-formed using press brake operation by a commercial manufacturer. Although one type of steel was specified, two types were used in the fabrication of the specimens. Tension test coupons, taken from various specimens covering all four length categories showed that the yield stress ranged from 42 ksi (282 MPa) to 60 ksi (422 MPa). The average cross-sectional properties for each category of specimens tested and their corresponding yield stress is given in Table 1. The parameters used in Table 1 are shown in Fig. 1a. The specimens were tested concentrically as pin-ended columns, using a ball and socket support arrangement which allowed complete rotational movement at the ends. The 18 in. (457 mm) and the 36 in. (914 mm) specimens were tested in a 60 kip (267 kN) hydraulic testing machine while the 60 in. (1524 mm) and the 96 in. (2438 mm) long specimens were tested in a test frame and the load was applied through a hydraulic jack. A pressure transducer was used to monitor the applied pressure. The data collected included vertical deflection (shortening), as well as lateral deflection at mid-height of the specimens.

The mode of failure depended on the orientation of the lip stiffeners and the length of the specimens. The predominant mode of failure for short members was one of local buckling followed by lateral buckling. Longer specimens failed by lateral buckling.

DISCUSSION OF RESULTS

The current AISI Specification (1) accounts for the interaction between local and lateral buckling of stiffened cold-formed Z-sections by computing the normal axial strength using the critical stress evaluated for the full section and the effective area evaluated at that critical stress. In the case of members with unstiffened flanges, the axial strength is limited to the local buckling capacity of the flanges (AISI-Section C4-(b)). The most significant departure from previous design methodologies is the adoption by the 1986 Edition of the AISI Specification (1) of the Unified Approach for computing the post buckling capacity of cold-formed members. Edge stiffened flanges in compression members are treated as fully or partially stiffened elements depending on the dimensions and orientations of the stiffeners. The Effective Width approach is used for all elements, including the edge stiffeners, to compute the effective area of the whole section.

The following discussion deals with the evaluation of the current AISI criteria through comparison with the experimental data. The average cross-sectional dimensions listed in Table 1 were used to establish the theoretical curves shown in Figs. 2 to 9. The ultimate capacity of the specimens neglecting the effect of local buckling is shown in Figs. 2, 4, 6 and 8. Two theoretical curves are shown in each figure: one based on $F_y = 42$ ksi (280 MPa) and the other on $F_y = 57$ ksi (398 MPa). As shown in Fig. 2, the effect of local buckling is quite pronounced in those sections with no lip stiffeners. As the angle of the lip stiffeners was changed from 0 degrees to 80 degrees, this effect became less important. Long specimens (96in. (2438 mm)) failed by elastic lateral buckling before any local buckling had taken place. Shorter columns failed by lateral buckling in the inelastic range preceded by local buckling of the web and the compression flanges. Clause C4(b) of the AISI Specification (1) limits the ultimate capacity of sections with unstiffened flanges to the local buckling capacity of the flanges. As shown in Fig. 3, this clause leads to very conservative results especially for shorter sections. Ignoring Clause C4(b) of the Specification and computing the ultimate loads using the effective width approach, more realistic results are obtained, as shown by the curves in Fig. 3.

In order to establish a statistical basis for evaluating the AISI Specification criteria, values for P_{test}/P_{spec} were computed as functions of the lip orientation, θ, shown in Fig. 10 and the length of the specimens, shown in Fig. 11. The average ratio of all sections, including those with unstiffened flanges is 1.524 and the standard deviation is 0.796. Ignoring Clause C4(b) the average ratio and standard deviation are 1.05 and 0.20 respectively.

CONCLUSIONS

This paper dealt with the ultimate capacity of cold-formed Z-sections loaded under direct compression. Forty six specimens ranging in length from 18 in. (457 mm) to 96 in. (2438 mm) were tested. The angle between the lip stiffeners and the flanges varied from 0 to 80 degrees. A comparison between the experimental data and the results obtained from the current AISI Specification indicates that the current treatment of partially stiffened flanges is quite appropriate for use in the design of sections with sloping edge stiffeners. The experimental results also indicate that basing the ultimate capacity of sections with unstiffened flanges on the local buckling capacity of the flanges leads to very conservative estimates of the members' capacity. It is thus recommended that clause C4(b) be eliminated from the Specification.

ACKNOWLEDGEMENTS

The experimental work reported herein was conducted at the University of Texas at Austin. The specimens were donated by Irwin Telescopic Platforms Company of Harlingen, Texas.

APPENDIX I. REFERENCES

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APPENDIX II. NOTATION

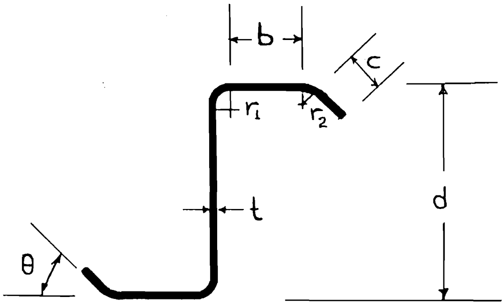
The following symbols are used in this paper

I_{min}	minimum moment of inertia of an edge stiffener about the centroidal axis parallel to the edge stiffened element
W	the width-to-thickness ratio of a stiffened element
t	thickness of cold-formed section
D_1	overall depth of stiffener
k	equivalent buckling coefficient at a partially stiffened element
k_0	buckling coefficient of an unstiffened element - 0.425
k_1	buckling coefficient determined by Eq.5
θ	angle between edge stiffener and stiffened element
F_y	yield stress of cold-formed sections
E	modulus of elasticity
ν	Poisson's ratio
ϕ	resistance factor for compression
P_{test}	ultimate capacity obtained through testing
P_{spec}	ultimate capacity determined through the specifications
L	length of specimens
d	overall depth of section
b	flat width of the flanges
c	flat width of the lip stiffeners
r_1, r_2	radii of curvature, as defined in Fig. 1

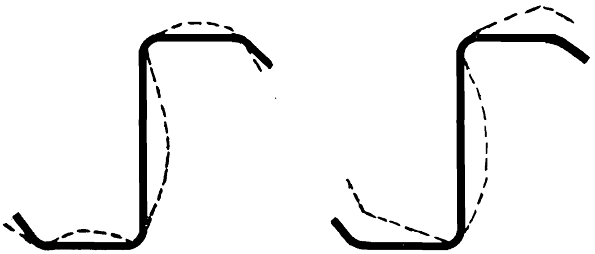
Table 1 Average Cross-Sectional Properties and Yield Stress

L (in)	θ (degrees)	No. of Specimens	d (in)	b (in)	c (in)	t (in)	r_1 (in)	r_2 (in)	F_y (ksi)
18	0	6	4.283	2.854	0.000	0.078	0.343	0.000	42
18	29.0	6	3.972	2.006	0.605	0.079	0.262	0.538	42
18	51.9	4	3.987	1.991	0.579	0.081	0.250	0.366	42
18	77.8	3	3.994	2.062	0.618	0.080	0.207	0.190	42
36	0	2	3.991	2.902	0.000	0.081	0.226	0.000	57
36	33.0	2	3.985	2.068	0.608	0.081	0.215	0.482	57
36	50.4	2	3.988	2.047	0.615	0.081	0.207	0.317	57
36	78.1	2	3.989	2.050	0.614	0.081	0.220	0.194	57
60	0	2	3.995	2.915	0.000	0.081	0.202	0.000	61
60	33.1	2	3.995	2.057	0.619	0.080	0.204	0.421	61
60	49.0	2	3.397	2.065	0.618	0.080	0.207	0.285	61
60	78.0	2	3.986	2.068	0.611	0.080	0.183	0.189	61
96	0.0	2	4.006	2.904	0.000	0.076	0.213	0.000	42
96	31.1	4	3.951	2.056	0.610	0.077	0.223	0.506	42
96	50.0	2	4.008	2.054	0.598	0.076	0.202	0.295	42
96	80.4	2	4.004	2.047	0.592	0.076	0.215	0.199	42

1 in. = 25.4 mm
1 ksi = 6.89 MPa



(a) Typical Z-section



(b) Local buckling (c) Distortional buckling

Fig. 1 Behavior of cold-formed Z-sections under compression

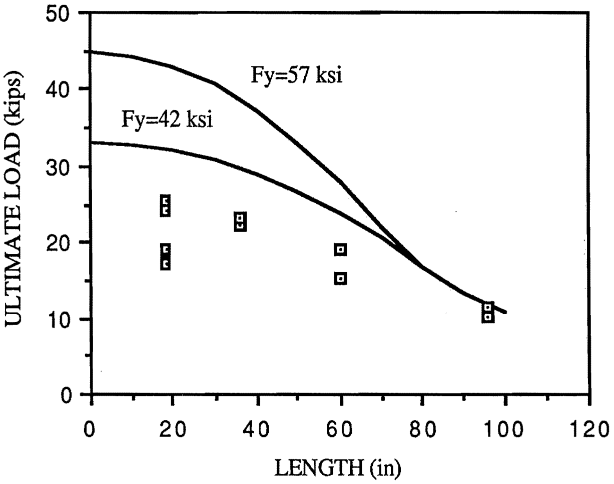


Fig. 2 Ultimate load with no local buckling for Theta = 0 degrees

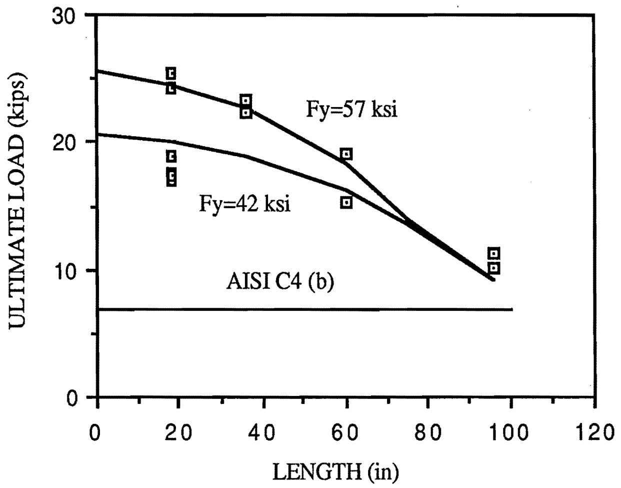


Fig. 3 AISI results for Theta=0

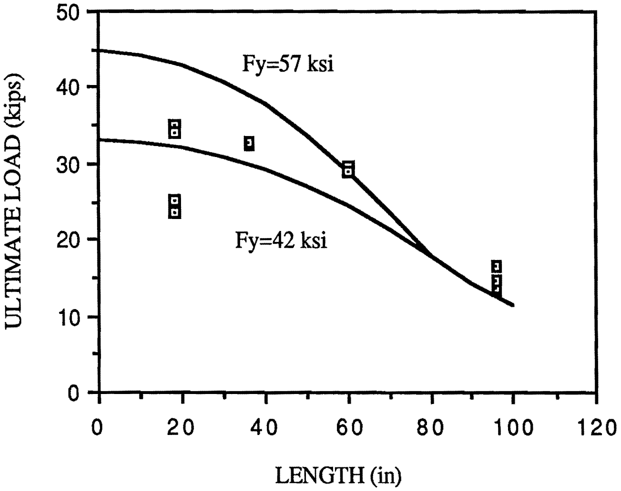


Fig. 4 Ultimate load with no local buckling for Theta = 30 degrees

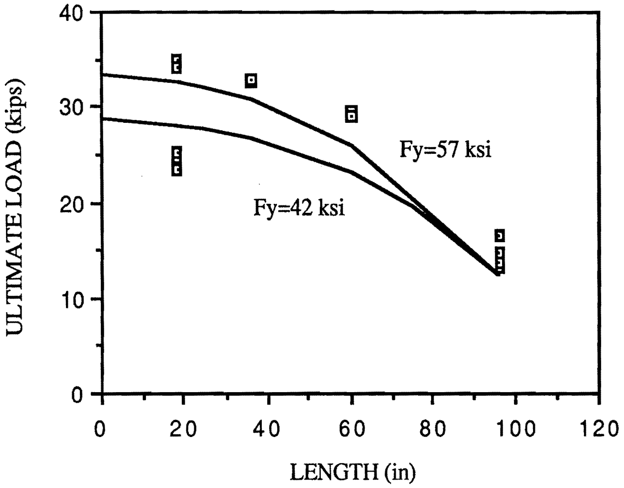


Fig. 5 AISI results for Theta = 30 degrees

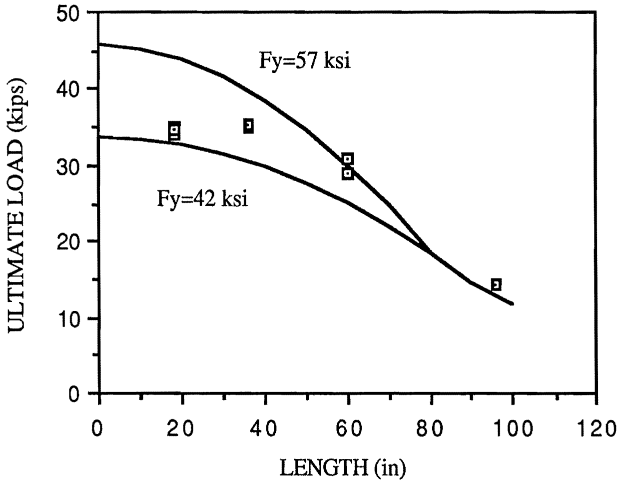


Fig. 6 Ultimate load with no local buckling for Theta = 50 degrees

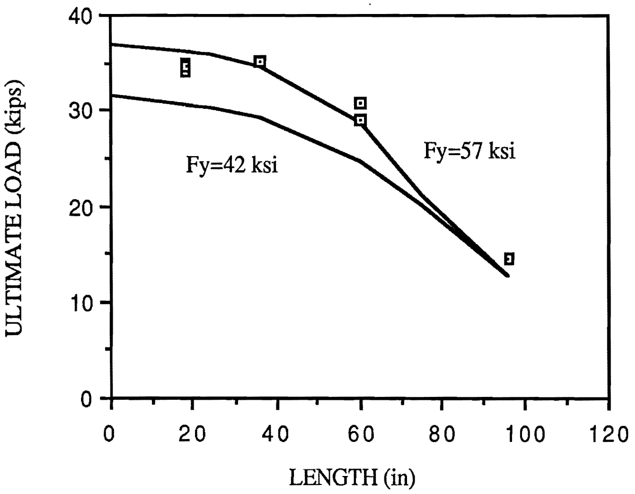


Fig. 7 AISI results for Theta = 50 degrees

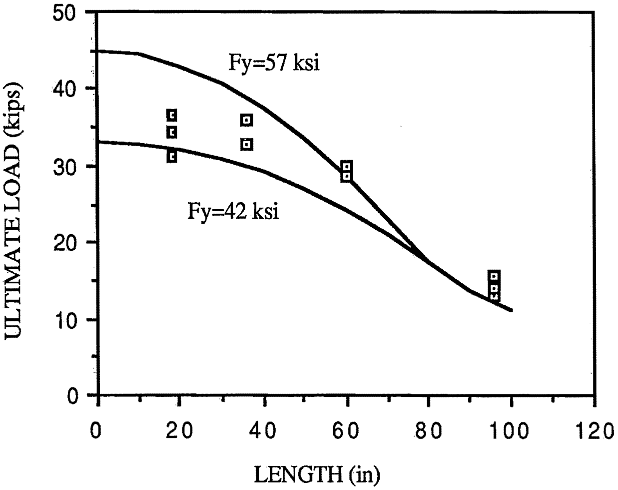


Fig. 8 Ultimate load with no local buckling for Theta = 80 degrees

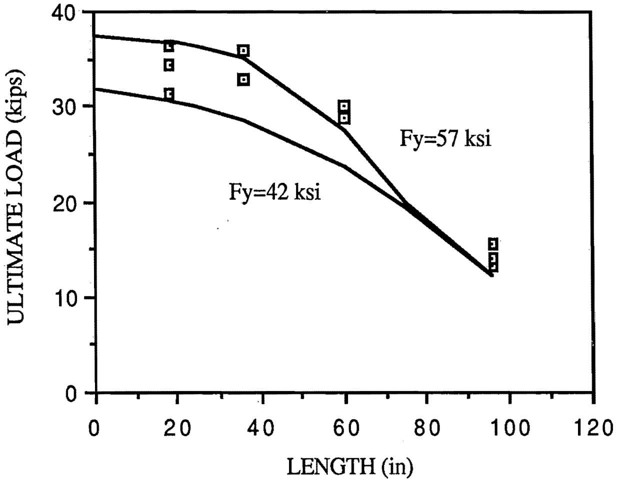


Fig. 9 AISI results for Theta = 80 degrees

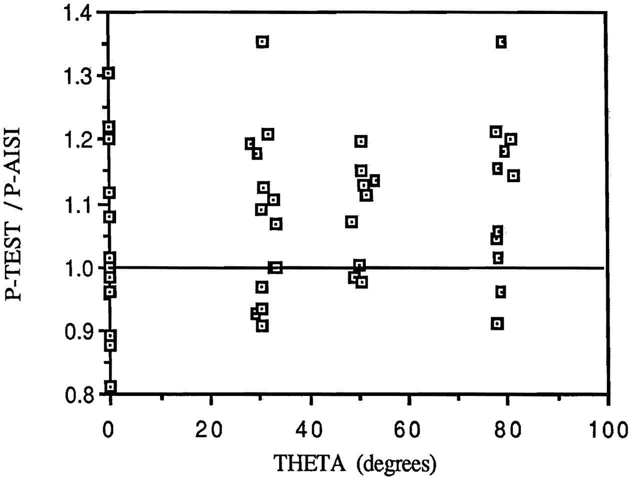


Fig. 10 P-TEST / P-AISI as a function of lip oriantation

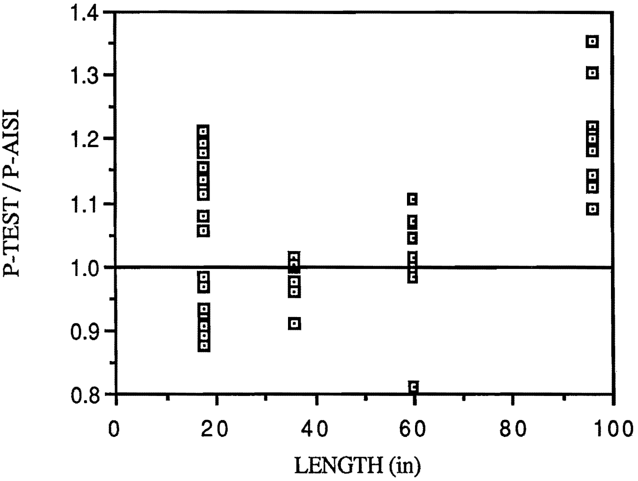


Fig. 11 P-TEST / P-AISI as a function of length