ROOF SYSTEMS BEHAVIOR

Research Report

ADEQUACY OF PROPOSED AISI EFFECTIVE WIDTH SPECIFICATION PROVISIONS FOR Z- AND C-PURLIN DESIGN

by

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Sponsored by

Metal Building Manufacturers Association

Report No. FSEL/MBMA 85-04

December 1985

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ADEQUACY OF PROPOSED AISI EFFECTIVE WIDTH SPECIFICATION PROVISIONS FOR Z- AND C- PURLIN DESIGN

CHAPTER I

INTRODUCTION

In the provisions currently used by the American Iron and Steel Institute (AISI) "Specification for the Design of Cold-Formed Steel Structural Members" [1], the flexural strength of a cold-formed Z- or C- section is based on two major concepts, 1) the effective compression flange width which depends on the actual flange width-to-thickness ratio, and 2) the allowable compressive stress acting on the flange which depends on whether the flange is stiffened (the provided lip is adequate) or unstiffened (lip is inadequate or is not provided). The major drawback of this procedure is that for a slight reduction in the length of the lip, the flange may become unstiffened and the flexural strength of the section is considerably reduced.

The purpose of the study reported herein is to investigate the adequacy of ten new design procedures that allow for the flange to be partially stiffened, fully stiffened or unstiffened. An effective web depth concept is used in some of the methods, in addition to the usual effective flange width concept.

For evaluation purposes, simple span test results were collected from six independent sources. Experimental failure loads were compared to predicted failure loads and statistical evaluations made to determine the most reliable method. The methods used are based on the work of Desmond, Pekoz and Winter [2] at Cornell University and LaBoube and Yu [3] at the University of Missouri at Rolla. Desmond, Pekoz and Winter developed an approach to predict the strength of longitudinally stiffened compression elements. The method initially included three different ways to analyze the adequacy of the edge stiffener, which will be referred to as Methods 1, 2 and 3, and will be introduced later in this report. Further, a modification to Method 1 was suggested by Golovan [5] which will be treated separately as Method 4. The only difference between these methods is the way the adequacy of the edge stiffener is evaluated. The effective web depth concept developed by LaBoube and Yu [3] was used to evaluate the effective compression part of the web in these methods.

LaBoube also proposed a second approach to evaluate the effective width of a longitudinally stiffened compression element. His approach, along with the effective web depth concept, constitutes Method 5.

Finally, Pekoz [4] proposed a design procedure which includes techniques to evaluate the adequacy of stiffened and unstiffened elements. Slight modifications were performed on this latter method which resulted in four additional methods. The basic procedure is referred to as Method 6, and the ones derived from it are numbered 7,8,9 and 10.

The current AISI [1] procedure was used for comparison purposes. It is referred to as Method 11. Details of all eleven methods are found in the appendices.

Computer programs were written to allow for automated analyses of the large set of experimental data collected from the six different sources. Data for 141 failed purlins was available, but only 119 data points were used for the analyses as twenty two tests were rejected because they were found to be inadequate for the purpose of this study. Each one of the retained purlins was analyzed by all of eleven methods. The results of the analyses were then used to check the adequacy of each proposed design procedure. This task is discussed in the next two chapters.

CHAPTER II

EVALUATION OF THE EXPERIMENTAL DATA AND THE DESIGN PROCEDURES

2.1 Experimental Data

Results of laboratory tests performed on 141 purlins loaded to failure were collected from six independent sources. The provided information included the measured dimensions, material properties and failure load of each purlin (Figure 2.1 and Table 2.1) and detailed descriptions of test setups and testing procedures. However, only 119 of these purlins were used to investigate the adequacy of the proposed design methods; the 22 other results were rejected because they were found to be inadequate for the purpose of this study.

To determine if the tested purlins adequately represent sections used in the metal building industry, the web, flange, and lip slendernesses and the lip angles of 92 sections produced by the metal building industry were collected, and their frequency distribution histograms plotted, Figures 2.2 through 2.5.

From Figure 2.2, it is evident that web slenderness (H/t, where H is the clear distance between flanges) can be assumed to be normally distributed. The mean value is 107.5 with a standard deviation of 28.42 and range from

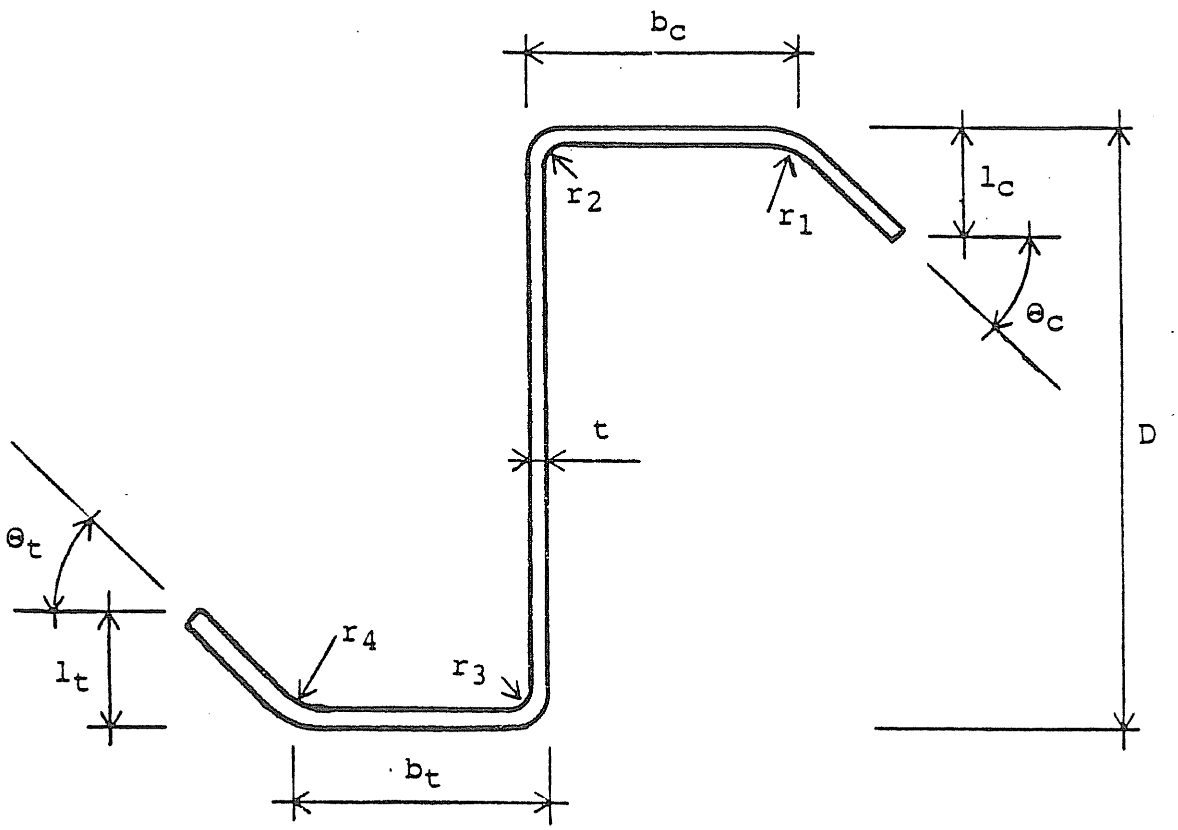


Figure 2.1 Purlin Cross-Sectional Dimensions

Table 2.1

Purlin Cross-Section Data and Failure Moments

CASE	D	t	b_c	b_t	l_c	l_t	Θ_c	Θ_t	F_y	M_{exp}	Failure Mode
Z1-1P2	8.12	0.093	2.50	2.56	0.50	0.50	44.0	44.0	57.3	127.04	Flange and lip buckling
Z1-2P2	8.04	0.090	2.40	2.42	0.52	0.60	41.0	38.0	57.3	130.62	Flange and lip buckling
Z1-4P2	7.90	0.087	2.34	2.43	0.45	0.48	43.0	44.0	57.0	108.73	Buckling of tension flange
Z1-5P1	8.14	0.090	2.55	2.50	0.46	0.48	43.0	42.0	56.9	111.84	Purlins rolled at center
Z1-5P2	8.00	0.092	2.45	2.55	0.48	0.50	42.0	45.0	56.9	111.84	Purlins rolled at center
Z1-6P2	8.10	0.086	2.38	2.38	0.55	0.62	42.0	42.0	59.4	133.45	Flange and lip buckling
Z1-8P2	8.13	0.086	2.34	2.80	0.48	0.47	44.0	44.0	55.0	132.87	Flange and web buckling
Z1Q-1P1	2.03	0.025	0.63	0.64	0.15	0.14	48.0	46.0	51.8	2.47	Flange and lip buckling
Z1Q-2P1	2.08	0.025	0.63	0.62	0.22	0.18	90.0	90.0	51.8	2.71	Flange and lip buckling
Z1Q-3P1	2.10	0.025	0.63	0.63	0.15	0.14	48.0	50.0	51.8	2.30	Flange and lip buckling
Z1Q-4P1	2.05	0.025	0.61	0.62	0.24	0.18	90.0	90.0	51.8	2.51	Flange and lip buckling
Z1Q-5P1	2.05	0.025	0.64	0.63	0.14	0.14	46.0	47.0	51.8	1.46	Excessive lateral movement
Z1Q-5P2	2.05	0.025	0.63	0.63	0.15	0.15	49.0	47.0	51.8	1.46	Excessive lateral movement
Z1Q-7P1	2.05	0.025	0.64	0.62	0.13	0.12	28.0	28.0	51.8	2.40	Flange and lip buckling
Z1Q-8P1	2.04	0.025	0.64	0.64	0.17	0.14	45.0	45.0	51.8	2.68	Flange and lip buckling
Z1Q-8P2	2.09	0.025	0.65	0.65	0.15	0.15	47.0	46.0	51.8	2.68	Flange and lip buckling
Z1Q-9P1	2.05	0.025	0.64	0.65	0.19	0.19	56.0	55.0	51.8	2.89	Flange and lip buckling
Z1Q-9P2	2.09	0.025	0.64	0.63	0.19	0.18	60.0	56.0	51.8	2.89	Flange and lip buckling
Z1Q-10P	2.05	0.025	0.63	0.63	0.23	0.22	75.0	75.0	51.8	2.92	Flange and lip buckling
Z1Q-10P	2.09	0.025	0.63	0.63	0.23	0.21	72.0	74.0	51.8	2.92	Flange and lip buckling
Z1Q-11P	2.05	0.025	0.63	0.62	0.28	0.23	90.0	90.0	51.8	2.61	Flange and lip buckling
Z1Q-12P	2.00	0.025	0.65	0.65	0.19	0.18	45.0	45.0	51.8	2.71	Opposed purlins (f&l b.)
Z1Q-12P	2.10	0.025	0.65	0.65	0.15	0.15	46.0	47.0	51.8	2.71	Opposed purlins (f&l b.)
Z1Q-13P	2.03	0.025	0.63	0.63	0.16	0.14	47.0	45.0	51.8	2.78	Flange and lip buckling
Z1Q-13P	2.03	0.025	0.63	0.63	0.15	0.15	46.0	46.0	51.8	2.78	Flange and lip buckling
Z1Q-14P	2.03	0.025	0.65	0.65	0.15	0.15	45.0	45.0	51.8	2.61	Flange and lip buckling
Z1Q-15P	2.02	0.025	0.65	0.65	0.15	0.15	45.0	45.0	51.8	2.47	Flange and lip buckling
Z1Q-15P	2.02	0.025	0.65	0.64	0.14	0.14	45.0	45.0	51.8	2.47	Flange and lip buckling
Z1Q-16P	2.03	0.025	0.63	0.63	0.13	0.13	45.0	45.0	51.8	2.51	Flange and lip buckling
Z1Q-16P	2.04	0.025	0.63	0.63	0.12	0.14	45.0	45.0	51.8	2.51	Flange and lip buckling
Z1Q-17P	2.03	0.025	0.63	0.62	0.15	0.12	45.0	45.0	51.8	2.40	Flange and lip buckling
Z1Q-18P	2.04	0.025	0.63	0.63	0.16	0.16	45.0	45.0	51.8	2.71	Flange and lip buckling
Z1Q-18P	2.02	0.025	0.65	0.65	0.14	0.14	45.0	45.0	51.8	2.71	Flange and lip buckling
Z1Q-19P	2.03	0.025	0.63	0.62	0.16	0.13	45.0	45.0	51.8	2.71	Flange and lip buckling
Z1Q-19P	2.00	0.025	0.63	0.63	0.16	0.15	45.0	45.0	51.8	2.71	Flange and lip buckling
Z1Q-20P	2.02	0.025	0.61	0.61	0.15	0.14	45.0	45.0	51.8	2.72	Flange and lip buckling
Z1Q-20P	2.03	0.025	0.63	0.62	0.15	0.16	45.0	45.0	51.8	2.72	Flange and lip buckling
Z1Q-21P	2.01	0.025	0.62	0.63	0.15	0.15	45.0	45.0	51.8	2.68	Flange and lip buckling
Z1Q-21P	2.03	0.025	0.61	0.65	0.13	0.13	45.0	45.0	51.8	2.68	Flange and lip buckling
Z1Q-22P	2.04	0.025	0.64	0.66	0.13	0.14	45.0	45.0	51.8	2.40	Flange and lip buckling
Z1Q-23P	2.08	0.025	0.65	0.65	0.15	0.15	45.0	46.0	51.8	3.15	Flange and lip buckling
Z1Q-23P	2.11	0.025	0.64	0.65	0.15	0.15	47.0	47.0	51.8	3.15	Flange and lip buckling
Z1Q-23P	2.05	0.025	0.63	0.63	0.16	0.15	46.0	47.0	51.8	3.15	Flange and lip buckling
Z1Q-23P	2.04	0.025	0.64	0.63	0.15	0.15	44.0	47.0	51.8	3.15	Flange and lip buckling
Z1Q-23P	2.05	0.025	0.64	0.63	0.15	0.14	45.0	48.0	51.8	3.15	Flange and lip buckling
Z1Q-23P	2.05	0.025	0.63	0.64	0.15	0.14	47.0	46.0	51.8	3.15	Flange and lip buckling

Table 2.1

Purlin Cross-Section Data and Failure Moments, continued

CASE	D	t	b_c	b_t	l_c	l_t	Θ_c	Θ_t	F_y	M_{exp}	Failure Mode
Z10-24P	2.03	0.025	0.63	0.63	0.14	0.14	45.0	45.0	51.8	2.09	Flange and lip buckling
Z10-24P	2.04	0.025	0.63	0.64	0.12	0.13	45.0	45.0	51.8	2.09	Flange and lip buckling
Z10-24P	2.04	0.025	0.63	0.64	0.13	0.12	45.0	45.0	51.8	2.09	Flange and lip buckling
Z10-24P	2.03	0.025	0.63	0.63	0.12	0.13	45.0	45.0	51.8	2.09	Flange and lip buckling
Z10-24P	1.99	0.025	0.63	0.63	0.14	0.13	45.0	45.0	51.8	2.09	Flange and lip buckling
Z10-24P	2.03	0.025	0.62	0.62	0.12	0.13	45.0	45.0	51.8	2.09	Flange and lip buckling
Z10-25P	1.97	0.025	0.62	0.61	0.14	0.14	45.0	45.0	51.8	2.76	Flange and lip buckling
Z10-25P	2.03	0.025	0.63	0.63	0.14	0.14	45.0	45.0	51.8	2.76	Flange and lip buckling
Z10-25P	2.01	0.025	0.63	0.62	0.14	0.14	45.0	45.0	51.8	2.76	Flange and lip buckling
Z10-25P	2.02	0.025	0.64	0.63	0.14	0.13	45.0	45.0	51.8	2.76	Flange and lip buckling
Z10-25P	2.01	0.025	0.63	0.63	0.14	0.14	45.0	45.0	51.8	2.76	Flange and lip buckling
Z10-25P	2.02	0.025	0.63	0.63	0.13	0.14	45.0	45.0	51.8	2.76	Flange and lip buckling
C2-1P1	9.00	0.074	2.98	2.92	0.76	0.74	93.0	91.0	56.0	140.18	Comp. flange/web buckling
C2-2P1	9.00	0.076	3.02	2.96	0.84	0.82	92.0	93.0	57.2	156.94	Flange and web buckling
C2-2P2	9.00	0.074	2.98	2.92	0.78	0.80	92.0	92.0	57.2	156.94	Flnage and web buckling
C2-3P1	9.00	0.074	2.96	2.92	0.76	0.74	87.0	89.0	57.7	152.16	Not specified
C2-3P2	9.00	0.075	2.96	2.94	0.74	0.72	88.0	85.0	55.7	152.16	Not specified
C2-4P1	9.00	0.075	2.97	2.95	0.75	0.77	87.0	87.0	55.5	144.94	Not specified
C2-4P2	9.00	0.074	2.98	2.92	0.76	0.72	88.0	86.0	56.9	144.94	Not specified
C2-5P1	9.00	0.100	2.99	3.03	0.81	0.79	84.0	90.0	54.7	249.66	Not specified
C2-5P2	9.00	0.100	2.99	3.03	0.81	0.79	85.0	87.0	55.5	249.66	Not specified
C2-6P1	9.00	0.057	2.99	2.95	0.73	0.73	87.0	86.0	58.7	91.59	Not specified
C2-6P2	9.00	0.057	2.93	2.97	0.73	0.75	85.0	86.0	60.2	91.59	Not specified
C2-7P1	9.00	0.079	2.99	3.03	0.75	0.85	87.0	88.0	52.2	166.84	Not specified
C2-7P2	9.00	0.080	2.99	2.99	0.85	0.77	90.0	88.0	51.4	166.84	Not specified
Z3-1P1	9.56	0.106	2.81	2.81	0.85	0.94	49.0	49.0	53.3	285.45	Flange buckling
Z3-2P1	9.63	0.104	2.75	2.84	0.76	0.99	46.0	46.0	55.1	274.22	Flange buckling
Z3-3P1	8.03	0.118	2.78	2.69	0.79	0.88	48.0	48.0	56.5	258.75	Flange buckling
Z3-4P1	8.00	0.113	2.72	2.72	0.82	0.85	47.0	47.0	56.6	243.57	Flange buckling
Z3-5P1	9.50	0.067	2.69	2.69	0.60	0.55	43.0	43.0	65.0	129.52	Flange buckling
Z3-6P1	9.50	0.066	2.75	2.75	0.57	0.62	45.0	45.0	65.0	130.78	Not available
Z3-7P1	9.50	0.062	2.75	2.69	0.62	0.53	45.0	45.0	62.7	125.15	Flange buckling
Z3-8P1	9.50	0.062	2.75	2.63	0.64	0.51	43.0	43.0	62.3	124.73	Not available
Z3-9P1	9.56	0.074	2.75	2.75	0.61	0.68	49.0	49.0	56.2	133.02	Not available
Z3-10P1	9.50	0.074	2.75	2.75	0.56	0.63	46.0	46.0	55.5	144.28	Not available
Z3-11P1	8.00	0.069	2.53	2.63	0.57	0.62	45.0	45.0	62.3	112.50	Not available
Z3-12P1	8.00	0.068	2.56	2.56	0.63	0.63	51.0	51.0	62.6	100.97	Not available
Z3-13P1	8.00	0.075	2.63	2.63	0.63	0.63	42.0	42.0	66.6	139.78	Not available
Z3-14P1	8.00	0.075	2.63	2.63	0.64	0.64	43.0	43.0	65.5	146.11	Not available
Z3-15P1	9.50	0.058	2.75	2.88	1.35	1.35	46.0	46.0	65.1	119.81	Not available
Z3-16P1	9.56	0.058	2.69	2.81	1.33	1.41	45.0	45.0	63.7	120.52	Not available
Z3-17P1	9.50	0.059	2.69	2.75	0.35	0.26	44.0	44.0	61.9	86.20	Flange buckling
Z3-18P1	9.50	0.058	2.75	2.69	0.26	0.34	43.0	43.0	64.9	85.65	Not available
Z3-19P1	9.50	0.089	2.75	2.88	1.06	1.28	45.0	45.0	58.9	254.01	Not available
Z3-20P1	9.50	0.089	2.75	2.81	1.13	1.22	44.0	44.0	58.7	265.31	Flange buckling
Z3-21P1	9.63	0.090	2.69	2.75	0.29	0.38	42.0	42.0	55.2	151.68	Not available
Z3-22P1	9.63	0.090	2.75	2.56	0.37	0.33	48.0	48.0	54.3	164.54	Flange buckling
Z3-23P1	7.56	0.068	2.88	2.56	1.00	1.00	40.0	40.0	62.9	132.21	Not available
Z3-24P1	7.81	0.068	2.81	2.81	1.03	1.03	41.0	41.0	65.5	125.30	Not available
Z3-25P1	9.25	0.074	2.63	2.75	1.28	0.54	52.0	52.0	56.9	170.16	Flange buckling

Table 2.1

Purlin Cross-Section Data and Failure Moments, continued

CASE	D	t	b_c	b_t	l_c	l_t	Θ_c	Θ_t	F_y	M_{exp}	Failure Mode
Z3-26P1	9.19	0.074	2.94	2.63	0.51	1.38	55.0	55.0	56.9	168.74	Not available
Z3-27P1	9.25	0.074	2.88	2.69	0.57	1.30	56.0	56.0	56.9	160.30	Not available
Z3-28P1	9.13	0.074	2.94	2.69	0.43	1.11	43.0	43.0	56.9	140.63	Flange buckling
Z3-29P1	9.13	0.074	3.00	2.63	0.48	1.09	44.0	44.0	55.0	146.25	Flange buckling
Z3-30P1	9.25	0.074	2.81	2.81	0.55	1.48	61.0	61.0	56.9	157.50	Flange/Lip buckling
Z3-31P1	9.25	0.074	2.81	2.81	0.48	1.45	59.0	59.0	56.9	151.88	Flange/Lip buckling
Z3-32P1	9.63	0.074	2.81	2.31	0.87	1.74	84.0	84.0	56.9	205.31	Flange/Lip buckling
Z3-33P1	9.63	0.074	2.63	2.81	0.47	1.59	70.0	70.0	56.9	150.46	Flange/Lip buckling
Z3-34P1	9.63	0.074	2.69	2.69	0.47	1.70	70.0	70.0	56.9	156.09	Flange/Lip buckling
Z3-35P1	9.69	0.074	2.56	2.75	0.53	1.59	70.0	70.0	56.9	156.09	Flange/Lip buckling
Z3-36P1	9.56	0.074	2.81	2.56	0.81	1.75	90.0	90.0	56.9	174.37	Flange/Lip buckling
Z3-37P1	9.56	0.074	2.69	2.50	0.69	1.88	90.0	90.0	56.9	163.13	Flange/Lip buckling
Z3-38P1	9.38	0.074	2.81	2.69	0.63	1.81	90.0	90.0	56.9	164.54	Flange/Lip buckling
Z5-1P1	8.09	0.069	2.73	2.46	0.78	0.78	77.0	81.0	70.0	128.70	Flange buckling
Z5-1P2	8.09	0.069	2.66	2.44	0.69	0.84	75.0	82.0	70.0	128.70	Flange buckling
Z5-2P1	8.09	0.070	2.71	2.46	0.70	0.79	75.0	83.0	70.0	132.42	Local flange buckling
Z5-2P2	8.09	0.067	2.70	2.46	0.73	0.81	75.0	81.0	70.0	132.42	Local flange buckling
Z5-3P1	8.11	0.069	2.75	2.46	0.73	0.80	76.0	82.0	70.0	131.70	Flange buckling at midspan
Z5-3P2	8.14	0.069	2.71	2.43	0.65	0.87	72.0	80.0	70.0	131.70	Flange buckling at midspan
Z5-4P1	8.04	0.069	2.72	2.39	0.69	0.83	76.0	79.0	70.0	123.78	Flange buckling
Z5-4P2	8.03	0.069	2.73	2.42	0.73	0.82	74.0	80.0	70.0	123.78	Flange buckling
Z5-5P1	8.11	0.070	2.63	2.39	0.68	0.87	71.0	78.0	70.0	114.00	Deck and flange failure
Z5-5P2	8.08	0.070	2.71	2.42	0.65	0.88	69.0	79.0	70.0	114.00	Deck and flange failure
Z5-6P1	8.11	0.069	2.75	2.44	0.67	0.84	76.0	81.0	70.0	113.88	Flange buckling
Z5-6P2	8.10	0.069	2.69	2.42	0.71	0.84	75.0	79.0	70.0	113.88	Flange buckling
Z5-7P1	8.06	0.067	2.61	2.24	0.67	0.88	70.6	70.5	70.0	113.88	Rolling of purlins
Z5-7P2	8.10	0.066	2.63	2.08	0.69	0.86	70.5	70.6	70.0	113.88	Rolling of purlins
Z5-8P1	8.05	0.066	2.60	2.31	0.66	0.84	70.1	70.0	70.0	118.80	Rolling of purlins
Z5-8P2	8.08	0.065	2.61	2.26	0.63	0.84	70.3	70.0	70.0	118.80	Rolling of purlins
Z5-9P1	8.09	0.066	2.61	2.26	0.65	0.83	70.1	70.0	70.0	123.78	Rolling of purlins
Z5-9P2	8.09	0.066	2.70	2.19	0.66	0.84	70.3	70.0	70.0	123.78	Rolling of purlins
Z5-10P1	8.09	0.064	2.65	2.24	0.69	0.88	71.3	70.0	70.0	113.88	Rolling of purlins
Z5-10P2	8.05	0.066	2.57	2.21	0.72	0.85	70.6	70.2	70.0	113.88	Rolling of purlins
Z6-1P1	8.16	0.099	2.70	2.86	0.75	0.76	88.0	85.0	49.6	199.13	Flange and web buckling
Z6-3P1	8.15	0.063	2.63	2.76	0.71	0.65	88.0	85.0	57.5	96.94	Flange buckling
Z6-4P1	8.06	0.063	2.51	2.82	0.75	0.65	85.0	88.0	53.2	87.94	Flange and web buckling
Z6-5P1	8.15	0.063	2.49	2.84	0.71	0.63	87.0	87.0	54.6	93.38	Flange and web buckling
Z7-1P1	6.19	0.060	2.19	2.31	0.53	0.48	50.0	50.0	56.9	72.90	Compression flange buckling
Z7-2P1	6.19	0.060	2.25	2.25	0.52	0.48	49.0	50.0	58.7	73.08	Compression flange buckling
Z7-3P1	8.00	0.063	2.58	2.52	0.43	0.48	46.0	48.0	60.6	95.16	Comp. flange/web buckling
Z7-4P1	8.00	0.062	2.52	2.60	0.48	0.45	46.0	46.0	60.6	91.50	Comp. flange/web buckling
Z7-5P1	8.00	0.062	2.64	2.52	0.49	0.44	46.0	46.0	60.6	95.16	Comp. flange/web buckling
Z7-6P1	8.00	0.088	2.45	2.60	0.60	0.54	47.0	46.0	70.8	180.75	Compression flange buckling
Z7-7P1	8.00	0.090	2.60	2.50	0.57	0.61	47.0	48.0	70.8	205.30	Compression flange buckling
Z7-8P1	8.00	0.085	2.50	2.61	0.60	0.55	47.0	46.0	70.8	177.00	Compression flange buckling

55.4 to 198. The 90% confidence interval to estimate the population mean is

$$102.6 \leq H/t \leq 112.4 \tag{2.1}$$

Based on Equation 2.1, one can divide the H/t range into three subranges as follows:

$$\text{Low range} \quad : H/t < 102.6 \tag{2.2}$$
$$\text{Intermediate} \quad : 102.6 \leq H/t \leq 112.4 \tag{2.3}$$
$$\text{High range} \quad : H/t > 112.4 \tag{2.4}$$

Figure 2.3 shows the frequency distribution of the flange slenderness (w/t) of industrial sections, where w is the flat flange width. Again normal distribution can be assumed with a mean value of 36.0, a standard deviation of 8.46 and range from 18.6 to 57.0. The 90% confidence interval to estimate the population mean is

$$34.5 \leq w/t \leq 37.4 \tag{2.5}$$

Hence, the w/t range is divided into the following portions:

$$\text{Low range} \quad : w/t < 34.5 \tag{2.6}$$
$$\text{Intermediate} \quad : 34.5 \leq w/t \leq 37.4 \tag{2.7}$$
$$\text{High range} \quad : w/t > 37.4 \tag{2.8}$$

Figure 2.4 shows the frequency distribution of the lip slenderness (b/t) of industrial sections, where b is the lip length . Again, the data can be assumed to be normally distributed with a mean value of 1.70, a standard deviation of 2.11 and range from 7.2 to 19.1. The 90% confidence interval to estimate the population mean is

$$11.3 \leq b/t \leq 12 \quad (2.9)$$

and the b/t data is partitioned as follows:

Low range	: $b/t < 11.3$	(2.10)
Intermediate	: $11.3 \leq b/t \leq 12.0$	(2.11)
High ranged	: $b/t > 12.0$	(2.12)

The assumption of normal distribution does not hold for the lip angle Θ, Figure 2.5. However, the following procedure allowed for the determination of low, intermediate, and high ranges:

a)	- The mean value of the 92 observations is	: Θ_A=59.6°
b)	- The number of observations $< \Theta_A$ is	: 61
c)	- Their mean value is	: Θ_L=46.5°
d)	- The number of observations $> \Theta_A$ is	: 31
e)	- Their mean value is	: Θ_H=85.2°

Now define

Low range	: $\Theta < \Theta_L = 46.5°$	(2.13)
Intermediate	: $\Theta_L = 46.5° \leq \Theta \leq \Theta_H = 85.2°$	(2.14)
High range	: $\Theta > \Theta_H = 85.2°$	(2.15)

Further, the collected experimental data was examined, and the web, flange, and lip slendernesses and the lip angle of each purlin was classified according to the ranges defined above. Then, the results were reported in a specially designed table, shown here in Figure 2.6. The

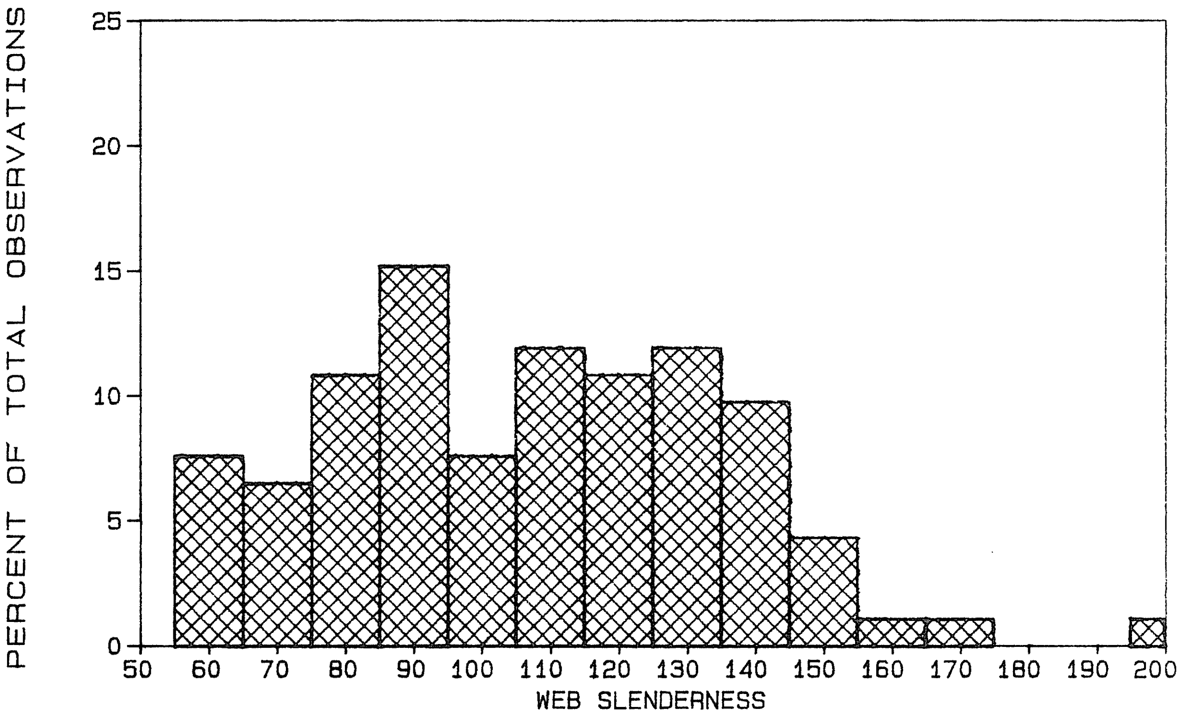


Figure 2.2 Frequency Distribution of Web Slenderness

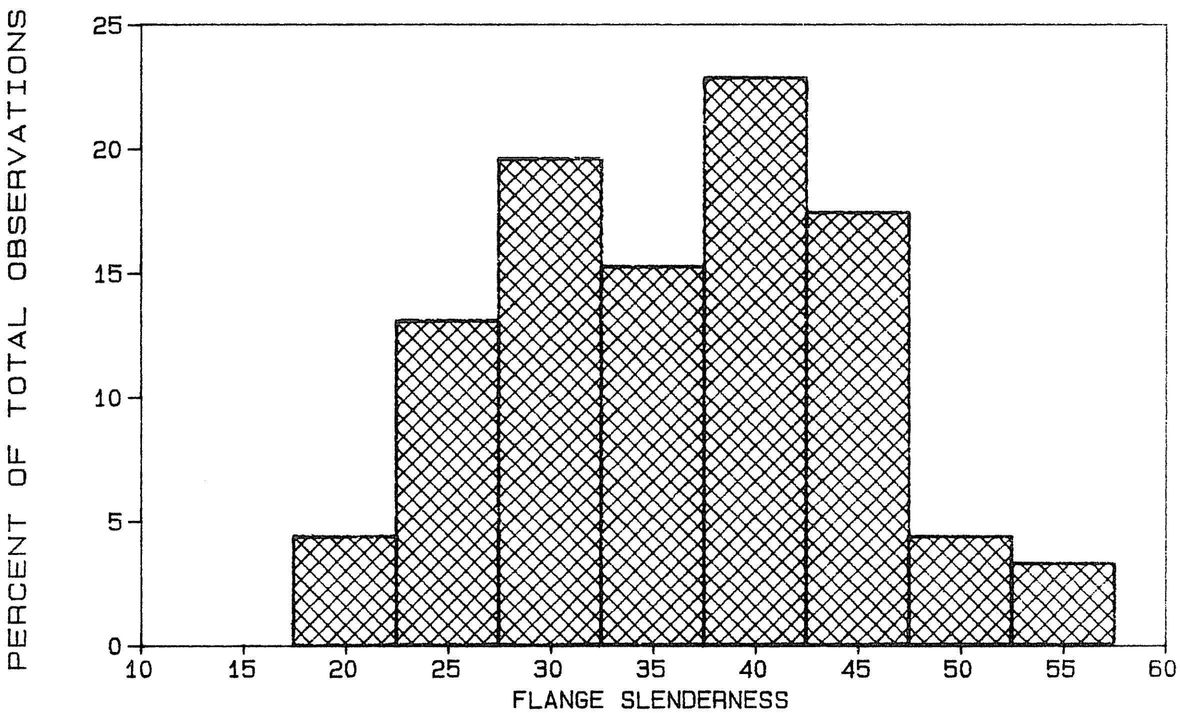


Figure 2.3 Frequency Distribution of Flange Slenderness

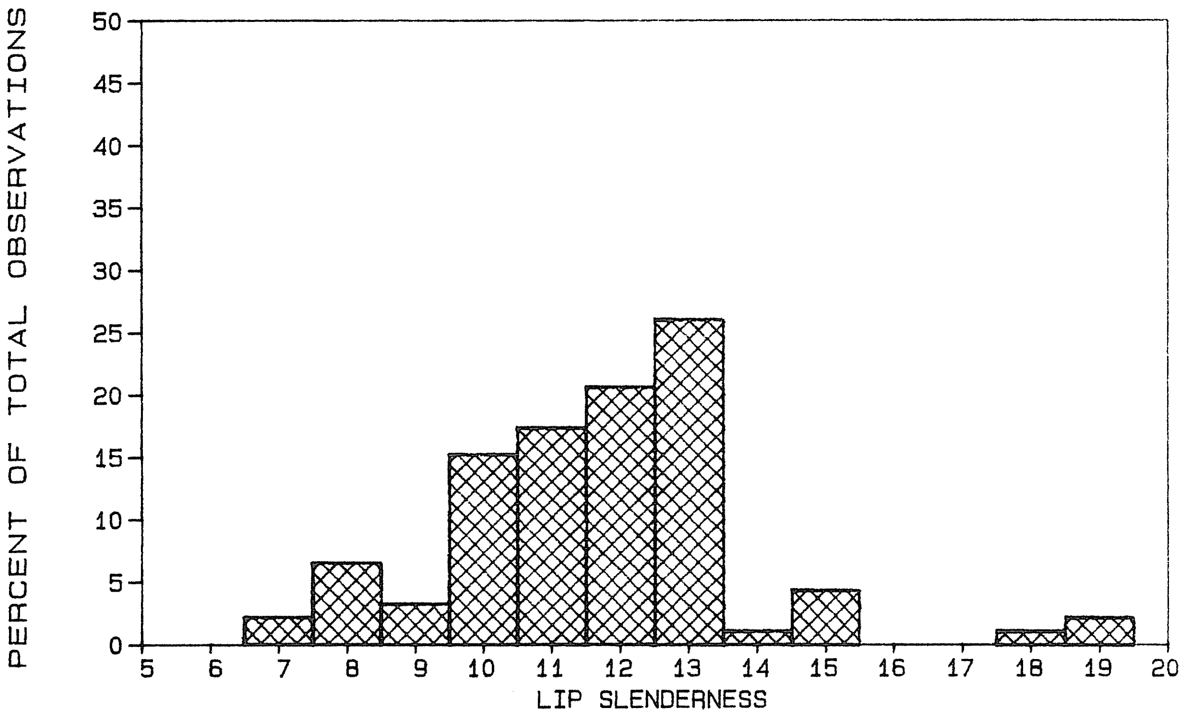


Figure 2.4 Frequency Distribution of Lip Slenderness

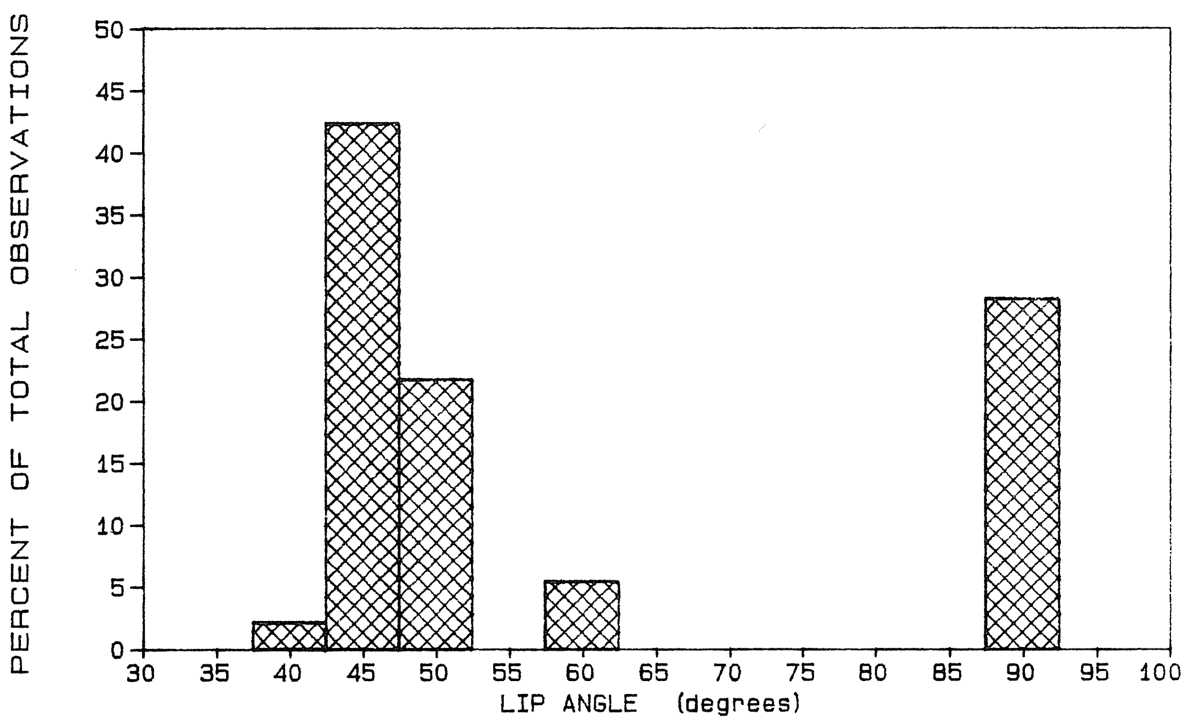


Figure 2.5 Frequency Distribution of Lip Angle

b/t	θ \ H/t	L			I			H		
	W/t	L	I	H	L	I	H	L	I	H
L	L	26			1				1	7
	I								1	
	H				2	2	1			7
I	L	17			1				4	20
	I		1	1			1			5
	H								1	1
H	L	4				1	1		1	8
	I									3
	H									1

(x) = number of observations

Figure 2.6 Distribution of Test Data Over Range of Available Sections interpretation of this table is very simple: the more the dashed squares are spread around the table, the better the experimental data covers the range of industrial sections, which happens to be the case of the study reported herein. Therefore, one can say that the collected experimental data is adequate, and can be used to investigate the adequacy of the proposed design procedures.

2.2 Design Procedures

2.2.1 Methods of Evaluation

The evaluation of the proposed design procedures was based on pure statistical considerations. Ratios of theoretical-to-experimental failure loads were the basis of comparisons. The most important measure is the mean value of these ratios. The method is good if the mean is equal to 1, conservative if less than 1, and unconservative if greater than 1. Practically, the method was judged acceptable if the mean value of the ratios is between 0.9 and 1.1, that is, a 10% error is allowed on either the conservative or unconservative side. Also of importance are the standard deviation and the range of the aforementioned ratios. These measures are most helpful in comparing the design methods with each other. Table 2.2 summarizes the results of the evaluations.

For further evaluation, scatter diagrams and frequency distribution histograms of the failure load ratios were plotted for each method. These plots are very important in the way that they help visualize the importance of the region where a given design method is "acceptable", and dispertion of the ratios around their mean. Particular results are discussed in the following sections.

Table 2.2

Results of Evaluation

Method	Mean	Standard Deviation	Minimum Value	Maximum Value
1	1.023	0.110	0.791	1.268
2	1.032	0.110	0.760	1.268
3	1.033	0.110	0.796	1.268
4	1.015	0.107	0.784	1.268
5	1.017	0.124	0.759	1.315
6	1.092	0.125	0.793	1.347
7	1.033	0.105	0.784	1.264
8	1.084	0.119	0.823	1.320
9	1.078	0.120	0.793	1.347
10	1.042	0.098	0.809	1.269
11	1.121	0.177	0.476	1.450

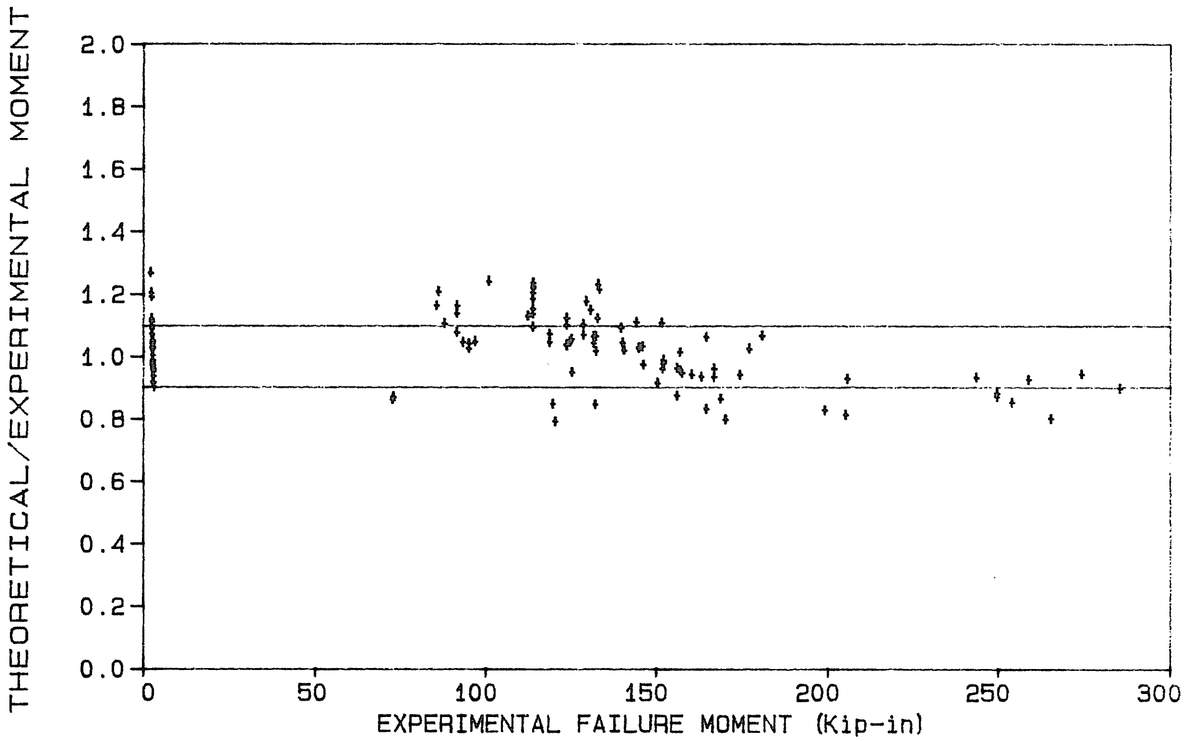
2.2.2 Methods 1, 2, 3 and 4

These methods are based on research work conducted at the University of Missouri-Rolla and at Cornell University. They basically follow the same steps and differ only in the way the effectiveness of the compression lip is treated. See Appendix A for details.

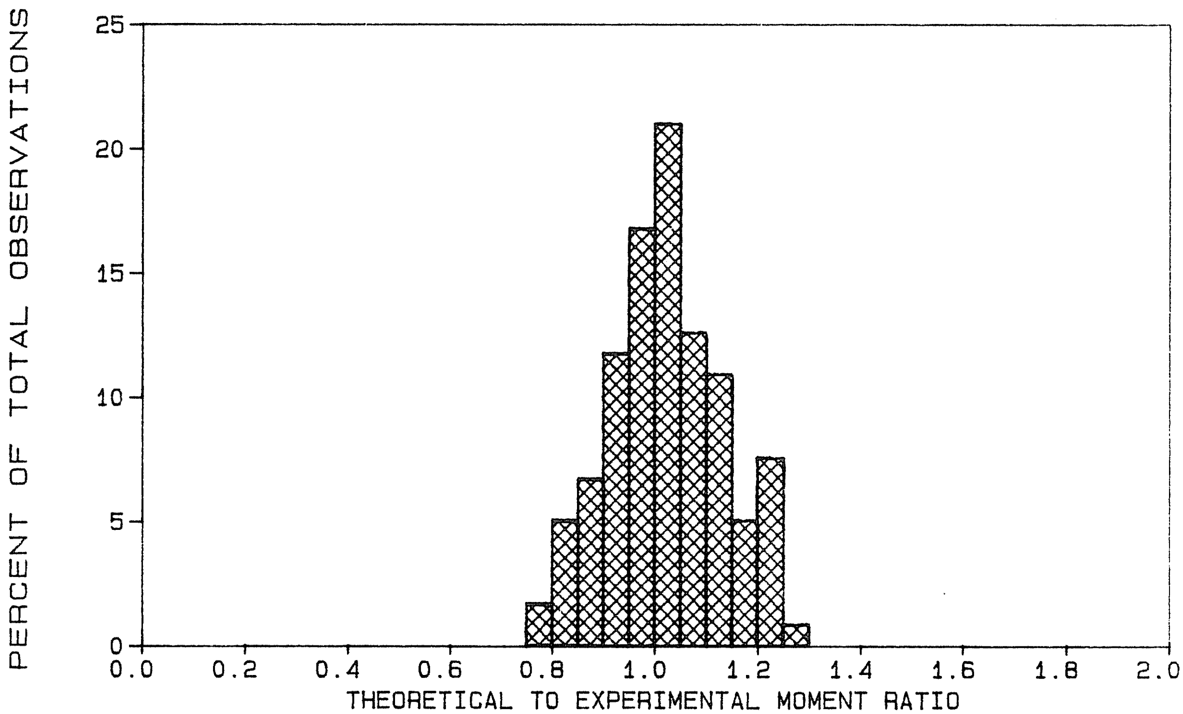
For Method 1, the mean value of the ratios of theoretical-to-experimental moment capacities is 1.023, their standard deviation is 0.110, mimimum value is 0.791 and maximum value is 1.268. Of the 119 observations, 79 were found to be satisfactory ($0.9 \leq R \leq 1.1$), 16 were conservative ($R<0.9$), and 24 were unconservative ($R>1.1$). Figure 2.7(a) shows the variation of the moment ratios with experimental failure moment, and Figure 2.7(b) shows the frequency distribution histogram of the moment ratios.

Method 2 gave a mean value of 1.032, a standard deviation of 0.110, a minimum value of 0.760, and a maximum value of 1.268. Of the 119 observations, 80 were found to be satisfactory, 13 in the conservative range, and 26 in the unconservative range. Variation of moment ratios with experimental moments and frequency distribution histograms for this method are shown in Figure 2.8.

For Method 3, the mean value of the ratios is 1.033, their standard deviation is 0.110, the minimum value is 0.796 and the maximum value is 1.268. Seventy eight observations are in the acceptable range, 14 are conservative and 27 are unconservative. Plots for this method are found in Figure 2.9.

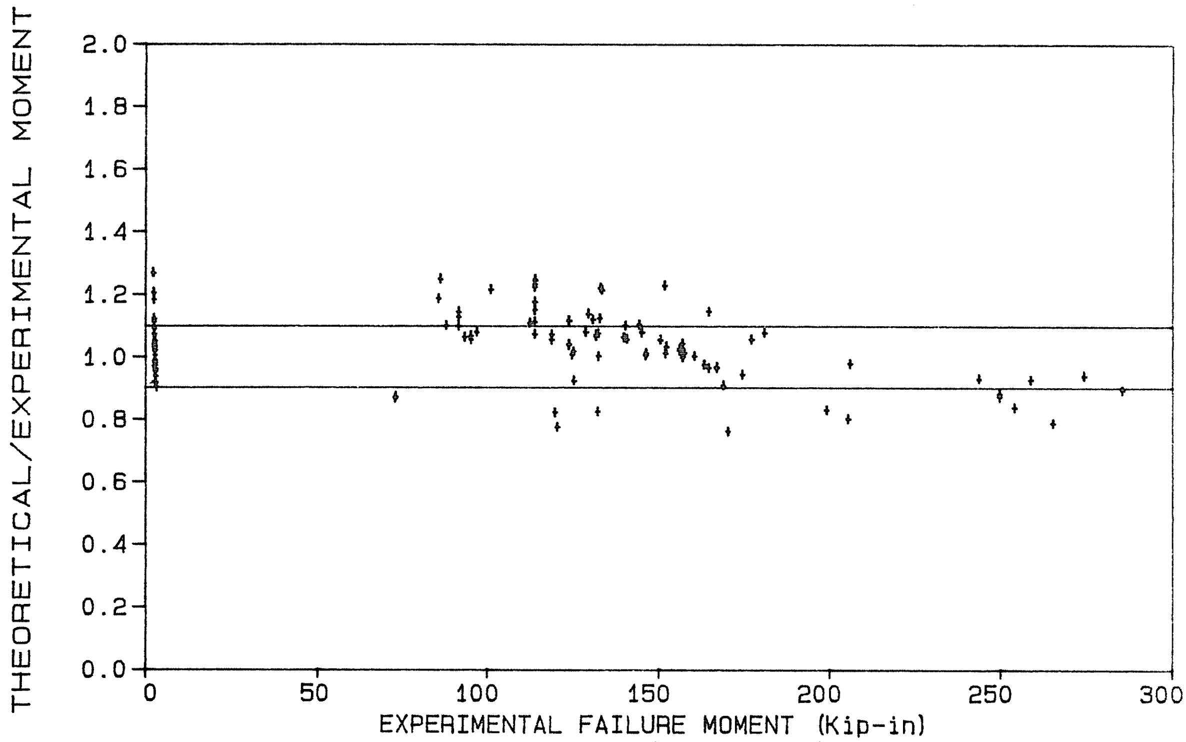


a) Scatter Diagram

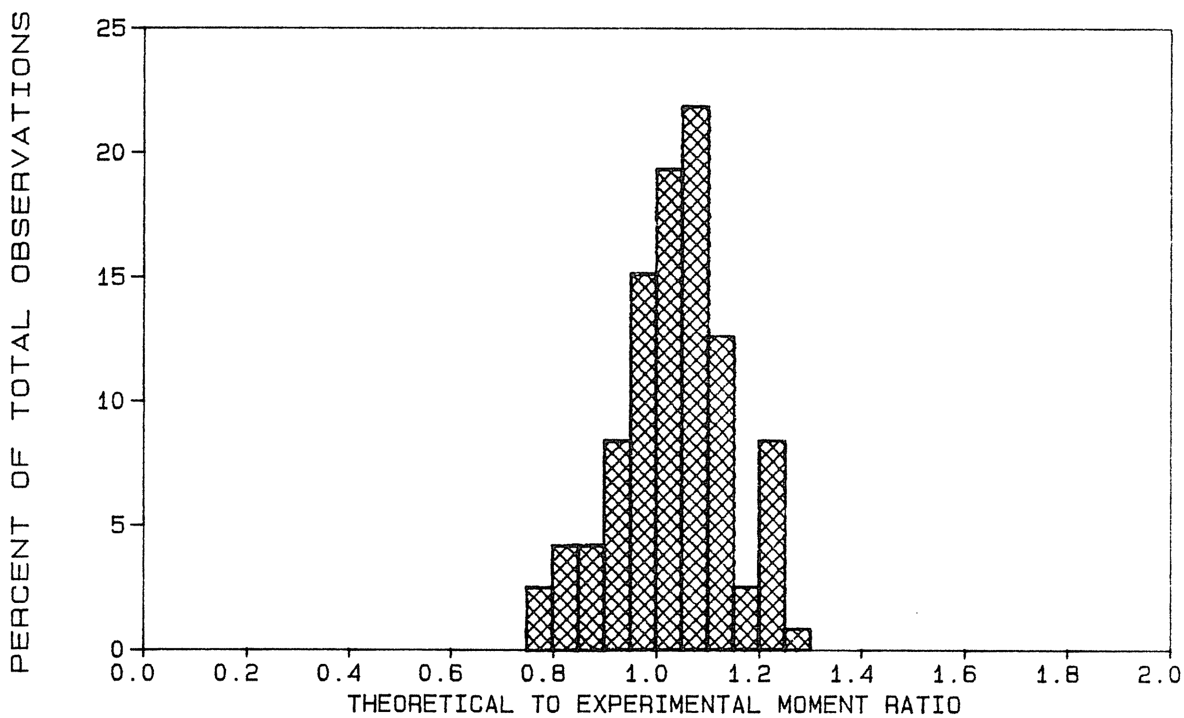


b) Frequency Distribution Diagram

Figure 2.7 Evaluation Diagrams for Method 1

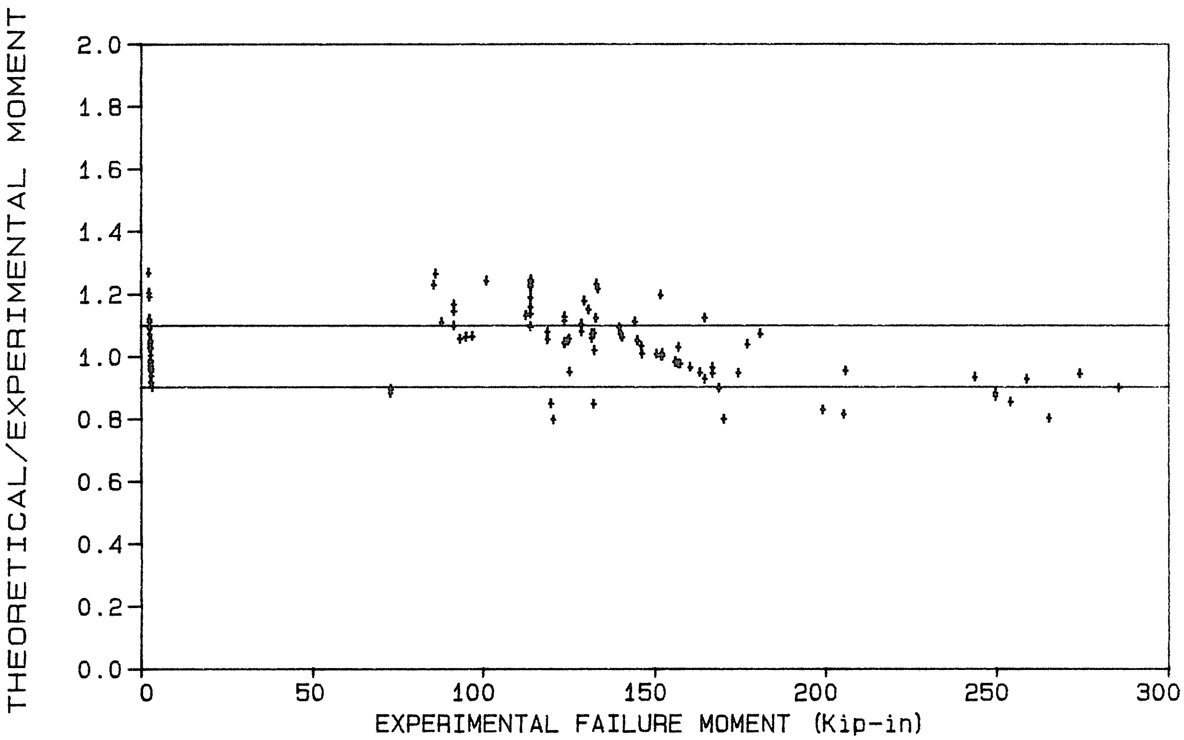


a) Scatter Diagram

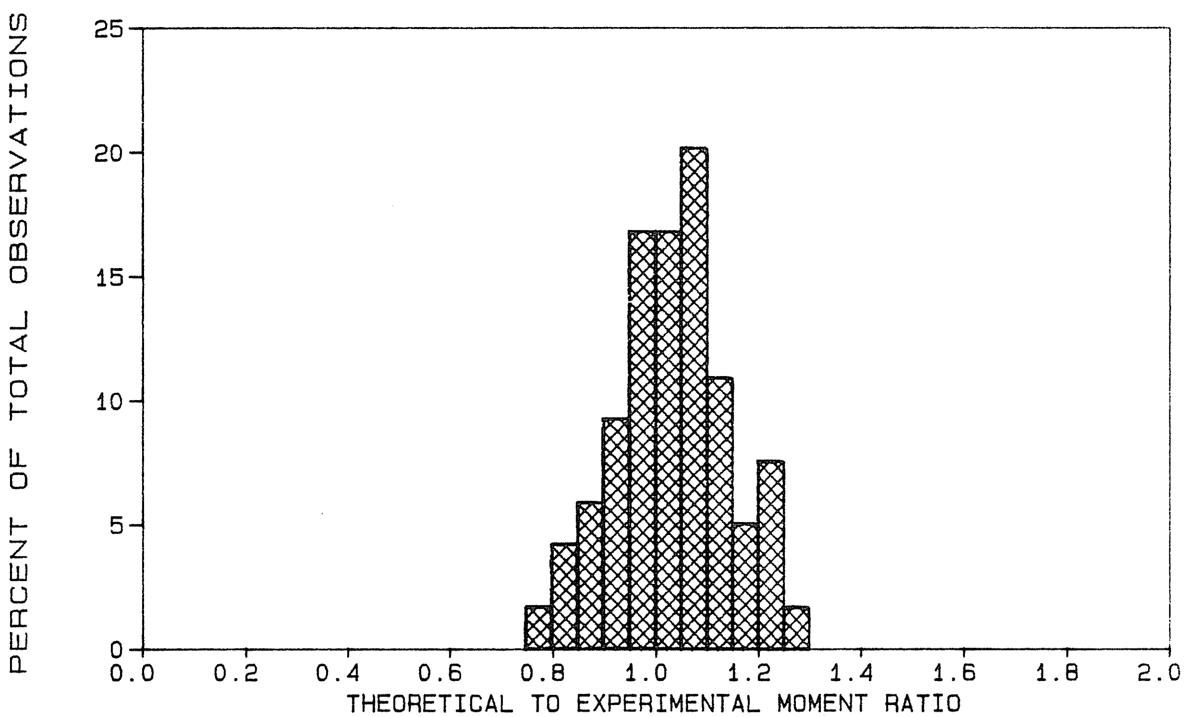


b) Frequency Distribution Diagram

Figure 2.8 Evaluation Diagrams for Method 2



a) Scatter Diagram



b) Frequency Distribution Diagram

Figure 2.9 Evaluation Diagrams for Method 3

Finally, Method 4 gave a mean value of 1.015, a standard deviation of 0.107, a minimum value of 0.784 and a maximum value of 1.268. Eighty observations were found to be acceptable, 16 were conservative, and 23 unconservative. See Figure 2.10 for plots.

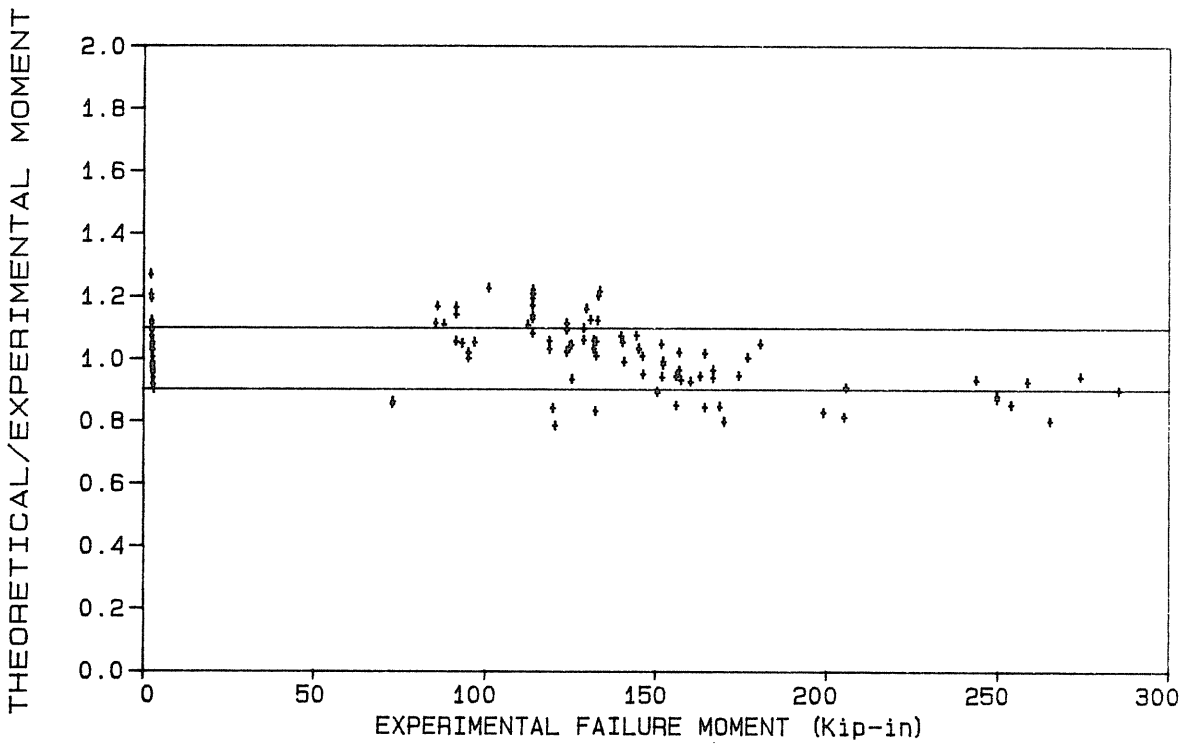
2.2.3 Method 5

This method differs from the first four methods not only in the way the lip is treated, but also in the way the effective flange width is determined. The web however, is treated in the same way. This procedure is the easiest of the eleven methods to use. It is described in Appendix B. The ratios of theoretical-to-experimental moment capacities according to this method have a mean value of 1.017, a standard deviation of 0.124, a mimimum value of 0.759, and a maximum value of 1.315. Of the 119 observations, 68 were in the acceptable range, 20 in the conservative range, and 31 in the unconservative range. The variation of moment ratios with experimental moments is shown in Figure 2.11(a), and the frequency distribution histogram of the moment ratios can be found in Figure 2.11(b).

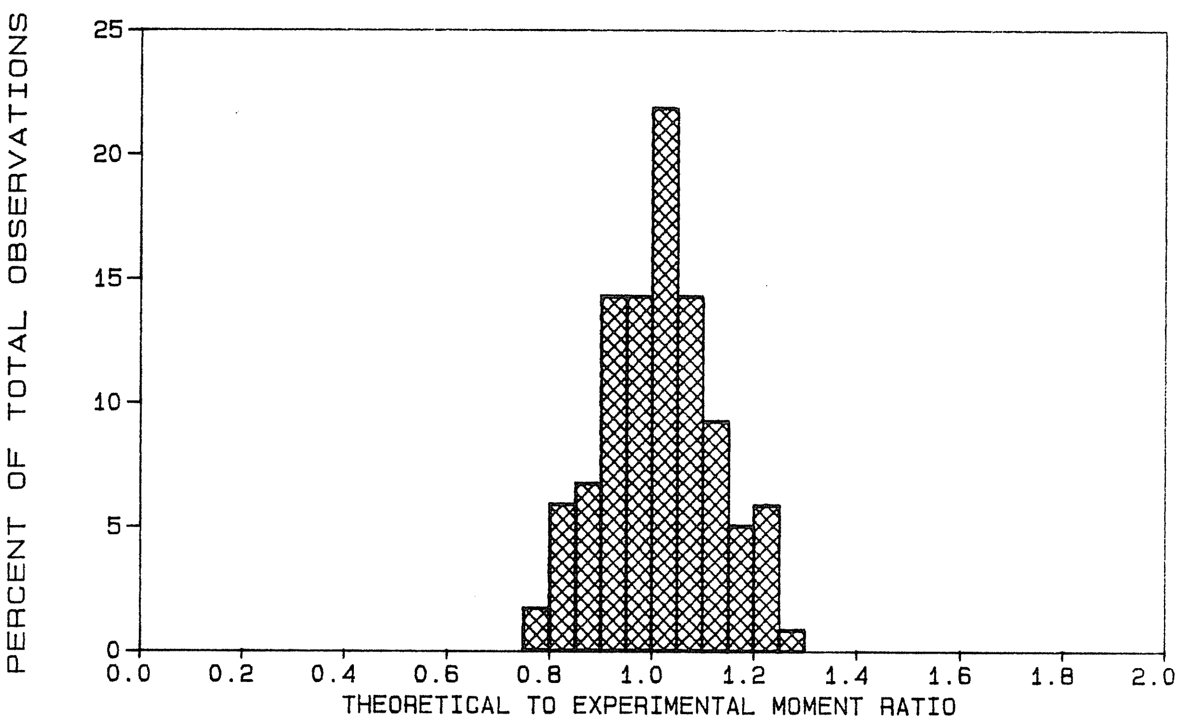
2.2.4 Methods 6, 7, 8, 9 and 10

These methods are described in Appendix C. They differ only in the way the lip is treated and are somewhat easier than Methods 1, 2, 3 and 4 to apply. Method 6 is the basic procedure proposed by Pekoz [4]; Methods 7, 8,9 and 10 are derived from it.

The ratios that were determined from Method 6 have a mean value of 1.092, a standard deviation of 0.125, a minimum value of 0.793 and a maximum value of 1.347. Sixty

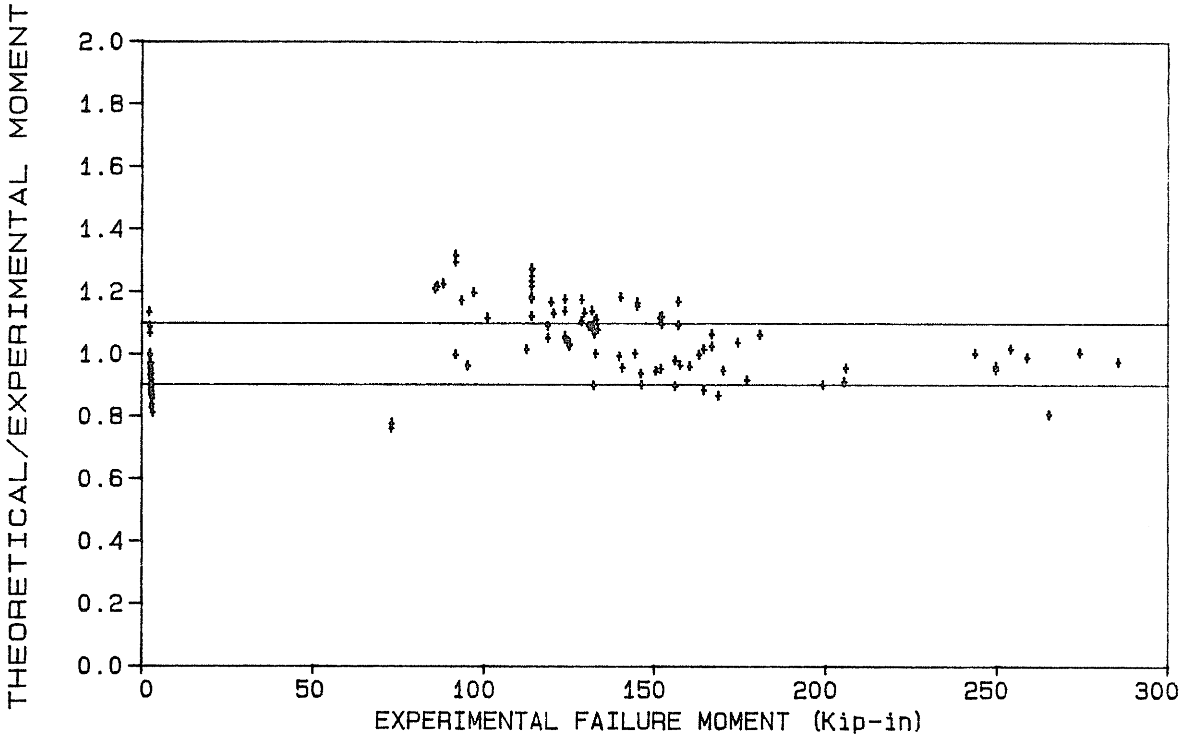


a) Scatter Diagram

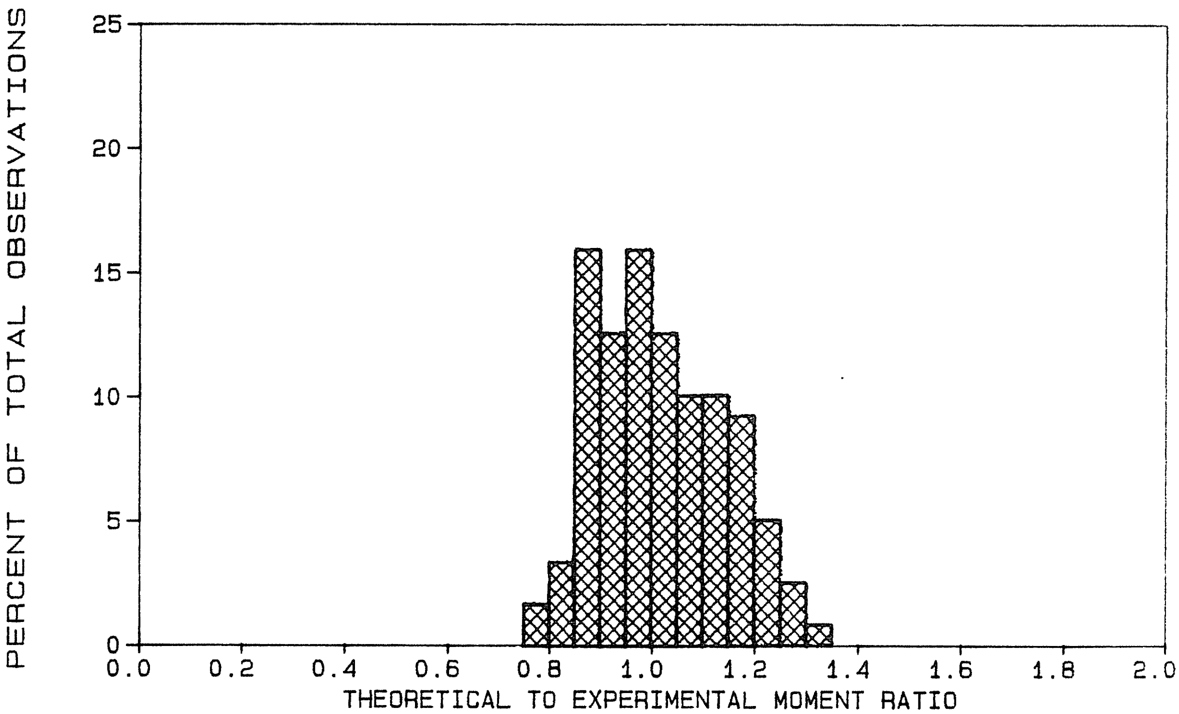


b) Frequency Distribution Diagram

Figure 2.10 Evaluation Diagrams for Method 4



a) Scatter Diagram



b) Frequency Distribution Diagram

Figure 2.11 Evaluation Diagrams for Method 5

observations were found to be satisfactory, 5 in the conservative range, and 54 in the unconservative range. Plots for this method are shown in Figure 2.12.

Method 7 gave ratios with a mean value of 1.033, a standard deviation of 0.105, a mimimum value of 0.784, and a maximum value of 1.264. Eighty six observations were found to be satisfactory, 10 were in the conservative range, and 23 in the unconservative range (See plots in Figure 2.13).

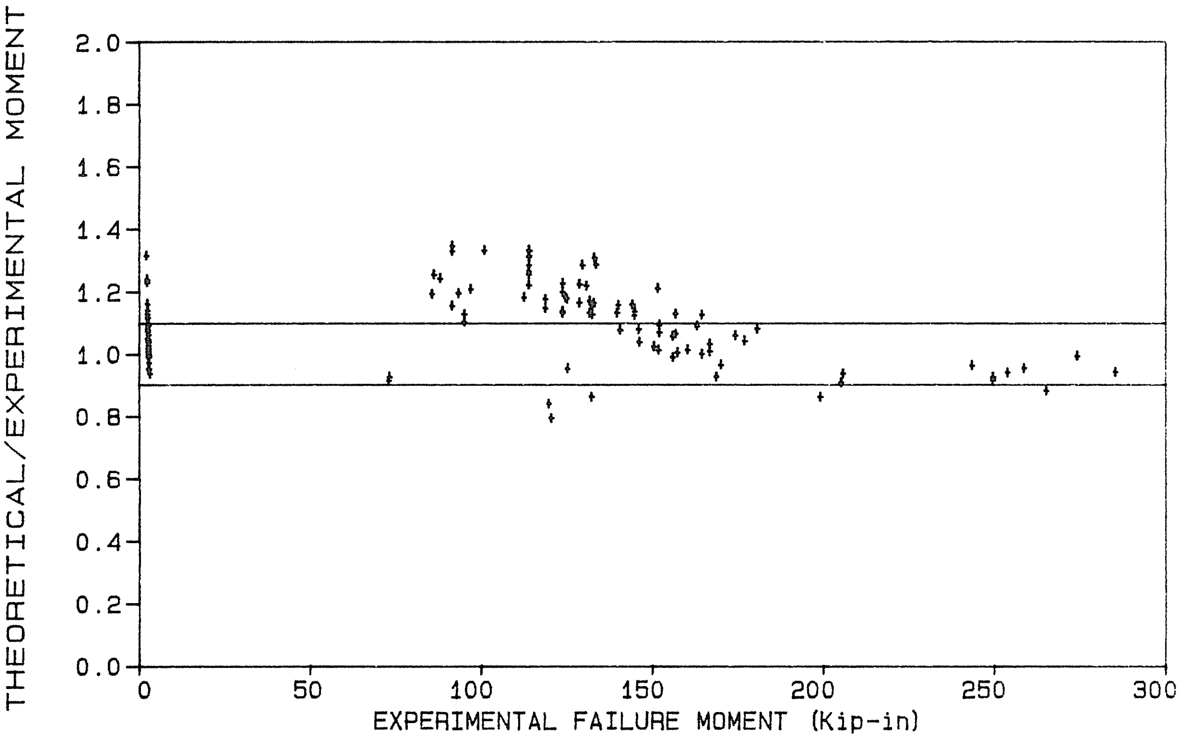
Method 8 gave ratios with a mean value of 1.084, a standard deviation of 0.119, a minimum value of 0.823, and a maximum value of 1.32. Sixty three observations were satisfactory, 5 were conservative, and 51 observations were unconservative. Plots for this method are shown in Figure 2.14.

Method 9 gave ratios with a mean value of 1.078, a standard deviation of 0.120, a minimum value of 0.793, and a maximum value of 1.347. Sexty seven observations were satisfactory, 5 were conservative, and 47 were unconservative. Plots for this method are found in Figure 2.15.

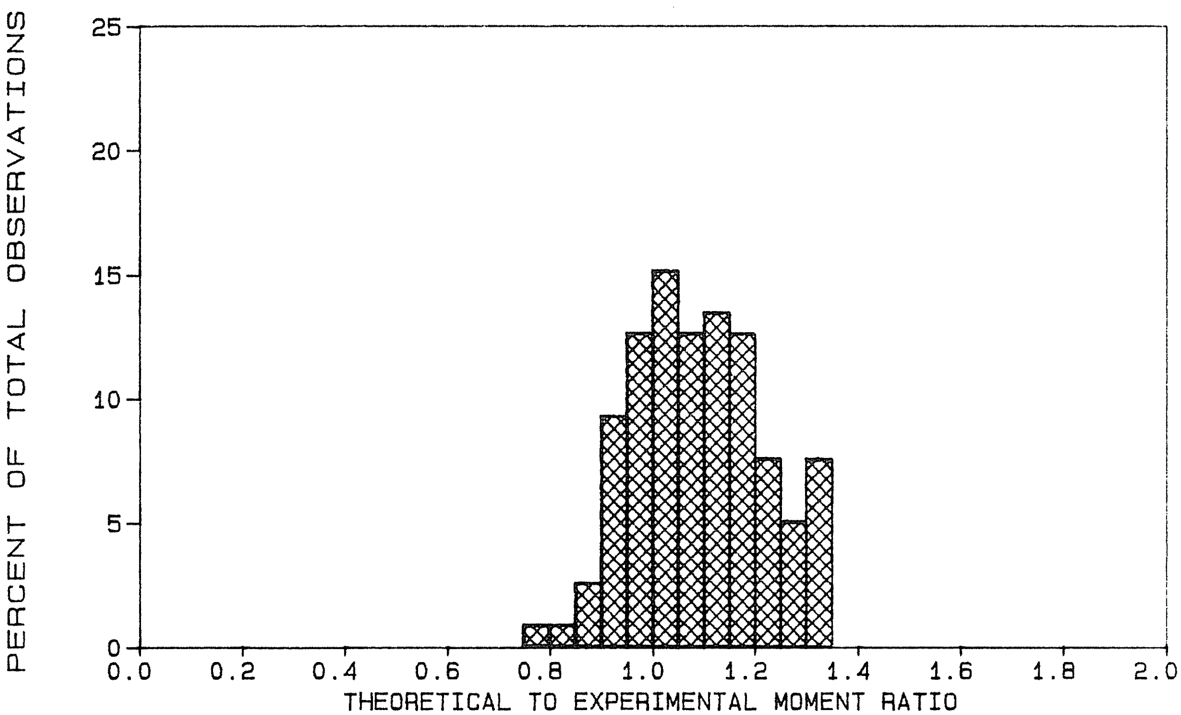
Finally Method 10 gave ratios with a mean value of 1.042, a standard deviation of 0.098, a minimum value of 0.809, and a maximum value of 1.269. Eighty six observations were satisfactory, 7 were conservative, and 26 were unconservative. Plots for this method are found in Figure 2.16.

2.2.5 Method 11

This method is the current AISI procedure and was

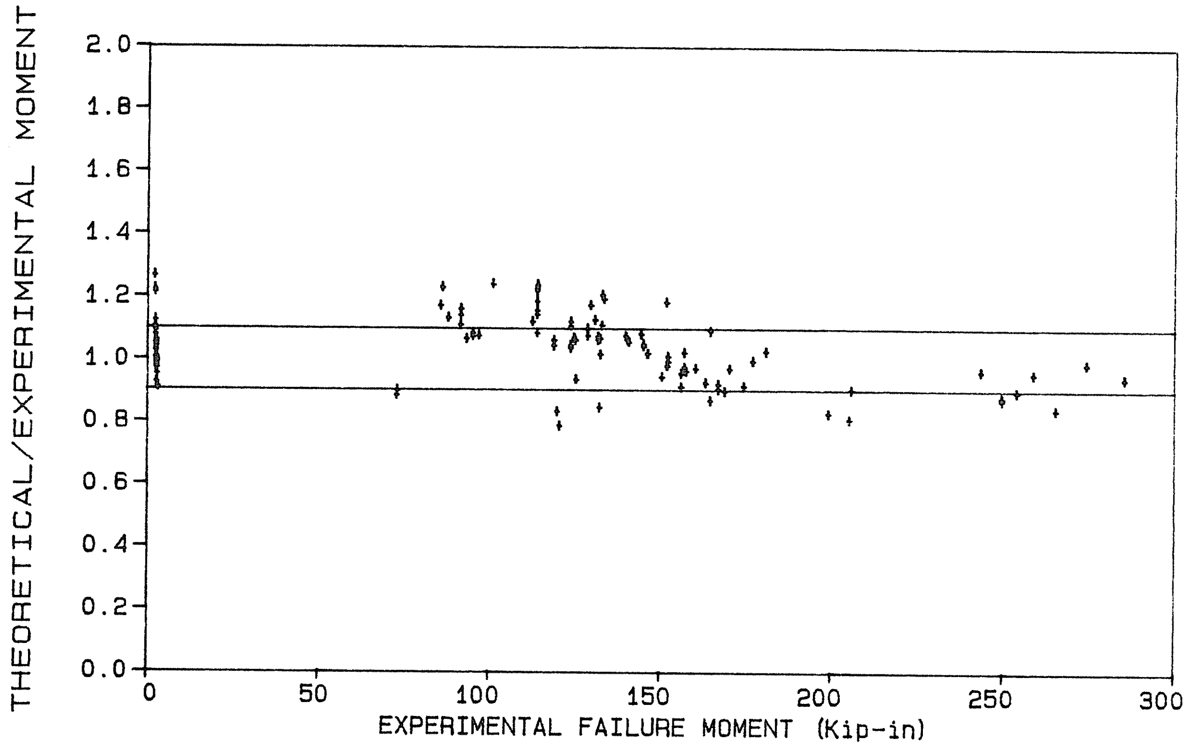


a) Scatter Diagram

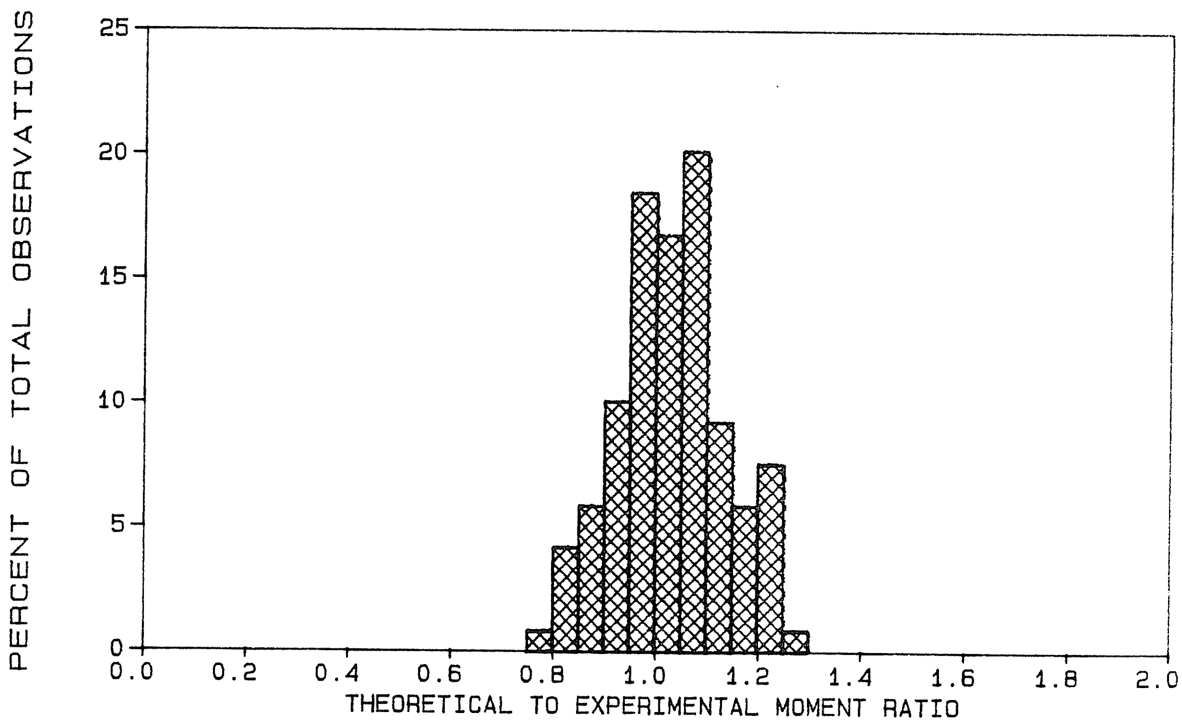


b) Frequency Distribution Diagram

Figure 2.12 Evaluation Diagrams for Method 6



a) Scatter Diagram



b) Frequency Distribution Diagram

Figure 2.13 Evaluation Diagrams for Method 7

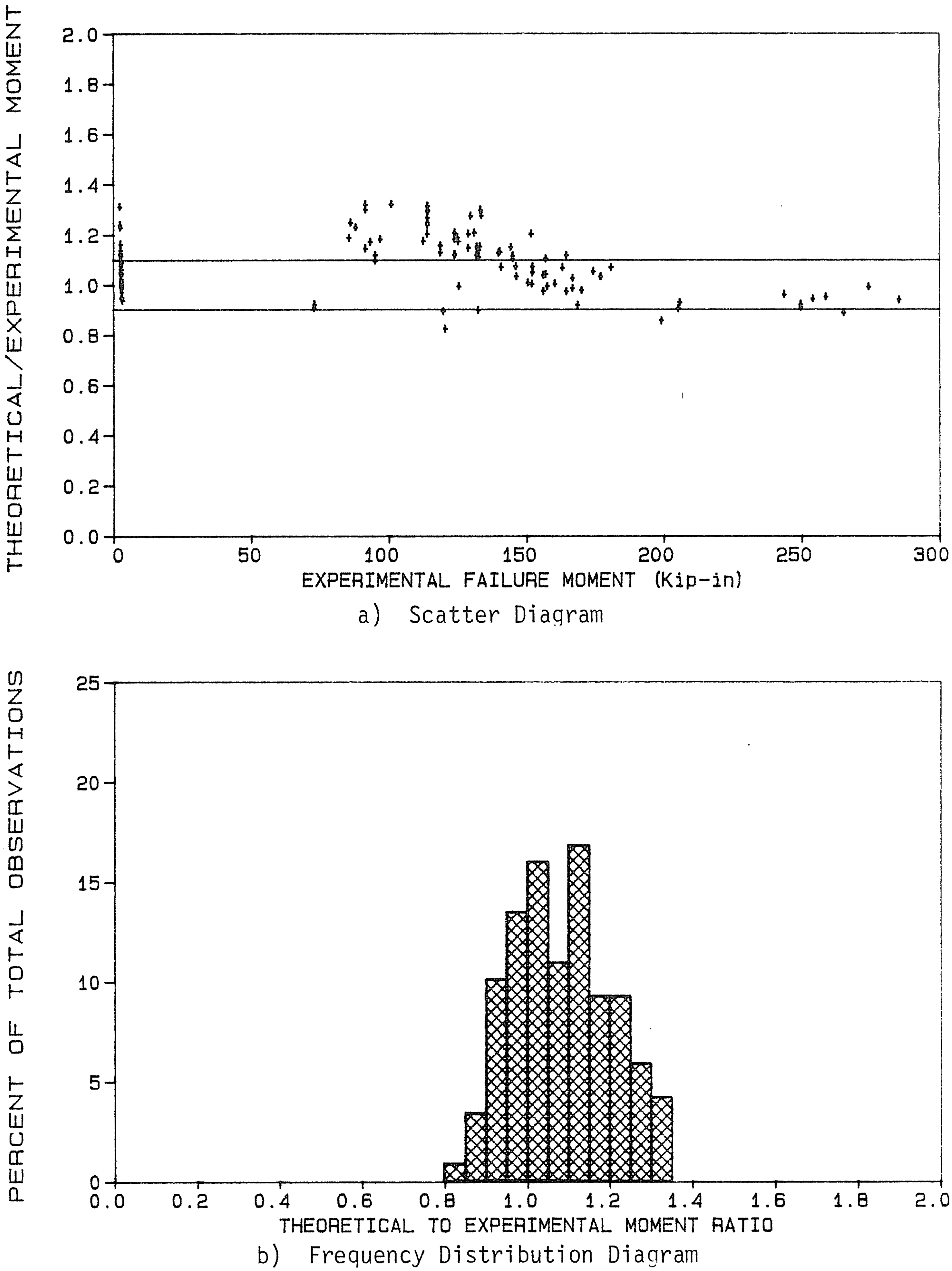
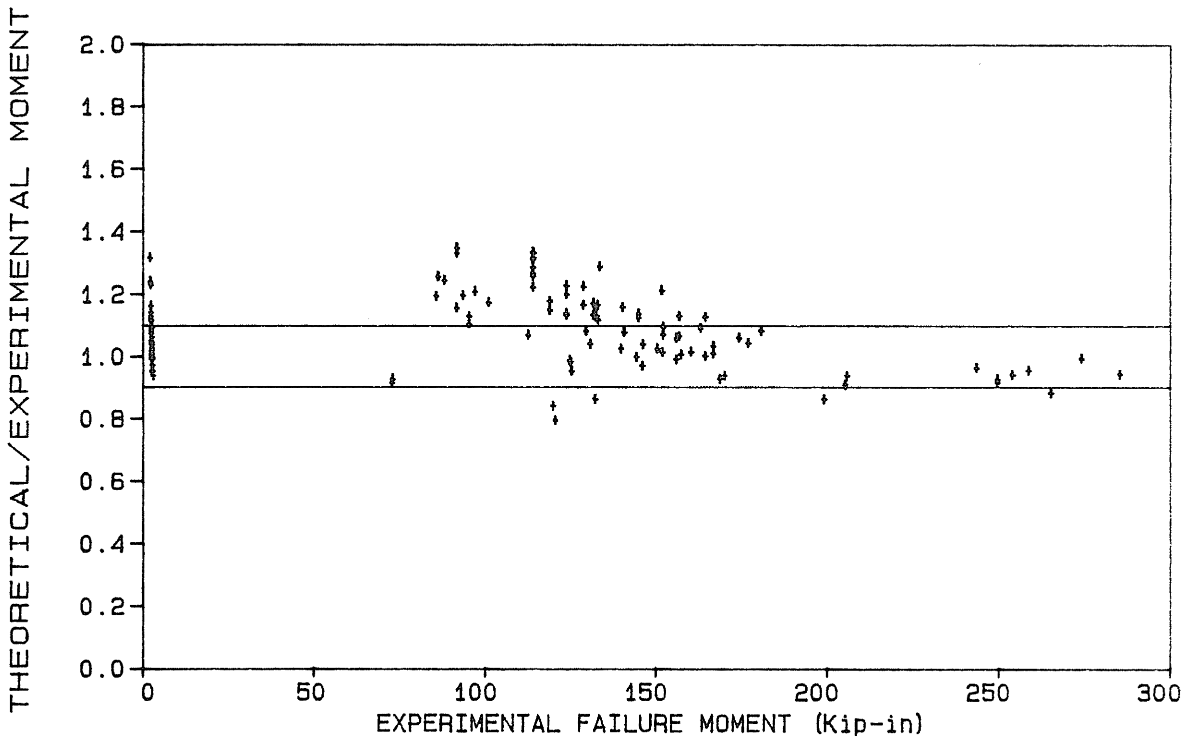
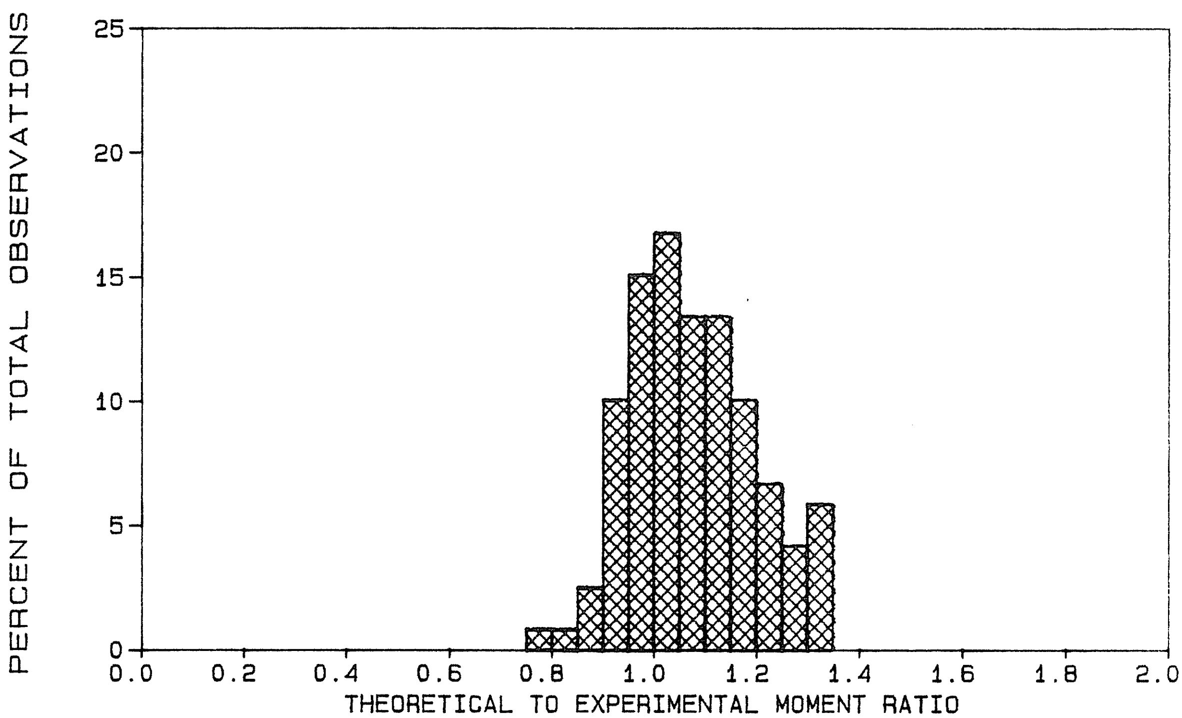


Figure 2.14 Evaluation Diagrams for Method 8

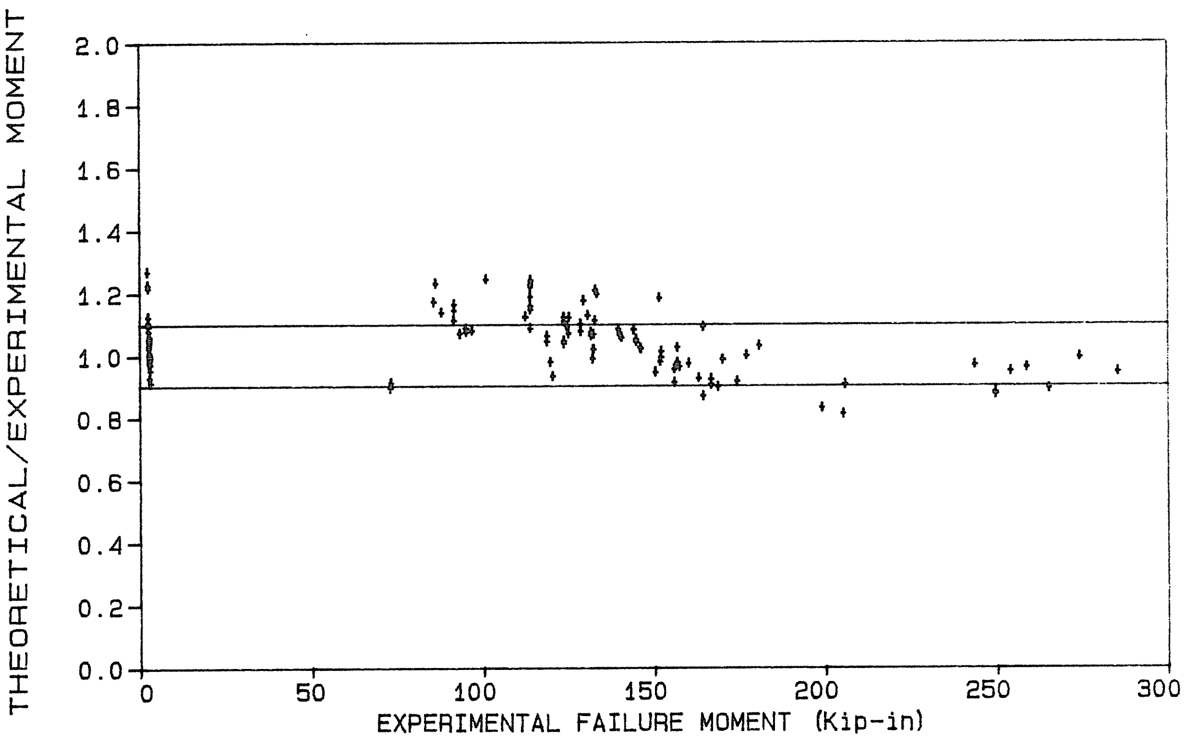


a) Scatter Diagram

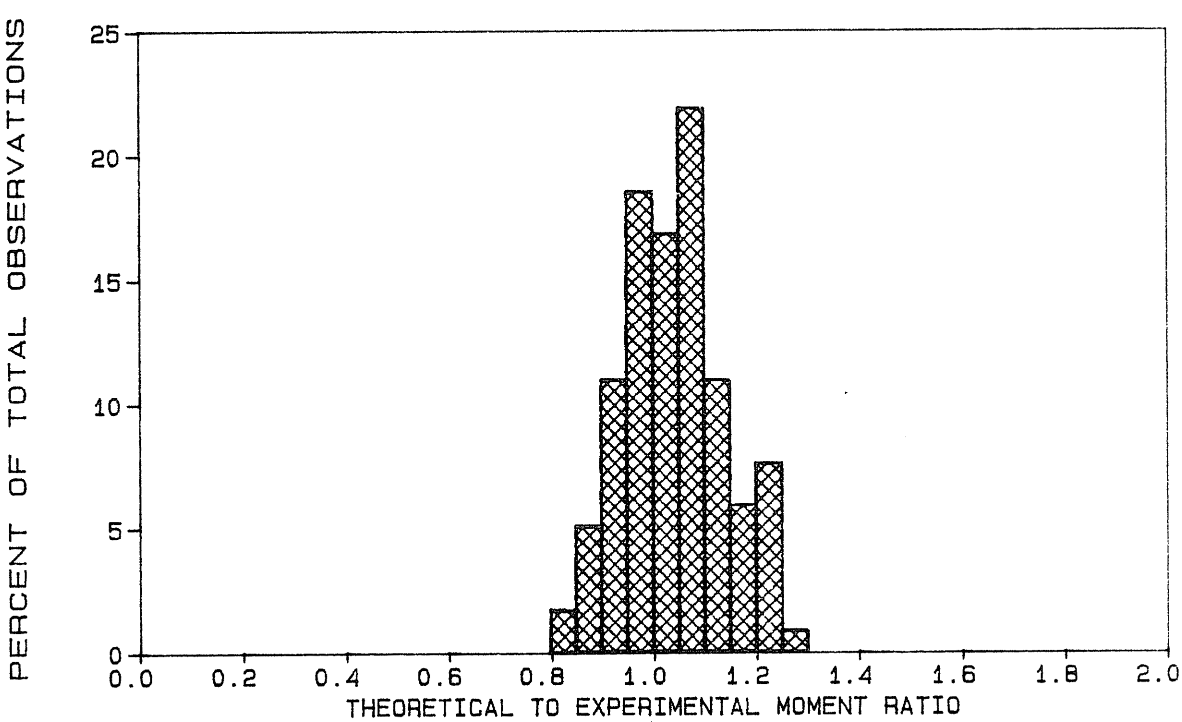


b) Frequency Distribution Diagram

Figure 2.15 Evaluation Diagrams for Method 9



a) Scatter Diagram



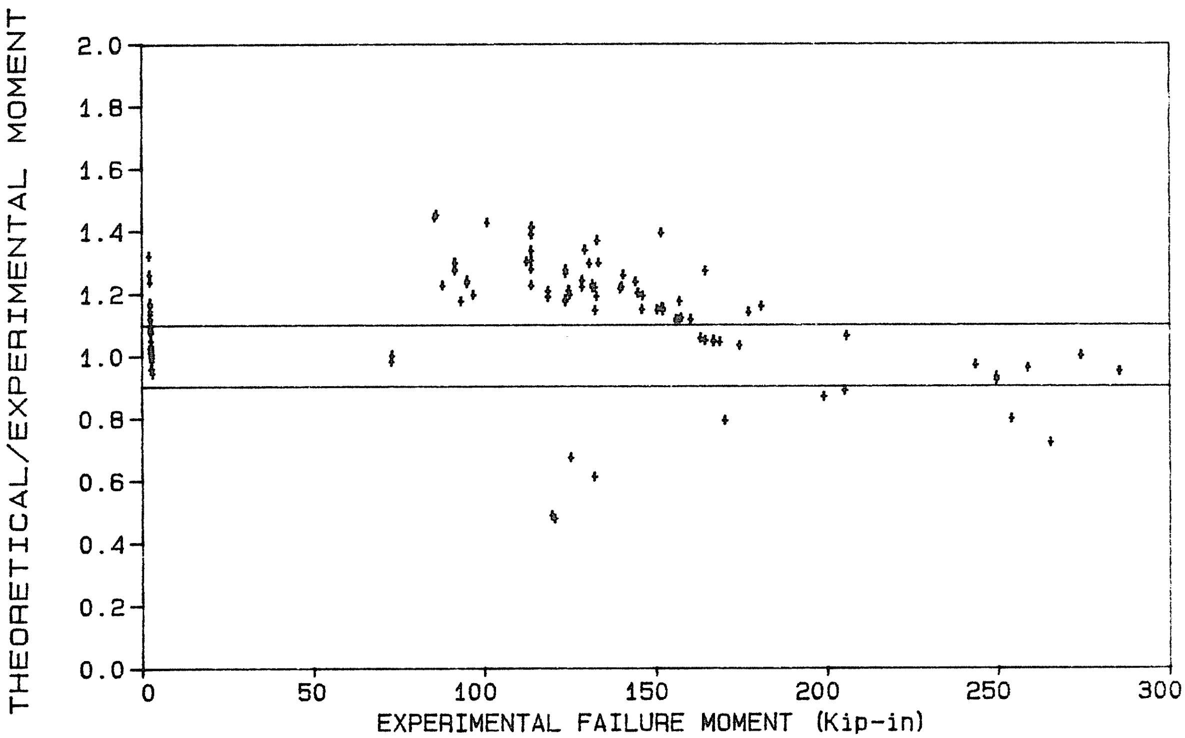
b) Frequency Distribution Diagram

Figure 2.16 Evaluation Diagrams for Method 10

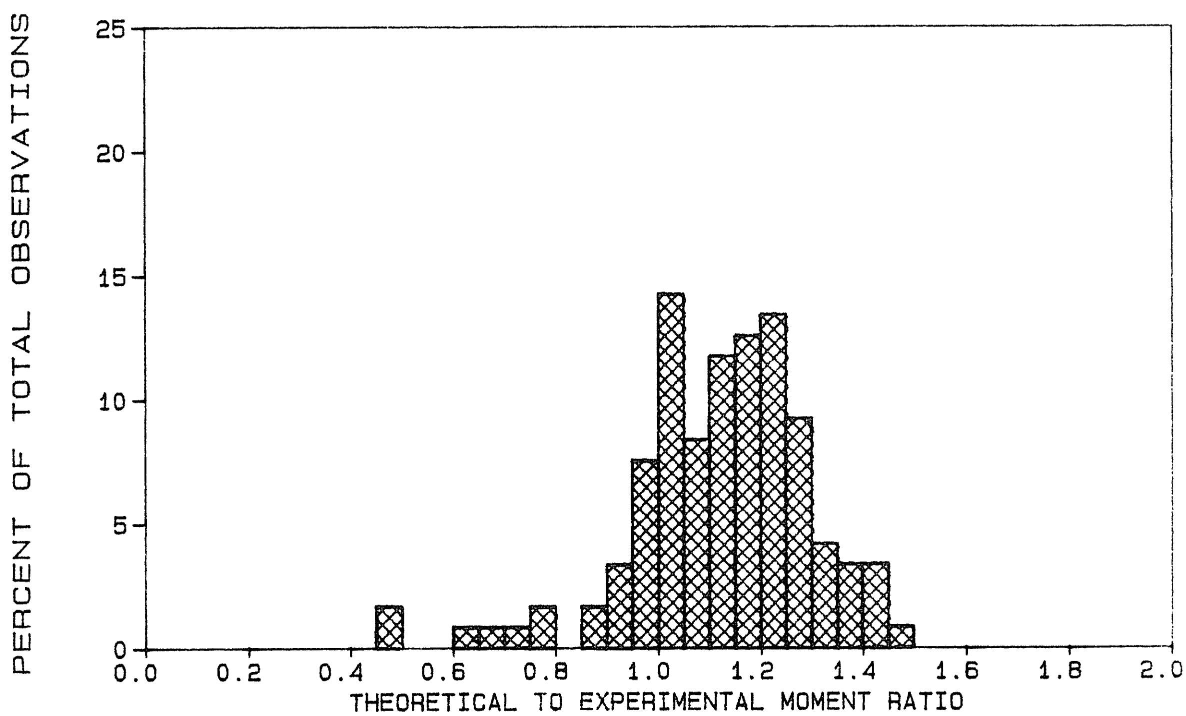
derived from Reference [1] (see Appendix D). This method was studied for comparison purposes only. The ratios have a mean value of 1.121, a standard deviation of 0.177, a mimimum value of 0.476, and a maximum value of 1.45. Of the 119 observations, 42 were found to be satisfactory, 9 were in the conservative range, and 68 were in the unconservative range. Plots for this method are found in Figure 2.17.

2.3 Conclusions

In this chapter, each of the eleven available procedures were used to analyze a set of 119 purlins that were previously tested experimentally, then the ratios of theoretical-to-experimental failure moments were determined and analyzed using statistical techniques. The collected statistical data will be used to compare the proposed methods with each other and to form a recommendation for replacing the current AISI specification, represented here by Method 11. This task is explained in the next chapter.



a) Scatter Diagram



b) Frequency Distribution Diagram

Figure 2.17 Evaluation Diagrams for Method 11

CHAPTER III

COMPARISON BETWEEN THE PROPOSED DESIGN PROCEDURES AND RECOMMENDATIONS

The purpose of this study was to determine which of the ten proposed methods is the most accurate when used to determine the cross-section flexural strength of Z- and C- purlins. The following comparison criteria were used to classify the proposed procedures.

The first criterion is the absolute difference between the mean value of the moment ratios of each method and 1.0. Table 3.1 shows the classification of the methods, in decreasing order, according to this measure. The best is Method 4, with an absolute difference of 0.015, followed by Method 5 with an absolute difference of 0.017, and Method 1 with an absolute difference of 0.023.

Next, the methods were classified by magnitude of standard deviation and by range of values as shown in Table 3.2; then by number of satisfactory, conservative (largest number is best) or unconservative observations (smallest number is best) as shown in Table 3.3. Method 10 results in the smallest standard deviation, 0.098, and the smallest range, 0.46. Methods 7 and 10 result in the maximum number of satisfactory observations, 86, and Methods 4 and 7 result in the minimum number of unconservative observations, 23. The best method

Table 3.1

Difference Between Mean and 1.0 Ranking

Method	Rank	Difference
1	3	0.023
2	4	0.032
3	5*	0.033
4	1	0.015
5	2	0.017
6	10	0.092
7	5*	0.033
8	9	0.084
9	8	0.078
10	7	0.042
11	11	0.121

Note : A rank of 1 is best
* : Tie

Table 3.2

Standard Deviation and Range Ranking

Method	Standard Deviation		Range of Values	
	Rank	Standard Deviation	Rank	Range
1	4*	0.110	3	0.477
2	4*	0.110	7	0.508
3	4*	0.110	2	0.472
4	3	0.107	5	0.484
5	9	0.124	10	0.556
6	10	0.125	8*	0.554
7	2	0.105	4	0.474
8	7	0.119	6	0.497
9	8	0.120	8*	0.554
10	1	0.098	1	0.460
11	11	0.177	11	0.974

Note : A rank of 1 is best
* : Tie

Table 3.3

Satisfactory, Conservative and Unconservative Rankings

Method	Satisfactory Cases		Conservative Cases		Unconservative cases	
	Rank	Number	Rank	Number	Rank	Number
1	5	79	2*	16	3	24
2	3*	80	5	13	4*	26
3	6	78	4	14	6	27
4	3*	80	2*	16	1*	23
5	7	68	1	20	7	31
6	10	60	9*	5	10	54
7	1*	86	6	10	1*	23
8	9	63	9*	5	9	51
9	8	67	9*	5	8	47
10	1*	86	8	7	4*	26
11	11	42	7	9	11	68

Note : A rank of 1 is best
* : Tie

according to the maximum number of conservative observations criterion is Method 5, 20 observations, followed by Methods 1 and 4 which have 16 conservative observations each.

Table 3.4 summarizes the classifications of the design methods by all measures. A general classification can easily be drawn from this table by examination of the individual classifications. Method 10 is ranked first by three out of the six criteria; therefore, Method 10 is ranked first in the general classification. Following the same logic, Methods 4 and 7 are ranked second and Method 1 is ranked forth and so on, with Method 11 (the current procedure) ranked last. To verify that the 26 unconservative cases were not caused by a specific parameter or due to a single source, Table 3.5 was prepared. The data in the table shows that no specific parameter nor source can be associated with the unconservative cases and, thus, the explanation is simply experimental scatter.

3.2 Conclusions

Data for 141 purlins failed in simple span, were collected from six sources to investigate the adequacy of ten proposed design approaches for determining cross-section flexural capacity. After a careful examination of the collected experimental data, 119 sets were used in the study. Each of the ten proposed methods and the current specification method was used to predict the failure moment for each of the 119 sets of test data. The ratio of theoretical-to-experimental moments were then calculated and statistics for each of the ten methods were determined.

Table 3.4

Ranking of Design Methods

Ranking	Criterion / Method						
	A	B	C	D	E	F	ALL
1	4	10	10	7,10	5	7,4	10
2	5	7	3	-	4,1	-	7,4
3	1	4	1	2,4	-	1	-
4	2	1,2,3	7	-	3	2,10	1
5	7,3	-	4	1	2	-	2
6	-	-	8	3	7	3	3
7	10	8	2	5	11	5	5
8	9	9	6,9	9	10	9	9
9	8	5	-	8	6,8,9	8	8
10	6	6	5	6	-	6	6
11	11	11	11	11	-	11	11

A : Difference between mean and 1.0

B : Standard deviation

C : Range

D : Satisfactory cases

E : Conservative cases

F : Unconservative cases

Table 3.5

Examination of Method 10 Unconservative Results

Case	Source	Θ	b/t	w/t	H/t
Z1-6P2	1	42°	9.6	27.7	92.2
Z1Q-3P1	1	48°	8.1	25.2	82.0
Z1Q-7P1	1	28°	10.7	25.4	79.8
Z1Q-17P1	1	45°	8.5	25.2	79.2
Z1Q-24P1	1	45°	7.8	25.2	79.0
C2-6P1	2	87°	12.8	52.5	155.9
C2-6P2	2	85°	12.9	51.4	155.9
Z3-5P1	3	43°	13.1	40.1	139.8
Z3-6P1	3	45°	12.3	41.7	141.9
Z3-9P1	3	49°	11.0	37.2	127.2
Z3-11P1	3	45°	11.8	36.7	113.9
Z3-12P1	3	51°	11.9	37.7	115.7
Z3-17P1	3	44°	8.5	45.6	159.0
Z3-18P1	3	43°	6.5	47.4	161.8
Z3-21P1	3	42°	4.9	29.9	104.9
Z3-24P1	3	41°	23.0	41.4	112.9
Z5-4P2	5	74°	11.0	39.6	114.4
Z5-5P1	5	71°	10.3	37.6	113.9
Z5-5P2	5	69°	9.9	38.7	113.4
Z5-6P1	5	76°	10.0	39.9	115.5
Z5-6P2	5	75°	10.6	39.0	115.4
Z5-7P1	5	71°	10.6	39.0	118.3
Z5-7P2	5	71°	10.9	38.7	117.1
Z5-10P2	5	71°	11.9	38.9	120.0
Z6-4P1	6	85°	11.9	40.0	126.3
Z7-4P1	7	46°	10.8	40.7	127.0

Statistical comparisons between the methods resulted in Method 10 being ranked first. The method is therefore recommended as a replacement of the current AISI specification provisions [1]. Example calculations for the use of method 10 are found in Appendix E.

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1. Specification for the Design of Cold-Formed Steel Structural Members, American Iron and Steel Institute, Washington, D.C., September 3, 1980.

2. Desmond, T.P., Pekoz, T. and Winter, G., "Edge Stiffeners for Thin-Walled Members", Journal of the Structural Division, ASCE, Vo. 107, No. ST7, February 1981, pp. 329-353.

3. LaBoube, R. and Yu, W., "Bending Strength of Webs of Cold-formed Steel Beams", Journal of the Structural Division, ASCE, Vol. 108, No. ST7, July 1982, pp. 1589-1604.

4. Teoman Pekoz, "A Unified Design Approach for Compression Elements and Webs", Commentary on the Proposed Specification Changes, Cornell University, June 3, 1985.

APPENDIX A

DESIGN METHODS 1,2,3 AND 4

A.1 General

These methods are based on the work of Desmond, Pekoz and Winter [2] at Cornell University, and LaBoube and Yu [3] at the University of Missouri Rolla. They basically follow the same steps and differ only in the way the effective compression lip dimension is calculated, which affects the evaluation of the effectiveness of the compression flange.

A.2 Details of the Procedures and Equations

Step 1. Maximum coession web depth $y_e(lim)$

$$y_e(lim) = y_{b1} - r_2 - t \qquad (A.1)$$

Step 2. Limit of compression flange width to thickness

$$(w_c/t)_{lim} = 171/\sqrt{0.6\ F_y} \qquad (A.2)$$

Step 3. Stress reduction factors

$$g_1 = 1.037 - 0.000125(H/t)\sqrt{F_y} \qquad (A.3)$$

$$g_2 = 1.074 - 0.0735(w_c/t)/(w_c/t)_{lim}$$

$$\text{if } (w_c/t)/(w_c/t)_{lim} \le 1 \text{ then } g_2 = 1 \qquad (A.4)$$

Step 4. Web limiting stress

$$F' = g_1 \cdot g_2 \cdot F_y \le F_y \qquad (A.5\text{-}a)$$

If the compression flange is unstiffened then :

$$F' = 0.8[1.024 - 0.024(w_c/t)/(w_c/t)_{lim}]\ F_y \le F_y \qquad (A.5\text{-}b)$$

$$\text{and } [1.024 - 0.024(w_c/t)/(w_c/t)_{lim}] \le 1$$

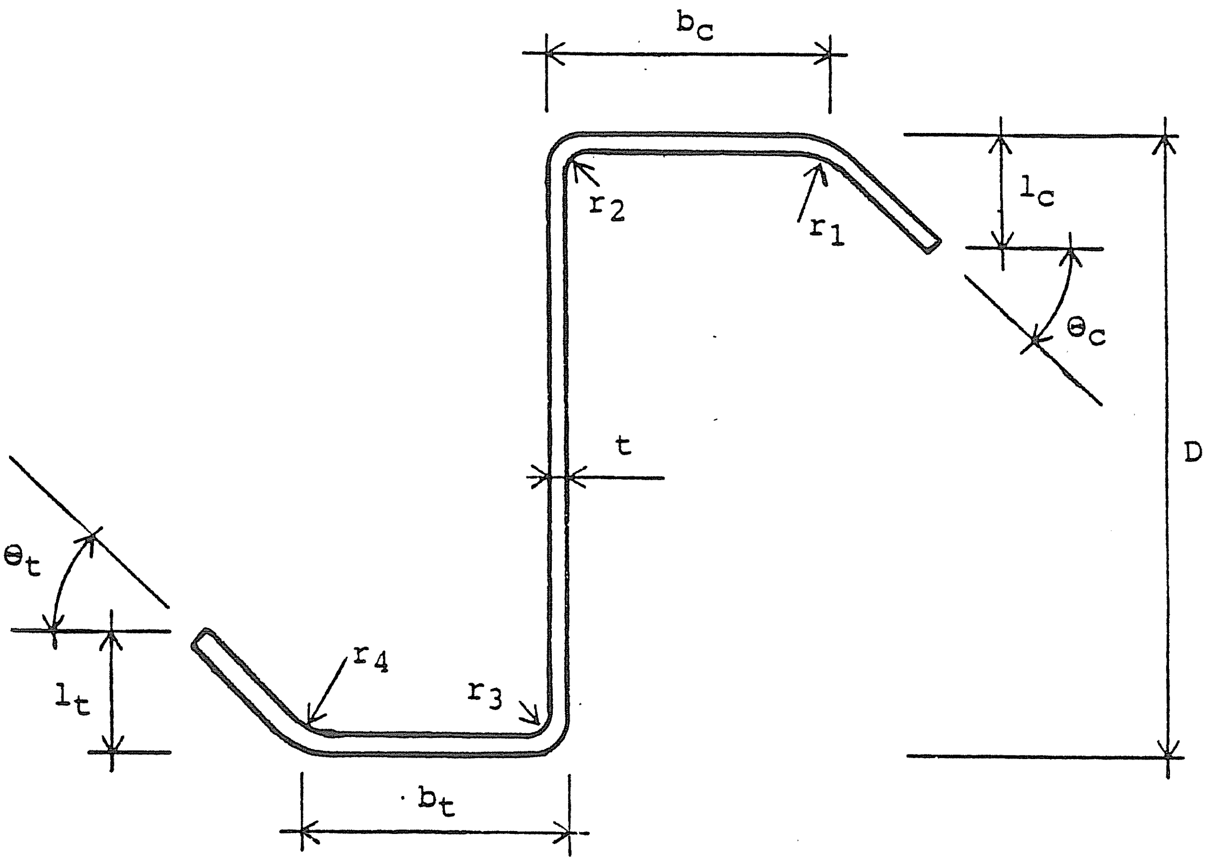


Figure A.1 Purlin Cross Sectional Geometry

Step 5. Determination of the effective compression flange width

a) width to thickness ratio limits:

$$(w/t)_\alpha = 221/\sqrt{F_y} \qquad (A.6)$$

$$(w/t)_\beta = 0.64\sqrt{0.425\ E/F_y} \qquad (A.7)$$

b) effective length of edge stiffener:

Figure A.2 shows a detail of the compression lip with all the dimensions.

$$D_s = l_c/\sin(\Theta_c) \qquad (A.8)$$

$$w_s = D_s - (r_1+t/2)\ \tan(\Theta_c/2) \qquad (A.9)$$

The effective length of the edge stiffener is determined according to the design method to be used

i) Method 1:

$$D_e = 0.95t\sqrt{0.425E/F_y}\ [1-(0.209/(w_s/t))\sqrt{0.425E/F_y}]$$
$$\text{and } D_e \le w_s \qquad (A.10)$$

The effective edge stiffener moment of inertia is given by

$$I_s = [(D_e+r_1)^3\ t/12]\ \sin^2\Theta_c \qquad (A.11)$$

ii) Method 2:

$$D_e = 0.95t\sqrt{0.425E/F_y}\ [1-(0.209/(D_s/t))\sqrt{0.425E/F_y}]$$
$$\text{and } D_e \le D_s \qquad (A.12)$$

The effective edge stiffener moment of inertia is given by

$$I_s = [(D_e+r_1)^3\ t/12]\ \sin^2\Theta_c \tag{A.13}$$

iii) Method 3:

$$D' = 0.95t\sqrt{0.425E/F_y}\ [1-(0.209/(w_s/t))\sqrt{0.425E/F_y}] \tag{A.14}$$

$$D_e = D' + (r_1+t/2).\Theta_c \tag{A.15}$$

The effective edge stiffener moment of inertia is given by

$$I_s = [(D_e+r_1)^3\ t/12]\ \sin^2\Theta_c \tag{A.16}$$

iv) Method 4:

$$D' = 0.95t\sqrt{0.425E/F_y}\ [1-(0.209/(w_s/t))\sqrt{0.425E/F_y}] \tag{A.17}$$

$$D_e = D' + (r_1+t/2)\ \tan(\Theta_c/2) \tag{A.18}$$

The effective edge stiffener moment of inertia is given by

$$I_s = [(D_e)^3\ t/12]\ \sin^2\Theta_c \tag{A.19}$$

c) Edge stiffener requirements:

i) If $(w_c/t) < (w/t)_\beta$ then the flange is fully effective as an unstiffened element and the adequate moment of inertia of the edge stiffener is given by

$$I_a = 0 \tag{A.20}$$

ii) If $(w/t)_\beta \le (w_c/t) < (w/t)_\alpha$ then the flange is fully effective when adequately stiffened, and the adequate moment of inertia of the edge stiffener is given by

$$I_a = t^4 \; 0.0000361 \; [(w_c/t)\sqrt{F_y} - 71.7]^3 \tag{A.21}$$

iii) If $(w_c/t) \ge (w/t)_\alpha$ then the flange is in the post buckling range, and the adequate moment of inertia of the edge stiffener is given by

$$I_a = t^4 \; 0.52 \; [(w_c/t)\sqrt{F_y} + 5] \tag{A.22}$$

d) Check the adequacy of the stiffener and calculate the effective compression flange width, w_e:

i) <u>Adequately stiffened flange</u>. If $I_s \ge I_a$ then the flange is adequately stiffened, and the effective flange width can be determined from the following:

$$\text{if} \quad (w_c/t) < (w/t)_\beta \quad \text{then } w_e = w_c \tag{A.23}$$

else

$$A = \sqrt{kw_{as} \, E/F_y}$$

$$w_e = 0.95 \; t \; A \; [1-(0.209/(w_c/t))A] \le w_c \tag{A.24}$$

where $kw_{as} = 4$ if $(w_s+r_1)/w_c \le 0.25$
or $kw_{as} = -5[(w_s+r_1)/w_c] + 5.25$, otherwise.

ii) Partially stiffened flange. If $0 < I_s < I_a$ then the flange is partially stiffened, and the effective flange width can be determined from the following:

$$\text{if} \quad (w_c/t) < (w/t)_\beta \quad \text{then } w_e = w_c \tag{A.25}$$

else, proceed as follows:

$$kw_{ps} = (I_s/I_a)^{(1/n)}.(kw_{as}-0.425) + 0.425 \tag{A.26}$$

where :

kw_{as} is defined in part i) above.

$n=2$ if $(w_c/t) < (w/t)_\alpha$

$n=3$ if $(w_c/t) \geq (w/t)_\alpha$

$$B = \sqrt{E\ kw_{ps}\ /F_y}$$

$$w_e = 0.95\ t\ B\ [1-(0.209/(w_c/t))B] \leq w_c \tag{A.27}$$

Now revise the effective length of the edge stiffener as follows

The effective area of the edge stiffener is given by

$$A_e = D_e\ t\ I_s/I_a \tag{A.28}$$

The revised effective length of the edge stiffener is given by

$$D_e = A_e/t \tag{A.29}$$

Finally revise the moment of inertia of the edge stiffener and the effective flange width by using Equations A.26 and A.27 and iterate for D_e until convergence.

iii) Unstiffened flange. If $I_s = 0$ then the flange is unstiffened and the effective flange width can be determined as follows

$$\text{If} \quad (w_c/t) < (w/t)_\beta \quad \text{then } w_e = w_c \tag{A.30}$$

else

$$C = \sqrt{0.425\ E\ /\ F_y}$$

$$w_e = 0.95\ t\ C\ [1-(0.209/(w_c/t))\ C] \leq w_c \tag{A.31}$$

6. Determination of the compression web depth:

$$\beta = f_t/F_y \tag{A.32}$$

Assume $f_t = 0.6\ F_y$, this value will be revised at a later step.

$$K = 4 + 2(1+\beta)^3 + 2(1+\beta) \tag{A.33}$$

The compression web depth can then be determined from:

$$y_e = 0.358\ t\ \sqrt{K\ E/F'} \leq y_e(\text{lim}) \tag{A.34}$$

7. Determination of the moment capacity:

The moment capacity of the section is based on the effective dimensions shown in Figure A.3. The location of the neutral axis is determined by solving for y_b, which is the distance between the top fiber of the compression flange and the neutral axis. Thereafter, the effective moment of inertia I_e of the cross section can be determined and the ultimate moment capacity is found from the following

$$M_u = F' \, I_e \, / \, Y_b \tag{A.35}$$

8. Calculation of stress in the tension flange

$$f_t = M_u \, (d-Y_b)/I_e < 0.6 \, F_y \tag{A.36}$$

Now revise the value of β that was assumed in step 6 using

$$\beta = f_t \, / \, F_y \tag{A.37}$$

and iterate to convergence.

APPENDIX B

DESIGN METHOD 5

In this method, the flexural capacity of a Z- or C-shaped purlin can be determined as follows:

<u>Step 1. Determine the effective flange width</u>

$$w_e = 0.95\ t\ \sqrt{A}\ [1- (0.209/(w_c/t))\sqrt{A}] \qquad \text{(B.1)}$$

where $A = E\ k\ /\ F_y$

k is defined as follows:

For $\Theta_c.t > 4$:

$$k = [-1.675+0.525\ (\Theta_c.t)].[-1.380+0.55(w_s/t)] \qquad \text{(B.2-a)}$$

For $\Theta_c.t \leq 4$:

$$k = 0.425 \qquad \text{(B.2-b)}$$

<u>Step 2. Determine the compression web depth</u>

$$y_e = 0.358\ t\ \sqrt{k_w.E/F'} \qquad \text{(B.3)}$$

where

$$k_w = 4 + 2(1+\beta)^3 + 2(1+\beta) \qquad \text{(B.4)}$$

$$\beta = f_t/f_c = 1.0 \qquad \text{(B.5)}$$

The assumption of β=1 in Equation B.5 is very reasonable for Z-sections.

<u>Step 3. Calculate the flexural capacity</u>

First the effective moment of inertia is to be calculated based on the effective dimensions shown in Figure B.1. If y_b is the distance from the top compression flange to the neutral axis then

$$M_u = (I_e/y_b).F_y \qquad \text{(B.6)}$$

APPENDIX C

DESIGN METHODS 6,7,8,9 AND 10

Notations

1986 AISI Method 10?

The following notations and definitions apply for this procedure:

$$s = 1.27 \sqrt{E/f} \qquad \text{(C.1) Eq (B4-1)}$$

f is defined as follows:

a) $f=F_y$ at M_u <u>or</u> if the initial yield is in compression in the element considered.

b) If the initial yield is not in the element considered, then the stress f shall be determined for the element considered on the basis of the effective section at M_y (moment causing initial yield).

I_a : adequate stiffener moment of inertia to insure each component element to behave as a stiffened element.

I_s : actual moment of inertia of the effective section of the stiffener about its own centroidal axis, parallel to the element to be stiffened.

A_e : actual effective area of the stiffener.

A_r : reduced effective area of the stiffener as specified in this section. A_e is to be used in computing the overall effective section properties.

Step 1. General

Assume stress at compression flange is $f=F_y$

Calculate s according to Equation C.1

Step 2. Calculate effective length of stiffener

Section 2.3.2.1-a of Reference [4] is applicable here.

$$D_s = l_c/\sin(\Theta_c) \quad \text{(C.2)}$$ Geometry

$$w_s = D_s - (r_1+t/2)\tan(\Theta_c/2) \quad \text{(C.3)}$$ Geometry

Method 6:

$$\mu = 1.604\ (w_s/t)\sqrt{f/E} \quad \text{(C.4)}$$

$$\text{if } \mu \le 0.673 \text{ then } \alpha = 1.0 \quad \text{(C.5)}$$

$$\text{else } \alpha = (1-0.22/\mu)/\mu \quad \text{(C.6)}$$

$$D_e = \alpha D_s \quad \text{(C.7)}$$

Methods 7 and 10:

$$\mu = 1.604\ (w_s/t)\sqrt{f/E} \quad \text{(C.8)}$$

$$\text{if } \mu \le 0.673 \text{ then } \alpha = 1.0 \quad \text{(C.9)}$$

$$\text{else } \alpha = (1-0.22/\mu)/\mu \quad \text{(C.10)}$$

$$D_e = \alpha w_s \quad \text{(C.11)}$$

Same as C.23 & C.24 1986 in AISI code w/ K=.43

Method 8:

$$\mu = 1.604\ (w_s/t)\sqrt{f/E} \quad \text{(C.12)}$$

$$\text{if } \mu \le 0.673 \text{ then } \alpha = 1.0 \quad \text{(C.13)}$$

$$\text{else } \alpha = (1-0.22/\mu)/\mu \quad \text{(C.14)}$$

$$D_e = \alpha w_s + (r_1+t/2)\tan(\Theta_c/2) \quad \text{(C.15)}$$

Method 9:

$$\text{If } r_1/t \le 7 \quad \text{use } D_e \text{ of Method 6.} \qquad (C.16\text{-}a)$$

$$\text{If } r_1/t > 7 \quad \text{use } D_e \text{ of Method 7.} \qquad (C.16\text{-}b)$$

For Methods 6,7,8 and 9 the effective moment of inertia of the lip is given by

$$I_s = (D_e)^3 \, t \, \sin^2(\Theta_c) \, / \, 12 \qquad (C.17\text{-}a)$$

For method 10 this moment is given by

$$I_s = (w_s)^3 \, t \, \sin^2(\Theta_c) \, / \, 12 \qquad (C.17\text{-}b)$$ Eq (B4-2)

<u>Step 3. Calculate effective flange width</u>

Section 2.3.3.2 of Reference [4] is applicable here.

Eq B4.2,1

$$\text{If } (w_c/t) \le s/3 \text{ then } w_e = w_c \qquad (C.18)$$ Eq B4,2,3

If $s/3 < (w_c/t) < s$ then:

$$I_a = 399 \, t^4 \, ((w_c/t)/s - 0.33)^3 \qquad (C.19\text{-}a)$$ B4.2-6

$$n = 1/2 \qquad (C.19\text{-}b)$$

If $(w_c/t) \ge s$ then:

$$I_a = (t^4) \, (115 \, (w_c/t)/s + 5.0) \qquad (C.20\text{-}a)$$ Eq B.2-13

$$n = 1/3 \qquad (C.20\text{-}b)$$

1. Case where $I_s < I_a$

The effective length of the stiffener has then to be adjusted as follows

$$\text{Adjusted } D_e = D_e(\text{old}) \, I_s/I_a \qquad (C.21\text{-}a)$$

↑ calculated according to B2.1 using k = .43

$$\text{if } D_s/w_c \le 0.25 \text{ then } k = 3.57\,(I_s/I_a)^n + 0.43 \qquad \text{(C.21-b)}$$ B4.2-10

$$\text{else} \qquad k = (I_s/I_a)^n\,(4.8 - 5\,D_s/w_c) + 0.43 \qquad \text{(C.21-c)}$$ B4.2-9

2. Case where $I_s \ge I_a$

$$\text{If } D_s/w_c \le 0.25 \quad \text{then} \quad k=4.0 \qquad \text{(C.22-a)}$$

$$\text{else} \qquad k = -5\,(D_s/w_c) + 5.25 \qquad \text{(C.22-b)}$$ B4.2-9

Now, using the appropriate vakues of k and f, the effective flange width can be determined as follows

$$\mu = (1.052/\sqrt{k}\,)(w_c/t)\,\sqrt{f/E} \qquad \text{(C.23)}$$ B2.1-4

$$\text{if } \mu \le 0.673 \quad \text{then} \quad \alpha = 1.0 \qquad \text{(C.24-a)}$$ B2.1-1

$$\text{else} \qquad \alpha = (1-0.22/\mu)/\mu \qquad \text{(C.24-b)}$$ B2.1-2, B2.1-3

and the effective flange width is

$$w_e = \alpha\, w_c \qquad \text{(C.25)}$$ (B2.1-2)

Step 4. Determine the effective web depth of the section

Section 2.3.1.3 of Reference [4] is applicable here.

Definition:

f_1 and f_2 are stresses calculated on the basis of effective yield in the section at M_y causing initial yield in the section, (see Figure C.1). f_1 is compression (+), and f_2 can either be tension (-), or compression (+). If both f_1 and f_2 are compression then $f_1 \ge f_2$.

$$\beta = f_2 / f_1 \qquad \text{(C.26)}$$

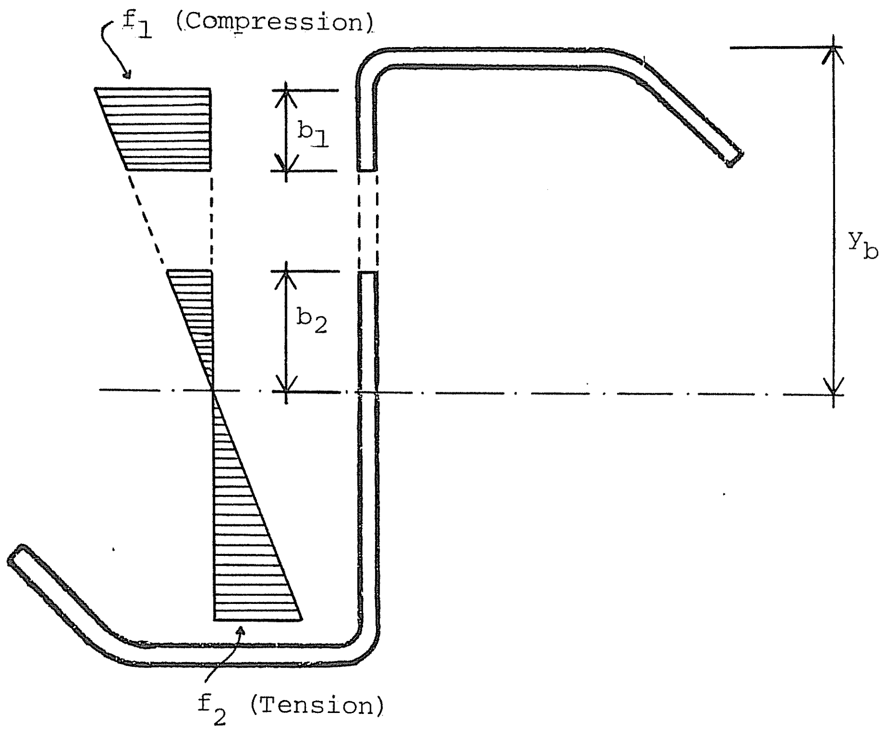


Figure C.1 Effective Web Stresses and Dimensions

$$k = 4 + 2\ (1-\beta)^3 + 2\ (1-\beta) \tag{C.27}$$

$$\mu = (1.052/\sqrt{k})(w_w/t)\ \sqrt{f_1/E} \tag{C.28}$$

where w_w is the flat dimension of the web.

$$\alpha = (1 - 0.22/\mu)/\mu \tag{C.29}$$

If $\mu \leq 0.673$ then the web is fully effective.

Else

$$b_2 = \alpha\ (w_w/2) \tag{C.30}$$

$$b_1 = b_2/(1.5 - 0.5\ \beta) \tag{C.31}$$

b_1+b_2 shall not exceed the compression portion of the web, calculated on the basis of effective section.

Step 5. Determine the moment capacity of the section

i) Assume that the web is fully effective and calculate the effective moment of inertia of the cross section, I_e.

ii) Calculate the ultimate moment capacity of the section as follows

1. Based on first yield at compression fiber:

$$M_c = (I_e/y_b)\ F_y \tag{C.32}$$

2. Based on first yield at tension fiber:

$$M_t = (I_e/(D-y_b))\ F_y \tag{C.33}$$

$$M_u = \min\ (M_c\ ,\ M_t) \tag{C.34}$$

If $M_u = M_t$ then $f = (M_u/I_e)\ y_b$
Revise $s=1.27\ \sqrt{E/f}$ and go back to Step 3.
Else, if $M_u = M_c$ then iterate for b_1 and b_2 as given in Step 4 until convergence.

APPENDIX D

METHOD 11 : CURRENT AISI PROCEDURE

Step 1. Stiffener requirements

$$I_{min} = 1.83\ t^4 \sqrt{(w_c/t)^2 - (4000/F_y)} \geq 9.2\ t^4 \qquad (D.1)\ \text{Eq}(2.3.2\text{-}1)$$

$$I_{prov} = [t\ (D_s)^3\ \ \sin^2(\Theta)]\ /\ 12 \qquad (D.2)$$

Step 2. Design stresses

1. Case where $I_{prov} > 0$ (stiffened flange)

i) If $(w_s/t) \leq 63.3/\sqrt{F_y}$

$$F_b = 0.6\ F_y \qquad (D.3)\ \text{Eq}(3.2\text{-}1)$$

ii) If $(63.3/\sqrt{F_y}) < (w_s/t) \leq (144/\sqrt{F_y})$ and $F_y \geq 33$ ksi

$$F_b = (0.767 - 0.00264\ (w_s/t)\ \sqrt{F_y})\ F_y \qquad (D.4)\ \text{Eq}(3.2\text{-}2)$$

iii) If $(144/\sqrt{F_y}) < (w_s/t) \leq 25$ and $F_y \geq 33$ ksi

$$F_b = 8000\ /\ (w_s/t)^2 \qquad (D.5)\ \text{Eq}(3.2\text{-}3)$$

iv) If $(66.3/\sqrt{F_y}) < (w_s/t) \leq 25$ and $F_y < 33$ ksi

$$F_b = \frac{0.6\ F_y - ((w_s/t) - (66.3/\sqrt{F_y}))(0.6F_y - 12.8)}{25\ (1 - 2.53\ /\ \sqrt{F_y})} \qquad (D.6)\ \text{Eq}(3.2\text{-}4)$$

v) If $25 < (w_s/t) \leq 60$

$$F_b = 19.8 - 0.28\ (w_s/t) \qquad (D.7)\ \text{Eq}(3.2.6)$$

The allowable stress at the web is given by

$$F_{bw} = (1.21 - 0.00034\ (H/t)\sqrt{F_y})\ 0.6F_y \leq 0.6\ F_y \qquad (D.8)\ \text{Eq}(3.4.2\text{-}1)$$

2. Case where $I_{prov} = 0$ (unstiffened flange)

i) If $(w_c/t) \leq 63.3/\sqrt{F_y}$

$$F_b = 0.6\ F_y \qquad (D.9)\ \text{Eq}(3.2\text{-}1)$$

ii) If $(63.3/\sqrt{F_y}) < (w_c/t) \leq (144/\sqrt{F_y})$ and $F_y \geq 33$ ksi

$$F_b = (0.767 - 0.00264\,(w_c/t)\,\sqrt{F_y})\,F_y \qquad \text{(D.10)}$$ Eq (3.2-2)

iii) If $(144/\sqrt{F_y}) < (w_c/t) \le 25$ and $F_y \ge 33$ ksi

$$F_b = 8000 / (w_c/t)^2 \qquad \text{(D.11)}$$ Eq (3.2-3)

iv) If $(66.3/\sqrt{F_y}) < (w_c/t) \le 25$ and $F_y < 33$ ksi

$$F_b = \frac{0.6\,F_y - ((w_c/t) - (66.3/\sqrt{F_y}))(0.6F_y - 12.8)}{25\,(1 - 2.53 / \sqrt{F_y})} \qquad \text{(D.12)}$$ Eq (3.2-4)

v) If $25 < (w_c/t) \le 60$

$$F_b = 19.8 - 0.28\,(w_c/t) \qquad \text{(D.13)}$$ Eq (3.2-6)

The allowable stress at the web is given by

$$F_{bw} = (1.26 - 0.00051\,(H/t)\sqrt{F_y})\,0.6F_y \le 0.6\,F_y \qquad \text{(D.14)}$$ Eq (3.4.2-2)

Step 3. Determine the effective flange width

Assume the stress at the flange is $F = F_b$
This assumption will be revised in a latter stage.

$$(w_c/t)_{lim} = 171 / \sqrt{F} \qquad \text{(D.15)}$$

If $(w_c/t) \le (w_c/t)_{lim}$ then

$$w_e = w_c \qquad \text{(D.16)}$$

If $(w_c/t) > (w_c/t)_{lim}$ then

$$w_e = (253t/\sqrt{F})[1 - 55.3/((w_c/t)\sqrt{F})] \qquad \text{(D.17)}$$ Eq 2.3.1-1

set 2.3.1.1

Step 4. Determine the allowable flexural capacity

If allowable stress is at flange then

$$M_{af} = F_b\,I_e/Y_b \qquad \text{(D.18)}$$

If allowable stress is at web then

$$M_{aw} = F_{bw}\, I_e/(y_b - r_2 - t) \tag{D.19}$$

The allowable moment capacity is given by

$$M_a = \min(M_{af}, M_{aw}) \tag{D.20}$$

Calculate the stress at flange

$$F = M_a\, y_b/I_e \tag{D.21}$$

If F is the same as assumed in Step 3 then the ultimate capacity of the section is given by

$$M_u = 1.67\, M_a \tag{D.22}$$

otherwise, go back to Step 3 using the value of F calculated from Equation D.21 and iterate until convergence.

APPENDIX E

NUMERICAL EXAMPLE

EXAMPLE CALCULATIONS--METHOD 10

Using Method 10, determine the flexural capacity of the cross-section shown in Figure E.1. Use F_y = 65 ksi and E = 29500 ksi.

Step 1. Assume stress at compression flange.

$$f = F_y = 65 \text{ ksi}$$

$$s = 1.27 \sqrt{\frac{29500}{65}} = 27.056 \qquad \text{(Eq. C.1)}$$

Step 2. Calculate effective length of stiffener.

$$D_s = \frac{0.597}{\sin(43)} = 0.875 \text{ in} \qquad \text{(Eq. C.2)}$$

$$W_s = 0.875-(0.4+0.067/2)\ \tan(43/2)=0.704 \text{ in.} \qquad \text{(Eq. C.3)}$$

$$\mu = 1.604\ \left(\frac{0.704}{0.067}\right) \sqrt{\frac{65}{29500}} = 0.791 \qquad \text{(Eq. C.8)}$$

$$\mu > 0.673 \text{ then } \alpha = \frac{1 - 0.22/0.791}{0.791} = 0.913 \qquad \text{(Eq. C.10)}$$

$$D_e = (0.913)\ (0.704) = 0.642 \text{ in.} \qquad \text{(Eq. C.11)}$$

$$I_s = \frac{(0.704)^3\ (0.067)\ \sin^2(43)}{12} \qquad \text{(Eq. C.17-b)}$$

$$= 0.000906 \text{ in.}^4$$

Step 3. Calculate effective flange width.

$$W_c = 2.75 - 0.284 - 0.067 - (0.4 + 0.067/2)\ \tan\ (43/2)$$

$$= 2.23 \text{ in.}$$

$$W_c/t = \frac{2.23}{0.067} = 33.28 > s = 27.056$$

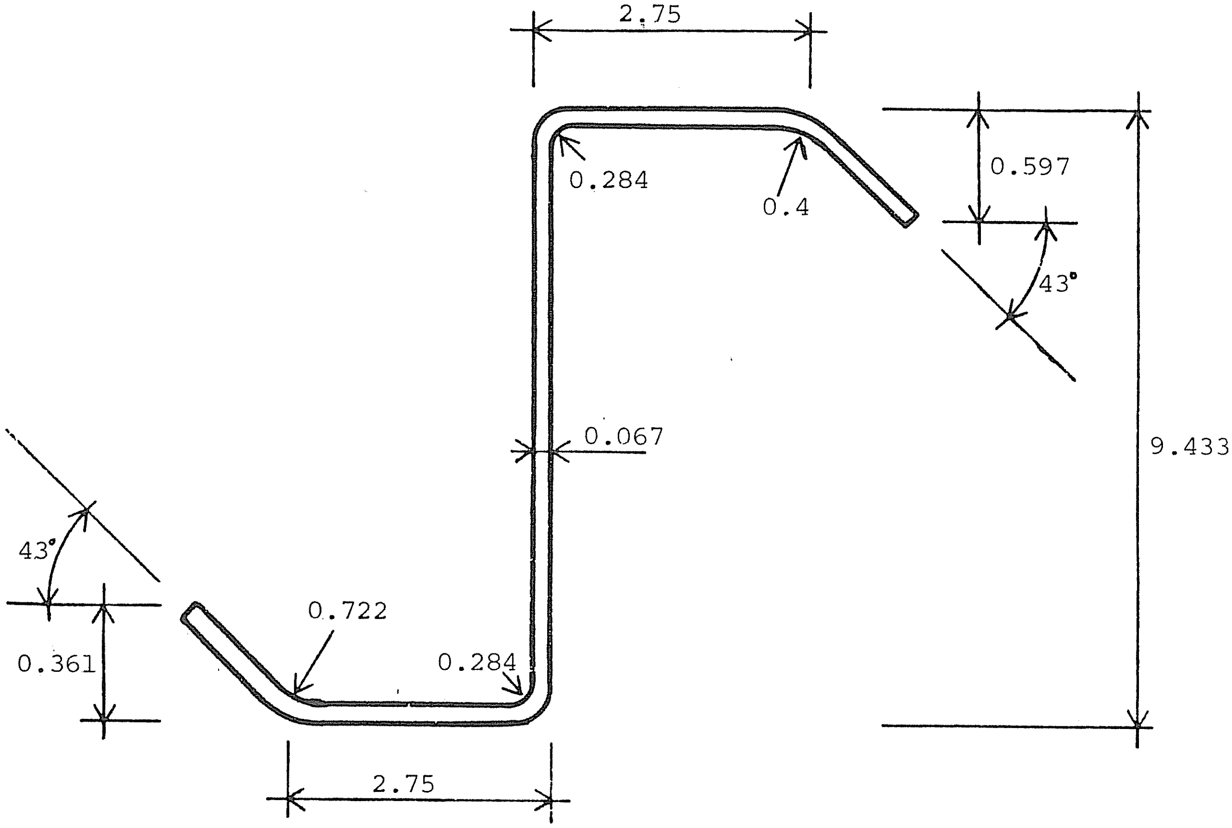


Figure E.1 Cross-Sectional Dimensions

$$I_a = (0.067)^4 \left[115 \left(\frac{33.28}{27.056}\right)+5\right]$$

$$= 0.00295 \text{ in}^4 > I_s \qquad \text{(Eq. C.20-a)}$$

Adjusted effective lip length

$$D_e = 0.642 \frac{0.000906}{0.00295} = 0.31 \text{ in.} \qquad \text{(Eq. C.21-a)}$$

$$k = \left(\frac{0.000906}{0.00295}\right)^{1/3} \left[4.8-5 \left(\frac{0.875}{2.23}\right)\right]+0.43 \qquad \text{(Eq. C.21-C)}$$

$$= 2.34$$

$$\mu = \frac{1.052}{\sqrt{2.34}} (33.28) \sqrt{\frac{65}{29500}} = 1.074 \qquad \text{(Eq. C.23)}$$

$$\mu > 0.673 \text{ then } \alpha = \frac{1 - 0.22/1.074}{1.074} = 0.74 \qquad \text{(Eq. C.24-b)}$$

$$W_e = (0.74)\,(2.23) = 1.65 \text{ in.} \qquad \text{(Eq. C.25)}$$

Step 4. Determine effective web depth.

Assume that web is fully effective and calculate the moment capacity of the section. The effective flange width and effective lip length are used to compute the moment of inertia of the section and the position of the neutral axis.

$$I_x = 12.50 \text{ in.}^4$$

$$\bar{y} = 4.92 \text{ in. (measured from top)}$$

Maximum moment if compression flange yields first:

$$M_c = \frac{12.5}{4.92}\, 65 = 165.1 \text{ kip-in.} \qquad \text{(Eq. C.32)}$$

Maximum moment if tension flange yields first:

$$M_t = \frac{12.5}{9.433-4.92}\, 65 = 180.0 \text{ kip-in.} > M_c \qquad \text{(Eq. C.33)}$$

Compression controls

$$M_u = \min(M_c, M_t) = 165.1 \text{ kip-in.}$$

Stress at top of web (compression)

$$f_1 = \frac{165.1}{12.5} (4.92 - 0.067 - 0.284) = 60.3 \text{ ksi}$$

Stress at bottom of web (tension)

$$f_2 = \frac{165.1}{12.5} = (4.92 - 9.433 + 0.067 + 0.284) = -55.0$$

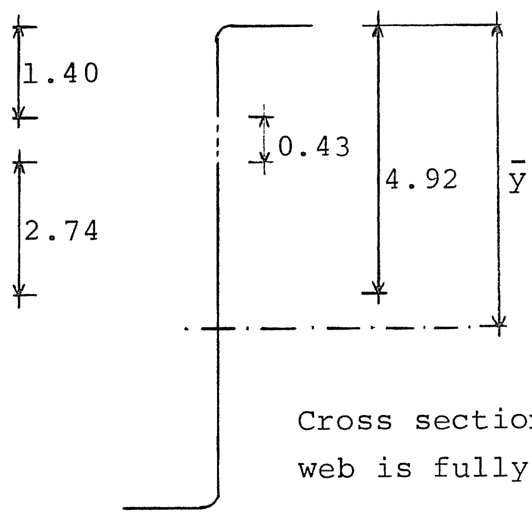
$$\beta = \frac{-55.0}{60.3} = -0.91 \qquad \text{(Eq. C.26)}$$

$$k = 4 + 2\,(1 + 0.91)^3 + 2(1 + 0.91) = 21.8 \qquad \text{(Eq. C.27)}$$

$$\mu = \frac{1.052}{\sqrt{21.8}} \; \frac{9.433-2(0.284+0.067)}{0.067} \sqrt{\frac{60.3}{29500}} = 1.327 \qquad \text{(Eq. C.28)}$$

$\mu > 0.673$ then web is not fully effective.

$$\alpha = \frac{1 - 0.22/1.327}{1.327} = 0.628 \qquad \text{(Eq. C.29)}$$



Cross sectional area assuming web is fully effective $A=0.983 \text{ in.}^2$

$$b_2 = 0.628\left(\frac{9.433-2(0.284+0.067)}{2}\right) = 2.74 \text{ in.} \quad \text{(Eq. C.30)}$$

$$b_1 = \frac{2.74}{1.5-0.5(-0.91)} = 1.40 \text{ in.} \quad \text{(Eq. C.31)}$$

Adjust the moment of inertia and distance to neutral axis.

$$\bar{y} = \frac{(0.983)\ (4.92)-(0.43)\ (0.067)\ (2.0)}{0.983 - 0.0288} = 5.0 \text{ in.}$$

$$I_e = 12.5+0.983(5.0-4.92)^2 - \frac{0.067\ (0.43)^3}{12} - 0.0288(3.035)^2$$

$$= 12.24 \text{ in.}^4$$

Revise the moment capacity.
If compression flange yields first

$$M_c = \frac{12.24}{5.0}\ 65 = 159.1 \text{ kip-in.} \quad \text{(Eq. C.32)}$$

If tension flange yields first

$$M_t = \frac{12.24}{9.433 - 5.0}\ 65 = 179.5 \text{ kip-in.} > M_c \quad \text{(Eq. C.33)}$$

Compression controls

$$\boxed{M_u = \min(M_c,\ M_t) = 159.1 \text{ kip-in}}$$

Revise stresses at top and bottom of web.

f_1 = 60.4 ksi (previous value 60.3 ksi)
f_2 = -53.1 ksi (previous value -55.0 ksi)

Iterations can be carried out until f_1 and f_2 converge to constant values. If this is done by computer, the capacity of the section will be

M_u = 153.4 kip-in.

and the corresponding effective moment of inertia will be

I_e = 12.0 in.^{4}