Directional Stress Indices and Stress Intensification Factors for 90° Elbows (PWRMRP-06)

PWR Materials Reliability Project (PWRMRP)

Directional Stress Indices and Stress Intensification Factors for 90° Elbows (PWRMRP-06)

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REPORT SUMMARY

This report provides equations, based on analyses and test data, for determining the directional stress indices and stress intensification factors (SIFs) for 90° elbows. Present methodologies used to determine these parameters are generally overly conservative. The report contains results of an investigation into the stress intensification factors and directional stress indices of 90° elbows.

Background
Fatigue is a major concern in the design and engineering of piping systems. The ASME Section III Code and ANSI B31 piping design codes use factors such as stress indices and stress intensification factors to account for fatigue effects produced by combined loading and moments.

Objectives
- To determine if the use of directional stress indices and SIFs is appropriate
- To establish a methodology for evaluating directionality effects

Approach
A review of the present approach for the evaluation of 90° elbows in accordance with the ASME and B31 piping design codes provided an understanding of the current methodology. Component tests and finite element analyses (FEAs) were performed on representative elbow configurations. Various methods of combining moments were performed. Results were compared to those generated by the FEAs.

Results
A more accurate method for combining moments was developed and is based on a modified version of the square root sum of the squares (SRSS) approach. Based on the models and loading conditions in this study, it was determined that the expression accounting for directionality in ASME Code Case N-319-2 yielded conservative results as high as 29% according to the FEA results. In contrast, the method used by ANSI B31.3 yielded non-conservative results as high as 49% when compared to FEA.

EPRI Perspective
Design for fatigue is a major concern for any power or process facility. Accurate methods of engineering for fatigue are important for cost-effective design, for root cause failures, and for evaluating remaining fatigue life of plant designs. The work being done under EPRI’s SIF optimization program continues to establish the technical justification to allow for reductions in current Code stress intensification factors. The results of this program can provide a basis to reduce the scope of ongoing pressure boundary component testing inspection programs in

operating nuclear power plants. Examples include reduction in the inspection scope of postulated high- and moderate-energy line break locations and reduction of snubber testing.

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Keywords
ASME Code
Fatigue
Piping design and analysis
Stress intensification factors
Stress indices

ABSTRACT

This report was prepared under the auspices of the EPRI project on Stress Intensification Factor Optimization. The behavior and fatigue life of elbows is a major consideration in the design and evaluation of piping systems. This report presents the results of an investigation of the directional stress intensification for 90° elbows. The investigation included a literature survey, testing program, finite element analysis, comparison of analysis to test results, and recommendations for removing conservatism in evaluating elbows.

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1
INTRODUCTION

The objective of this study was to investigate methodologies and determine if the use of directional stress indices and SIFs are appropriate. Finite element analyses were conducted as a part of this study to develop a moment combination methodology appropriate for elbows. Test data for combined loading serve as a basis for establishing a methodology for evaluating directionality effects.

1.1 Nomenclature

Figure 1-1 shows the configuration and applied moments for the evaluation of stress indices and stress intensification factors for 90° elbows. Table 1-1 lists nomenclature used in this report.

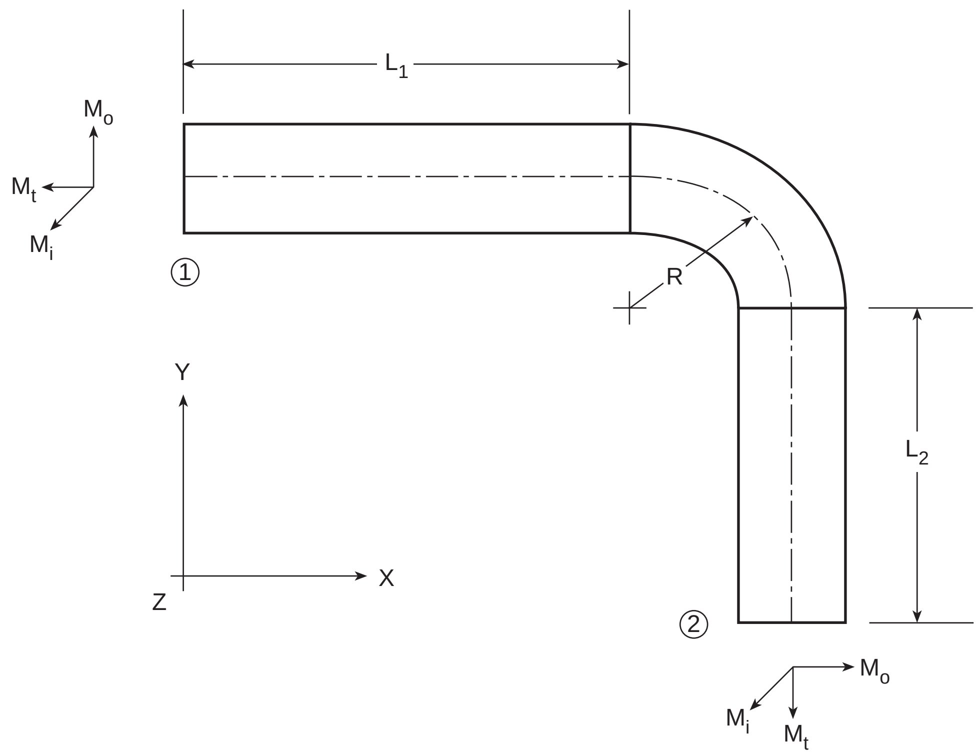


Figure 1-1
90° Elbow Configuration

Table 1-1
Nomenclature

Term	Description
a, b, n	constants used in SQ-SUM(ADJUSTED) methodology to represent stress intensities
A, B, C	constants used to represent load cases, for example, M_i = A M, M_o = B M, M_i = C M
D_o	outside diameter of the elbow or attached pipe
E	Young's modulus
B31.3-EQ17	stress intensity calculated using a method corresponding to the approach used by B31.3 (eq. 2-7)
h	characteristic of the elbow, $h=(t_n/r)(R/r)=t_nR/r^2$
i_i	stress intensification factor for in-plane bending moments
i_o	stress intensification factor for out-of-plane bending moments
i_t	stress intensification factor for torsion moments
G	Bulk modulus
L_1, L_2	attached pipe tangent lengths, in.
M	moment that produces a nominal stress of 10 ksi in the pipe
$M_{i1,}$ M_{i2}	in-plane bending moments, in-lb
M_{o1}, M_{o2}	out-of-plane bending moments, in-lb
M_{t1}, M_{t2}	torsion moments, in-lb
r	mean radius of the elbow or attached pipe, $r = (D_o-t_n)/2$, in.
R	bend radius of the elbow, in.
SQ-SUM	stress intensity calculated using a method which adds torsion and out-of-plane bending effects directly (eq. 2-10)
SQ-SUM (ADJUSTED)	stress intensity using a modified SQ-SUM methodology (eq. 2-12)
SRSS	stress intensity calculated using the "square root-sum of the squares methodology" (eq. 2-6)
S_1, S_2, S_3	stress intensity due to M applied to the pipe as in-plane, out-of-plane and torsion respectively
t_n	wall thickness of the elbow or attached pipe, in.
Z	section modulus, $(in^3) = 0.0982(D_o^4-(D_o-2t_n)^4)/D_o$
r^2	correlation factor squared
ν	Poisson's ratio

1.2 Background

The objective of this study was to investigate methodologies and determine if the use of directional stress indices and SIFs are appropriate. Finite element analyses were conducted as a part of this study to develop a moment combination methodology appropriate for elbows. Test data for combined loading serves as a basis for establishing a methodology for evaluating directionality effects.

At present, the ASME Section III Code [1] defines the SIF for an elbow by the equation:

$$i = 0.9/h^{2/3} \quad \text{(equation 1-1)}$$

where h is defined as the elbow "flexibility characteristic" given by:

$$h = t_n R/r^2 \quad \text{(equation 1-2)}$$

where

t_n = the nominal wall thickness of the elbow (or attached pipe)

R = the bend radius of the elbow or pipe bend

r = the mean radius of the elbow or attached pipe

Stresses at a point j are calculated using the resultant moment:

$$M_j = [M_{xj}^2 + M_{yj}^2 + M_{zj}^2]^{1/2} \quad \text{(equation 1-3)}$$

and the expression:

$$S = iM/Z \quad \text{(equation 1-4)}$$

where

M is given by M_j.

M_{xj}, M_{yj}, and M_{zj} are the moments about the x, y, and z axes at point j.

Z is the section modulus of the attached pipe.

The assumption, which is the focus of this study, is that the SIF given by eq. 1-1 is applicable for all moments (for example, in-plane, out-of-plane, and torsion for the elbow). ANSI B31.1 [2] follows the same approach. However, ANSI B31.3 [3] uses a different methodology that takes into account the directionality of the loading. B31.3 defines SIFs for in-plane loading, i_i which is the same as eq. 1-1. However, for out-of-plane loading, the SIF is defined as:

$$i_o = 0.75/h^{2/3} \quad \text{(equation 1-5)}$$

In B31.3, the stresses used to evaluate thermal expansion are calculated using equation 17 in *Process Piping, B31.3, Power Piping* [3]:

$$S_E = [S_b^2 + 4S_t^2]^{1/2} \quad \text{(equation 1-6)}$$

where S_b is the resultant bending stress given by:

$$S_b = [(i_i M_i)^2 + (i_o M_o)^2]^{0.5} / Z \quad \text{(equation 1-7)}$$

where

M_i = the in-plane bending moment

M_o = the out-of-plane bending moment

S_t = the torsional stress given by $M_t/2Z$ where M_t is the torsional moment

This approach is clearly less conservative than the approach followed by ASME Section III.

The objective of this study is to investigate these methodologies and to determine if the directional SIFs are applicable. This study is limited to 90° bends or elbows with a length of straight pipe welded to both ends such that end effects are precluded (generally considered to be four or more pipe diameters). More significant end effects exist when a flange or another component is attached to the elbow such that the deformation of the elbow is restrained.

1.3 Symmetry

Figure 1-1 shows that, for a 90° elbow, there is a transformation of the out-of-plane and torsional moments at the opposite ends of the elbow. Torsion on one end is resisted by an equal (in magnitude) out-of-plane bending moment at the other end. Out-of-plane bending is resisted by an equal-in-magnitude torsional moment at the other end. In-plane bending is resisted by an equal (but opposite in sign) in-plane bending at the other end.

This is true only for 90° elbows or bends. The response (for example, stresses and deflections) of the elbow to moment M_o at one is the same as the response to the moment M_t at the other. Thus, a 90° elbow has two characteristic response behaviors, not three. The stress intensification factors for out-of-plane bending and torsion should be the same.

1.4 Literature Summary

Many investigations of the behavior of elbows have been reported in the literature. Dodge, Moore, and Rodabaugh [4, 5] discuss a number of these investigations. Markl in 1952 reported the results of tests of various elbows for both in-plane and out-of plane, loading [6]. The tests were performed on a deflection controlled, bending type machine. Various wall thicknesses and bend radii were used in the testing. Markl correlated the test data with the theory proposed by

Beskin [7] and others. Based upon this, he proposed the following expressions for estimating the i-factors for in-plane and out-of-plane bending of an elbow:

$$i_i = 0.9/h^{2/3} \quad \text{(equation 1-8)}$$

$$i_o = 0.75/h^{2/3} \quad \text{(equation 1-9)}$$

These expressions are the same as those used today by many of the piping design codes.

Markl also noted that the test data SIFs corresponded to about one-half the theoretical stress. This is in line with the ASME Section III position that the SIF, i, is given by:

$$i = C_2K_2/2 \quad \text{(equation 1-10)}$$

where

C_2 = the primary plus secondary stress intensity factor

K_2 = the peak stress intensity factor

Code Case N-319-2, provides guidance for evaluating elbows in Class 1 piping considering the directionality of the loads [8]. This approach takes into account the directionality of the loadings and provides separate stress indices for in-plane and out-of-plane/torsional loadings. These are given by:

Out-of-plane/torsion: $C_{2x} = 1.71/h^{0.56}$ (equation 1-11)

In-plane: $C_{2z} = 1.95/h^{2/3}$ (equation 1-12)

Code Case N-319-2 suggests that to calculate stresses for combination of moments, the following equation be used:

$$[(C_{2X}M_x)^2+(C_{2Y}M_y)^2+(C_{2Z}M_z)^2]^{1/2} \quad \text{(equation 1-13)}$$

where

X = out-of-plane loading

Y = torsion

Z = in-plane loading

Equation 1-13 is permitted to be used only if the flexibility factors listed in the Code Case are used in piping system analyses. See Section 2.10 for a discussion of flexibility factors for selected FEA models.

2 FINITE ELEMENT ANALYSIS INVESTIGATION

2.1 Objectives

An elbow lends itself to straightforward analysis by the finite element method. An elbow has no discontinuities and can be modeled with a uniform size finite element mesh. Finite element analyses (FEA) were conducted as a part of this study to develop a moment combination methodology appropriate for elbows. In addition, FEA was performed to investigate elbow flexibility.

2.2 Models

The parameters of the FEA models are shown in Table 2-1. The basic model had an outside diameter of 4.5 in. The thickness was varied in order to investigate the effects of varying D_o/t_n values. The bend radius varied from 4.0 to 18 in.

Table 2-1
Summary of FEA Models

							In-Plane Moment			Out-of-Plane Moment		
Model	D_o	t_n	D_o/t_n	R	r	h	FEA S1	$C_2 = 1.95/h^{2/3}$	% DIF	FEA S2=S3	$C_2 = 1.71/h^{0.56}$	% DIF
1	4.5	0.2370	19.0	6.0	2.13	0.313	4.11	4.23	2.84	2.88	3.28	12.12
2	4.5	0.0446	101.0	6.0	2.23	0.054	13.55	13.67	0.90	7.75	8.78	11.73
3	4.5	0.2370	19.0	4.0	2.13	0.209	5.17	5.54	6.73	3.48	4.11	15.38
4	4.5	0.2370	19.0	12.0	2.13	0.626	2.51	2.66	5.81	2.03	2.22	8.68
5	4.5	0.0446	101.0	4.0	2.23	0.036	17.5	17.92	2.32	10.4	11.02	5.61
6	4.5	0.1185	38.0	6.0	2.19	0.148	6.91	6.96	0.79	4.33	4.98	13.09
7	4.5	0.1185	38.0	4.0	2.19	0.099	8.83	9.13	3.25	5.35	6.25	14.43
8	4.5	0.0446	101.0	18.0	2.23	0.162	6.71	6.57	-2.08	4.81	4.75	-1.36
9	4.5	0.0446	101.0	12.0	2.23	0.108	8.79	8.61	-2.05	5.87	5.96	1.43
10	4.5	0.1185	38.0	12.0	2.19	0.296	4.41	4.39	-0.51	3.21	3.38	5.01
								Maximum Value =	6.73		Maximum Value =	15.38
								Average Value =	1.80		Average Value =	8.61

Notes:

1. FEA results are the maximum stress intensity divided by the nominal bending stress in the pipe.
2. All dimensions are in inches.
3. The expressions for C_2 for in-plane and out-of-plane bending are from Code Case N-319-2.
4. This table was produced on an Excel spreadsheet. The number of significant figures is greater than indicated.

All models were based on 90° bends or elbows. The elbows were attached to equal length straight sections of pipe with a length equivalent to five pipe diameters. (This corresponds to L_1 and L_2 of Figure 1-1.) This represents the case where there are no "end effects" that might exist if there were a flange or other component attached that could affect the deflection (ovalization) of the elbow.

A typical finite element model is shown in Figure 2-1. Approximately 3600 shell elements were used in each model. The material properties used in the analyses are E=30,000,000 psi, G=12,000,000 psi, and ν=0.28. The finite element analyses were conducted with the COSMOS, version 1.75, software from Structural Research and Analysis Corporation.

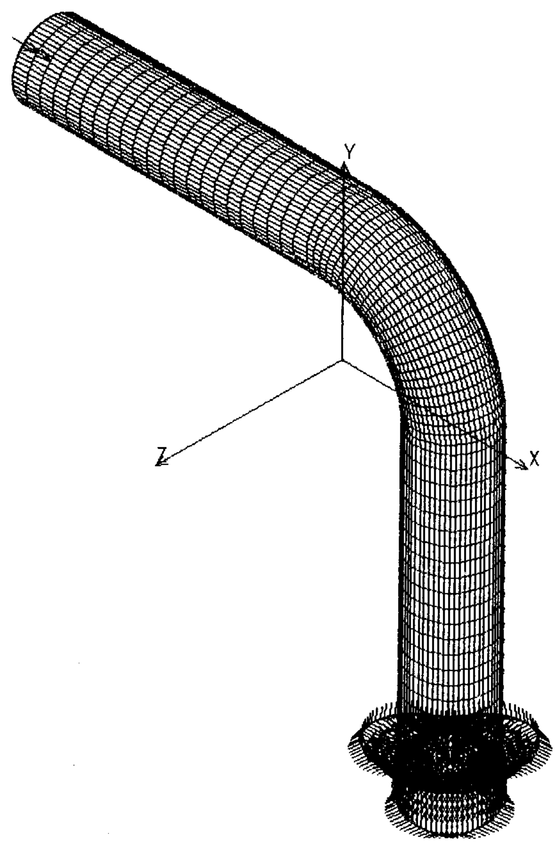


Figure 2-1
FEA Model

One end of the model was fixed and combinations of three orthogonal moments were applied at the other end of the model. Ten configurations were investigated. Twelve load case combinations were applied to each model. Load combinations were selected using the following procedure:

1. The magnitude of the moment was calculated such that the nominal bending stress in a straight pipe would be 10.0 ksi. This moment was defined as "M."

2. This moment was applied at point 1 (Figure 1-1) in the three orthogonal directions, that is, in-plane, out-of-plane, and torsion, corresponding to M_i, M_o, and M_t. The end of the model is

fixed at point 2. The maximum stress intensity from the FEA results for these three cases is delineated as S1, S2, and S3 respectively for each load case. (S1, S2 and S3 are used in the evaluation of the data as described later.) The maximum stress intensities are divided by the nominal stress intensity in the pipe. S1, S2, and S3 are in the form of stress indices and, thus, are independent of the particular choice of E and M. For example, the same S1 would be obtained by using, for example, E = 10e7 psi and M/Z = 1 psi.

3. A series of load cases were defined where:

$$M_i = A\ M \qquad \text{(equation 2-1)}$$

$$M_o = B\ M \qquad \text{(equation 2-2)}$$

$$M_t = C\ M \qquad \text{(equation 2-3)}$$

$$A^2 + B^2 + C^2 = 1.0 \qquad \text{(equation 2-4)}$$

In other words, the magnitude of the applied moment remained constant for all load cases. However, the ratios of in-plane to out-of-plane and torsion were varied.

For each model, five values of the ratio of the torsion moment to the out-of-plane moment (C/B) were selected (0, 0.1, 0.25, 0.5, 1.0). As discussed earlier, the symmetry of a 90° elbow or bend is such that out-of-plane bending at one end of an elbow is the same as torsion at the other end. This symmetry will be considered when the results are evaluated.

For each value of C/B, ten values of A/B, the ratio of the in-plane moment to the out-of-plane moment, were selected (0.0, 0.100, 0.250, 0.500, 0.750, 1.000, 1.333, 2.000, 4.000 and 10.000).

As an example, the results of the analyses for model 1 are listed in Tables 2-2 and 2-3 for these values of C/B and A/B. Because of the volume of data, the results of the other models are not listed in as much detail. A summary of the FEA results is provided in Table 2-6 for all models. See Section 2.9 for the significance of Tables 2-4 and 2-5.

Table 2-2
FEA Summary, Model 1, Combined Loads, C/B = 0 and 0.1

M_{ip} =A*M		M_{op}=B*M		M_t = C*M									
LOAD		In-Plane	Out of-Plane	Torsion	FEA Stress								
CASE	A/B	A	B	C	x104								
LC-1		1	0	0	4.107	= S1							
LC-2		0	1	0	2.884	= S2							
LC-3		0	0	1	2.884	= S3							
COMBINED LOADS, C/B = 0										SQ-SUM			
	A/B	A	B	C	FEA	SRSS	% Dif	SQ-SUM	% Dif	ADJUSTED	% Dif	B31.3-EQ17	% Dif
LC-4	0.1	0.10	1.00	0.00	2.91	2.90	-0.34	2.90	-0.34	2.90	-0.34	2.90	-0.34
LC-5	0.25	0.24	0.97	0.00	2.99	2.97	-0.81	2.97	-0.81	2.97	-0.81	2.97	-0.81
LC-6	0.5	0.45	0.89	0.00	3.20	3.17	-1.01	3.17	-1.01	3.17	-1.01	3.17	-1.01
LC-7	0.75	0.60	0.80	0.00	3.44	3.38	-1.79	3.38	-1.79	3.38	-1.79	3.38	-1.79
LC-8	1	0.71	0.71	0.00	3.63	3.55	-2.23	3.55	-2.23	3.55	-2.23	3.55	-2.23
LC-9	1.333	0.80	0.60	0.00	3.79	3.71	-2.08	3.71	-2.08	3.71	-2.08	3.71	-2.08
LC-10	2	0.89	0.45	0.00	3.97	3.89	-1.94	3.89	-1.94	3.89	-1.94	3.89	-1.94
LC-11	4	0.97	0.24	0.00	4.09	4.05	-1.12	4.05	-1.12	4.05	-1.12	4.05	-1.12
LC-12	10	1.00	0.10	0.00	4.10	4.10	-0.11	4.10	-0.11	4.10	-0.11	4.10	-0.11
						MAX =	-0.11	MAX =	-0.11	MAX =	-0.11	MAX =	-0.11
NOTE:						MIN =	-2.23	MIN =	-2.23	MIN =	-2.23	MIN =	-2.23
COMBINED LOADS, C/B = 0.1										SQ-SUM			
	A/B	A	B	C	FEA	SRSS	% Dif	SQ-SUM	% Dif	ADJUSTED	% Dif	B31.3-EQ17	% Dif
LC-4	0.1	0.099	0.990	0.099	3.09	2.90	-6.29	3.17	2.41	3.10	0.20	2.89	-6.69
LC-5	0.25	0.241	0.966	0.097	3.17	2.97	-6.43	3.22	1.47	3.16	-0.54	2.96	-6.79
LC-6	0.5	0.445	0.891	0.089	3.36	3.16	-5.70	3.37	0.33	3.31	-1.22	3.16	-5.97
LC-7	0.75	0.598	0.797	0.080	3.56	3.37	-5.36	3.53	-1.06	3.49	-2.17	3.37	-5.56
LC-8	1	0.705	0.705	0.071	3.71	3.55	-4.40	3.66	-1.30	3.63	-2.11	3.54	-4.54
LC-9	1.333	0.798	0.599	0.060	3.86	3.71	-3.93	3.79	-1.87	3.77	-2.40	3.71	-4.02
LC-10	2	0.894	0.447	0.045	4.00	3.89	-2.65	3.93	-1.59	3.92	-1.86	3.89	-2.70
LC-11	4	0.970	0.242	0.024	4.11	4.04	-1.54	4.06	-1.25	4.05	-1.32	4.04	-1.55
LC-12	10	0.995	0.099	0.010	4.10	4.10	-0.13	4.10	-0.08	4.10	-0.09	4.10	-0.13
						MAX =	-0.13	MAX =	2.41	MAX =	0.20	MAX=	-0.13
						MIN =	-6.43	MIN =	-1.87	MIN =	-2.40	MIN =	-6.79

Notes: 1. FEA results are the maximum stress intensity divided by the nominal bending stress in the pipe.
2. This table was produced on an Excel spreadsheet. The number of significant figures is greater than indicated.

Table 2-3
FEA Summary, Model 1 Combined Loads, C/B = 0.25, 0.5, and 1.0

COMBINED LOADS, C/B = 0.25										SQ-SUM			
	A/B	A	B	C	FEA	SRSS	% Dif	SQ-SUM	% Dif	ADJUSTED	% Dif	B31.3-EQ17	% Dif
LC-4	0.1	0.097	0.966	0.241	3.31	2.90	-12.45	3.50	5.85	3.37	1.72	2.82	-14.71
LC-5	0.25	0.236	0.943	0.236	3.39	2.97	-12.58	3.53	4.18	3.40	0.38	2.90	-14.63
LC-6	0.5	0.436	0.873	0.218	3.55	3.15	-11.21	3.62	1.95	3.51	-1.08	3.10	-12.78
LC-7	0.75	0.588	0.784	0.196	3.71	3.36	-9.50	3.72	0.25	3.64	-2.03	3.32	-10.64
LC-8	1	0.696	0.696	0.174	3.80	3.53	-7.07	3.81	0.17	3.74	-1.53	3.50	-7.90
LC-9	1.333	0.791	0.593	0.148	3.94	3.70	-6.24	3.89	-1.34	3.84	-2.51	3.68	-6.79
LC-10	2	0.889	0.444	0.111	4.02	3.88	-3.52	3.99	-0.92	3.96	-1.55	3.87	-3.81
LC-11	4	0.968	0.242	0.061	4.13	4.04	-2.12	4.07	-1.39	4.06	-1.56	4.04	-2.20
LC-12	10	0.995	0.099	0.025	4.10	4.10	-0.14	4.10	-0.02	4.10	-0.05	4.10	-0.15
						MAX =	-0.14	MAX =	5.85	MAX =	1.72	MAX=	-0.15
						MIN =	-12.58	MIN =	-1.39	MIN =	-2.51	MIN =	-14.71
COMBINED LOADS, C/B = 0.5										SQ-SUM			
	A/B	A	B	C	FEA	SRSS	% Dif	SQ-SUM	% Dif	ADJUSTED	% Dif	B31.3-EQ17	% Dif
LC-4	0.1	0.089	0.891	0.445	3.56	2.90	-18.73	3.87	8.65	3.63	1.96	2.63	-26.10
LC-5	0.25	0.218	0.873	0.436	3.63	2.95	-18.63	3.88	6.91	3.65	0.63	2.71	-25.41
LC-6	0.5	0.408	0.816	0.408	3.76	3.12	-17.00	3.91	3.97	3.71	-1.27	2.92	-22.37
LC-7	0.75	0.557	0.743	0.371	3.86	3.31	-14.14	3.94	2.25	3.78	-1.92	3.16	-18.18
LC-8	1	0.667	0.667	0.333	3.95	3.48	-11.81	3.98	0.75	3.85	-2.49	3.36	-14.82
LC-9	1.333	0.766	0.575	0.287	4.01	3.65	-9.03	4.01	-0.10	3.92	-2.44	3.57	-11.12
LC-10	2	0.873	0.436	0.218	4.09	3.85	-5.93	4.05	-1.03	4.00	-2.33	3.81	-7.04
LC-11	4	0.963	0.241	0.120	4.10	4.03	-1.76	4.09	-0.31	4.07	-0.70	4.02	-2.08
LC-12	10	0.994	0.099	0.050	4.10	4.09	-0.22	4.10	0.03	4.10	-0.04	4.09	-0.27
						MAX =	-0.22	MAX =	8.65	MAX =	1.96	MAX=	-0.27
						MIN =	-18.73	MIN =	-1.03	MIN =	-2.49	MIN =	-26.10
COMBINED LOADS, C/B = 1.0										SQ-SUM			
	A/B	A	B	C	FEA	SRSS	% Dif	SQ-SUM	% Dif	ADJUSTED	% Dif	B31.3-EQ17	% Dif
LC-4	0.1	0.071	0.705	0.705	3.69	2.89	-21.58	4.08	10.62	3.68	-0.20	2.17	-41.08
LC-5	0.25	0.174	0.696	0.696	3.75	2.93	-21.93	4.08	8.76	3.69	-1.59	2.24	-40.22
LC-6	0.5	0.333	0.667	0.667	3.84	3.04	-20.64	4.08	6.41	3.73	-2.82	2.45	-36.06
LC-7	0.75	0.469	0.625	0.625	3.91	3.19	-18.38	4.08	4.42	3.78	-3.48	2.71	-30.75
LC-8	1	0.577	0.577	0.577	3.98	3.34	-15.99	4.09	2.77	3.83	-3.82	2.95	-25.73
LC-9	1.333	0.686	0.515	0.515	4.04	3.51	-13.13	4.09	1.19	3.89	-3.92	3.23	-20.25
LC-10	2	0.816	0.408	0.408	4.12	3.74	-9.12	4.10	-0.54	3.97	-3.66	3.58	-13.16
LC-11	4	0.943	0.236	0.236	4.16	3.99	-4.03	4.10	-1.28	4.06	-2.30	3.94	-5.26
LC-12	10	0.990	0.099	0.099	4.13	4.09	-0.98	4.11	-0.50	4.10	-0.68	4.08	-1.19
						MAX =	-0.98	MAX =	10.62	MAX =	-0.20	MAX=	-1.19
						MIN =	-21.93	MIN =	-1.28	MIN =	-3.92	MIN =	-41.08

Notes: 1. FEA results are the maximum stress intensity divided by the nominal bending stress in the pipe.
2. This table was produced on an Excel spreadsheet. The number of significant figures is greater than indicated.

Table 2-4
FEA Summary, Model 1 Combined Loads, C/B = 1.5, 2.0, and 4.0

COMBINED LOADS, C/B = 1.5										SQ-SUM			
	A/B	A	B	C	FEA	SRSS	% Dif	SQ-SUM	% Dif	ADJUSTED	% Dif	B31.3-EQ17	% Dif
LC-4	0.1	0.055	0.554	0.831	3.62	2.89	-20.25	4.00	10.43	3.70	2.16	1.81	-49.90
LC-5	0.25	0.137	0.549	0.824	3.68	2.91	-20.90	4.00	8.71	3.71	0.71	1.87	-49.11
LC-6	0.5	0.267	0.535	0.802	3.72	2.99	-19.74	4.01	7.64	3.73	0.18	2.06	-44.79
LC-7	0.75	0.384	0.512	0.768	3.83	3.09	-19.12	4.02	4.94	3.76	-1.69	2.29	-40.06
LC-8	1	0.485	0.485	0.728	3.87	3.21	-16.99	4.02	3.96	3.80	-1.87	2.54	-34.37
LC-9	1.333	0.595	0.446	0.669	3.96	3.37	-14.90	4.04	2.04	3.85	-2.75	2.84	-28.23
LC-10	2	0.743	0.371	0.557	4.02	3.61	-10.22	4.06	0.94	3.93	-2.28	3.28	-18.41
LC-11	4	0.912	0.228	0.342	4.11	3.93	-4.54	4.09	-0.61	4.04	-1.77	3.82	-7.22
LC-12	10	0.984	0.098	0.148	4.15	4.07	-1.78	4.10	-1.07	4.09	-1.28	4.05	-2.25
						MAX =	-1.78	MAX =	10.43	MAX =	2.16	MAX=	-2.25
						MIN =	-20.90	MIN =	-1.07	MIN =	-2.75	MIN =	-49.90
COMBINED LOADS, C/B = 2.0										SQ-SUM			
	A/B	A	B	C	FEA	SRSS	% Dif	SQ-SUM	% Dif	ADJUSTED	% Dif	B31.3-EQ17	% Dif
LC-4	0.1	0.045	0.447	0.894	3.53	2.89	-18.22	3.87	9.63	3.63	2.83	1.58	-55.28
LC-5	0.25	0.111	0.444	0.889	3.58	2.90	-18.93	3.87	8.17	3.64	1.54	1.63	-54.60
LC-6	0.5	0.218	0.436	0.873	3.63	2.95	-18.63	3.88	6.91	3.65	0.63	1.77	-51.11
LC-7	0.75	0.318	0.424	0.848	3.69	3.03	-17.88	3.89	5.53	3.68	-0.27	1.98	-46.34
LC-8	1	0.408	0.408	0.816	3.76	3.12	-16.99	3.91	3.99	3.71	-1.25	2.21	-41.34
LC-9	1.333	0.512	0.384	0.768	3.80	3.25	-14.49	3.93	3.50	3.76	-1.05	2.50	-34.26
LC-10	2	0.667	0.333	0.667	3.95	3.48	-11.87	3.98	0.68	3.85	-2.56	2.98	-24.62
LC-11	4	0.873	0.218	0.436	4.09	3.85	-5.84	4.05	-0.94	4.00	-2.24	3.67	-10.37
LC-12	10	0.976	0.098	0.195	4.15	4.06	-2.19	4.10	-1.25	4.09	-1.51	4.02	-3.02
						MAX =	-2.19	MAX =	9.63	MAX =	2.83	MAX=	-3.02
						MIN =	-18.93	MIN =	-1.25	MIN =	-2.56	MIN =	-55.28
COMBINED LOADS, C/B = 4.0										SQ-SUM			
	A/B	A	B	C	FEA	SRSS	% Dif	SQ-SUM	% Dif	ADJUSTED	% Dif	B31.3-EQ17	% Dif
LC-4	0.1	0.024	0.242	0.970	3.273	2.88	-11.86	3.50	6.87	3.36	2.64	1.20	-63.34
LC-5	0.25	0.061	0.242	0.968	3.289	2.89	-12.15	3.50	6.41	3.36	2.22	1.22	-62.92
LC-6	0.5	0.120	0.241	0.963	3.336	2.91	-12.91	3.51	5.12	3.37	1.05	1.29	-61.45
LC-7	0.75	0.179	0.239	0.954	3.37	2.93	-13.02	3.52	4.41	3.39	0.46	1.39	-58.83
LC-8	1	0.236	0.236	0.943	3.392	2.97	-12.58	3.53	4.19	3.40	0.38	1.51	-55.41
LC-9	1.333	0.308	0.231	0.923	3.443	3.02	-12.26	3.56	3.38	3.44	-0.18	1.70	-50.61
LC-10	2	0.436	0.218	0.873	3.5519	3.15	-11.21	3.62	1.96	3.51	-1.07	2.09	-41.14
LC-11	4	0.696	0.174	0.696	3.7987	3.53	-7.07	3.81	0.17	3.74	-1.53	2.99	-21.40
LC-12	10	0.925	0.092	0.370	4.087	3.95	-3.28	4.02	-1.54	4.01	-1.96	3.82	-6.43
						MAX =	-3.28	MAX =	6.87	MAX =	2.64	MAX=	-6.43
						MIN =	-13.02	MIN =	-1.54	MIN =	-1.96	MIN =	-63.34

Notes: 1. FEA results are the maximum stress intensity divided by the nominal bending stress in the pipe.
2. This table was produced on an Excel spreadsheet. The number of significant figures is greater than indicated.

Table 2-5
FEA Summary, Model 1 Combined Loads, C/B = 10.0, 20.0, and 100.0

COMBINED LOADS, C/B = 10.0										SQ-SUM			
	A/B	A	B	C	FEA	SRSS	% Dif	SQ-SUM	% Dif	ADJUSTED	% Dif	B31.3-EQ17	% Dif
LC-4	0.1	0.010	0.099	0.995	3.0576	2.88	-5.67	3.16	3.24	3.09	0.98	1.04	-66.11
LC-5	0.25	0.025	0.099	0.995	3.0592	2.88	-5.70	3.16	3.21	3.09	0.95	1.04	-65.99
LC-6	0.5	0.050	0.099	0.994	3.06	2.89	-5.63	3.16	3.25	3.09	0.99	1.05	-65.55
LC-7	0.75	0.074	0.099	0.992	3.073	2.89	-5.88	3.16	2.92	3.09	0.69	1.08	-64.95
LC-8	1	0.099	0.099	0.990	3.0929	2.90	-6.29	3.17	2.41	3.10	0.20	1.11	-64.18
LC-9	1.333	0.131	0.099	0.986	3.1169	2.91	-6.65	3.18	1.88	3.11	-0.29	1.16	-62.78
LC-10	2	0.195	0.098	0.976	3.1541	2.94	-6.79	3.20	1.39	3.13	-0.69	1.29	-58.98
LC-11	4	0.370	0.092	0.925	3.295	3.08	-6.52	3.30	0.24	3.25	-1.49	1.80	-45.44
LC-12	10	0.705	0.071	0.705	3.709	3.55	-4.41	3.66	-1.31	3.63	-2.11	2.99	-19.43
						MAX =	-4.41	MAX =	3.25	MAX =	0.99	MAX=	-19.43
						MIN =	-6.79	MIN =	-1.31	MIN =	-2.11	MIN =	-66.11
COMBINED LOADS, C/B = 20.0										SQ-SUM			
	A/B	A	B	C	FEA	SRSS	% Dif	SQ-SUM	% Dif	ADJUSTED	% Dif	B31.3-EQ17	% Dif
LC-4	0.1	0.005	0.050	0.999	2.974	2.88	-3.02	3.02	1.70	2.98	0.27	1.01	-66.06
LC-5	0.25	0.012	0.050	0.999	2.974	2.88	-3.02	3.02	1.70	2.98	0.27	1.01	-66.03
LC-6	0.5	0.025	0.050	0.998	2.977	2.88	-3.09	3.03	1.62	2.98	0.19	1.01	-65.94
LC-7	0.75	0.037	0.050	0.998	2.9778	2.89	-3.08	3.03	1.63	2.98	0.20	1.02	-65.75
LC-8	1	0.050	0.050	0.998	2.9781	2.89	-3.04	3.03	1.66	2.99	0.24	1.03	-65.47
LC-9	1.333	0.066	0.050	0.997	2.9778	2.89	-2.93	3.03	1.75	2.99	0.34	1.04	-64.97
LC-10	2	0.099	0.050	0.994	3.004	2.90	-3.51	3.04	1.10	3.00	-0.30	1.08	-63.92
LC-11	4	0.196	0.049	0.979	3.067	2.94	-4.13	3.07	0.20	3.03	-1.12	1.28	-58.42
LC-12	10	0.447	0.045	0.894	3.278	3.17	-3.41	3.27	-0.27	3.24	-1.22	2.04	-37.62
						MAX =	-2.93	MAX =	1.75	MAX =	0.34	MAX=	-37.62
						MIN =	-4.13	MIN =	-0.27	MIN =	-1.22	MIN =	-66.06
COMBINED LOADS, C/B = 100.0										SQ-SUM			
	A/B	A	B	C	FEA	SRSS	% Dif	SQ-SUM	% Dif	ADJUSTED	% Dif	B31.3-EQ17	% Dif
LC-4	4	0.040	0.010	0.999	2.907	2.89	-0.71	2.91	0.27	2.90	-0.23	1.01	-65.15
LC-5	10	0.099	0.010	0.995	2.928	2.90	-1.00	2.93	-0.04	2.91	-0.53	1.08	-63.25
LC-6	30	0.287	0.010	0.958	3.052	3.00	-1.58	3.03	-0.75	3.02	-1.17	1.52	-50.19
LC-7	60	0.514	0.009	0.857	3.328	3.25	-2.26	3.27	-1.70	3.26	-1.99	2.28	-31.48
LC-8	100	0.707	0.007	0.707	3.6383	3.55	-2.47	3.56	-2.15	3.55	-2.31	2.99	-17.85
LC-9	200	0.894	0.004	0.447	3.9733	3.89	-2.01	3.90	-1.91	3.90	-1.96	3.70	-6.87
LC-10	500	0.981	0.002	0.196	4.0946	4.07	-0.68	4.07	-0.66	4.07	-0.67	4.03	-1.53
LC-11	1000	0.995	0.001	0.100	4.1012	4.10	-0.11	4.10	-0.11	4.10	-0.11	4.09	-0.33
LC-12	10000	1.000	0.000	0.010	4.1086	4.11	-0.04	4.11	-0.04	4.11	-0.04	4.11	-0.04
						MAX =	-0.04	MAX =	0.27	MAX =	-0.04	MAX=	-0.04
						MIN =	-2.47	MIN =	-2.15	MIN =	-2.31	MIN =	-65.15

Notes: 1. FEA results are the maximum stress intensity divided by the nominal bending stress in the pipe.
2. This table was produced on an Excel spreadsheet. The number of significant figures is greater than indicated.

Table 2-6
FEA Results

Mip =A*M   Mop=B*M   Mt = C*M

C/B	A/B	A	B	C	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8	Model 9	Model 10
0	0.100	0.100	0.995	0.000	2.91	8.13	3.55	2.05	10.81	4.43	5.57	4.85	5.94	3.26
	0.250	0.243	0.970	0.000	2.99	8.69	3.74	2.07	11.29	4.62	5.92	4.97	6.20	3.30
	0.500	0.447	0.894	0.000	3.20	10.14	4.07	2.13	13.18	5.10	6.63	5.35	6.78	3.44
	0.750	0.600	0.800	0.000	3.44	11.11	4.34	2.20	14.27	5.57	7.14	5.66	7.38	3.61
	1.000	0.707	0.707	0.000	3.63	11.63	4.63	2.25	14.81	5.93	7.63	5.93	7.78	3.79
	1.333	0.800	0.600	0.000	3.79	12.45	4.83	2.33	15.89	6.29	8.08	6.20	8.04	3.99
	2.00	0.894	0.447	0.000	3.97	13.26	5.03	2.42	17.03	6.58	8.43	6.38	8.41	4.19
	4.00	0.970	0.243	0.000	4.09	13.72	5.20	2.49	17.67	6.82	8.68	6.65	8.78	4.38
	10.00	0.995	0.100	0.000	4.10	13.70	5.18	2.52	17.70	6.92	8.83	6.73	8.84	4.42
0.1	0.100	0.099	0.990	0.099	3.09	8.78	3.81	2.13	11.63	4.74	6.00	5.03	6.25	3.40
	0.250	0.241	0.966	0.097	3.17	9.33	3.98	2.15	12.03	4.93	6.34	5.17	6.40	3.45
	0.500	0.445	0.891	0.089	3.36	10.51	4.26	2.20	13.72	5.32	6.93	5.47	6.98	3.56
	0.750	0.598	0.797	0.080	3.56	11.44	4.52	2.26	14.76	5.77	7.42	5.78	7.47	3.72
	1.000	0.705	0.705	0.071	3.71	11.94	4.74	2.30	15.27	6.02	7.76	5.98	7.87	3.89
	1.333	0.798	0.599	0.060	3.86	12.49	4.92	2.37	16.00	6.38	8.20	6.25	8.13	4.04
	2.00	0.894	0.447	0.045	4.00	13.31	5.07	2.44	17.11	6.65	8.52	6.43	8.41	4.23
	4.00	0.970	0.242	0.024	4.11	13.76	5.22	2.49	17.74	6.83	8.69	6.66	8.80	4.38
	10.00	0.995	0.099	0.010	4.10	13.72	5.19	2.52	17.73	6.93	8.84	6.74	8.85	4.43
0.25	0.100	0.097	0.966	0.241	3.31	9.59	4.14	2.23	12.69	5.12	6.53	5.23	6.61	3.57
	0.250	0.236	0.943	0.236	3.39	10.11	4.28	2.25	13.06	5.30	6.85	5.41	6.74	3.63
	0.500	0.436	0.873	0.218	3.55	10.91	4.49	2.29	14.34	5.61	7.29	5.59	7.18	3.75
	0.750	0.588	0.784	0.196	3.71	11.83	4.73	2.33	15.36	6.00	7.75	5.91	7.53	3.87
	1.000	0.696	0.696	0.174	3.80	12.31	4.86	2.37	15.84	6.21	7.94	6.04	7.95	4.01
	1.333	0.791	0.593	0.148	3.94	12.54	5.03	2.42	16.06	6.46	8.32	6.30	8.22	4.10
	2.00	0.889	0.444	0.111	4.02	13.33	5.11	2.46	17.18	6.73	8.63	6.49	8.42	4.28
	4.00	0.968	0.242	0.061	4.13	13.80	5.25	2.50	17.81	6.83	8.69	6.66	8.81	4.39
	10.00	0.995	0.099	0.025	4.10	13.75	5.20	2.52	17.76	6.93	8.84	6.74	8.86	4.43
0.5	0.100	0.089	0.891	0.445	3.56	10.46	4.49	2.33	13.81	5.55	7.11	5.43	6.96	3.74
	0.250	0.218	0.873	0.436	3.63	10.94	4.60	2.35	14.15	5.69	7.41	5.61	7.07	3.82
	0.500	0.408	0.816	0.408	3.76	11.31	4.76	2.38	14.90	5.98	7.62	5.74	7.42	3.91
	0.750	0.557	0.743	0.371	3.86	12.15	4.94	2.41	15.90	6.22	8.08	5.98	7.63	4.03
	1.000	0.667	0.667	0.333	3.95	12.64	5.03	2.44	16.38	6.43	8.28	6.15	7.93	4.12
	1.333	0.766	0.575	0.287	4.01	12.89	5.13	2.46	16.55	6.52	8.40	6.30	8.26	4.21
	2.00	0.873	0.436	0.218	4.09	13.27	5.22	2.49	17.14	6.74	8.74	6.54	8.45	4.32
	4.00	0.963	0.241	0.120	4.10	13.83	5.28	2.52	17.88	6.82	8.74	6.65	8.80	4.39
	10.00	0.994	0.099	0.050	4.10	13.79	5.22	2.52	17.82	6.93	8.84	6.75	8.87	4.44
1	0.100	0.071	0.705	0.705	3.69	10.89	4.69	2.38	14.41	5.77	7.39	5.50	7.09	3.82
	0.250	0.174	0.696	0.696	3.75	11.30	4.74	2.38	14.72	5.84	7.65	5.65	7.20	3.88
	0.500	0.333	0.667	0.667	3.84	11.70	4.91	2.42	14.87	6.13	7.89	5.77	7.47	3.97
	0.750	0.469	0.625	0.625	3.91	11.91	4.97	2.45	15.77	6.25	8.07	5.96	7.74	4.08
	1.000	0.577	0.577	0.577	3.98	12.52	5.10	2.47	16.41	6.43	8.35	6.08	7.84	4.13
	1.333	0.686	0.515	0.515	4.04	12.95	5.16	2.49	16.80	6.60	8.50	6.24	8.15	4.22
	2.00	0.816	0.408	0.408	4.12	13.12	5.27	2.51	16.79	6.73	8.68	6.47	8.43	4.28
	4.00	0.943	0.236	0.236	4.16	13.78	5.28	2.53	17.84	6.89	8.85	6.62	8.75	4.39
	10.00	0.990	0.099	0.099	4.13	13.84	5.29	2.52	17.89	6.93	8.83	6.74	8.88	4.44

Notes:

1. FEA results are the maximum stress intensity divided by the nominal bending stress in the pipe.
2. This table was produced on an Excel spreadsheet. The number of significant figures is greater than indicated.

2.3 Analysis of Results

Tables 2-2 and 2-3 list the results of the FEA for model 1. Load cases LC-1, LC-2, and LC-3 represent the response to in-plane, out-of-plane and torsion moments. As stated earlier, these results are defined as S1, S2, and S3 respectively. For each of the six values of C/B, there are eight load cases (LC-4 to LC-12). The values of A, B, and C are also listed. The column listed as "FEA" is the maximum stress intensity corresponding to the loads of the particular load case. Note that in all cases, LC-2 is equal to LC-3. This is due to the symmetry of 90° elbows discussed earlier.

To check results, the values of S1, S2, and S3 for all of the models were compared to the "secondary" stress indices as defined in Code Case N-319-2 [8]. The differences were very small (see Table 2-1); the average difference for in-plane bending was 1.8% and 8.6% for out-of-plane or torsion. The maximum differences were 6.7% and 15.4%. This served to verify the results.

By using eq. 2-4, the magnitude of the applied moment was kept constant. Load cases 1 to 3 are defined in COSMOS as "primary load cases. " The other load cases are defined as "secondary" and are obtained by scaling and superposing the results of the primary cases. (These definitions should not be confused with primary and secondary stresses, defined in ASME Section III). This uses the principal of superposition and thus is valid only for linear analysis. For in-plane bending (LC-1), the stress distribution is symmetric about the x-y plane (Figure 1-1). However, the stress distribution for out-of-plane bending and torsion are not symmetrical about the x-y plane. Thus, the results of a moment vector defined by the parameters A, B, and C may not have the same local stress results as the moment defined by A, -B, and C, even though the magnitude of the moment is equal. For example,

$$(A^2+B^2+C^2)^{1/2} = (A^2+(-B)^2+C^2)^{1/2} \qquad \text{(equation 2-5)}$$

In investigating this, the maximum stress intensity for various load combinations where the signs of the moment components were varied were determined for model 1 listed in Table 2-2. From this study, it is concluded that the following sets of load multipliers will yield the same results:

Set 1: (+A, +B, +C), (+A,-B, -C), (-A, +B, +C), (-A, -B, -C)

Set 2: (+A, -B, +C), (+A, +B, -C), (-A, -B,+C), (-A,+B, -C)

Within each set, the maximum stress intensities were essentially identical. The stress intensity obtained from Set 2 is less than that derived from Set 1.

In order to be conservative, the combination method will always follow that of Set 1.

2.4 Combination Methodologies

In order to evaluate existing and potential new methods of combining the effects of different moments, various combination methods were investigated. The methods considered are discussed in the following sections. Tables 2-2 through 2-5 contain detailed comparisons of the

FEA and the various combination methodologies discussed in the following sections for model 1. Table 2-7 contains a summary for other models investigated.

2.5 SRSS Combination Methodology

The values listed in the SRSS column in Tables 2-2 through 2-5 and 2-7 uses the “square root sum of the squares methodology. ” This approach uses the FEA results for the pure in-plane, out-of-plane, and torsion as a basis for evaluating the effects of various combinations. SRSS is calculated using:

$$SRSS = ((A*S1)^2+(B*S2)^2+(C*S3)^2)^{1/2} \qquad \text{(equation 2-6)}$$

A review of the tables indicates that for the models investigated, for the case with no torsion (C=0), the maximum percentage difference between the FEA and SRSS results occurs in model 5 and is 7.8%. The average percentage difference for all the models is small, only a few percent.

However, when torsion is included (for example, C/B is greater than 0), the percentage difference increases to a maximum of -29.3% (Test 2) and an average of about 7.69%. The standard deviation is 7.05%, and the correlation factors squared is r^2 = 0.973. (See Table 2-7.)

Table 2-7
Summary of FEA and Expressions—Percentage Difference from FEA Results

	Combination Methodology	SRSS	SQ-SUM	SQ-SUM (ADJUSTED)	B31.3-EQ17
Model 1	Maximum	21.9	2.23	3.92	41.1
	Minimum	0.108	-10.6	-1.96	0.108
	Average	7.46	-1.05	1.38	10.3
Model 2	Maximum	29.3	9.17	11.5	48.6
	Minimum	1.40	-0.748	1.40	1.40
	Average	11.1	4.04	6.07	13.8
Model 3	Maximum	25.6	4.85	8.05	45.0
	Minimum	0.573	-4.99	0.573	0.57
	Average	9.81	1.80	4.09	12.6
Model 4	Maximum	14.7	0.669	0.669	32.6
	Minimum	-1.29	-20.4	-9.41	-1.29
	Average	4.58	-5.17	-2.39	7.39
Model 5	Maximum	27.5	7.8	9.76	48.1
	Minimum	1.43	-2.17	1.43	1.43
	Average	10.1	2.78	4.89	12.9
Model 6	Maximum	24.8	2.98	7.20	45.1
	Minimum	0.426	-6.00	0.0780	0.426
	Average	8.28	0.486	2.72	11.1
Model 7	Maximum	28.3	6.42	10.4	47.4
	Minimum	0.190	-2.37	-0.002	0.19
	Average	9.88	2.48	4.60	12.6
Model 8	Maximum	13.8	2.06	2.06	36.5
	Minimum	0.0648	-23.5	-11.4	0.0648
	Average	4.56	-4.66	-2.02	7.99
Model 9	Maximum	17.0	4.31	4.31	40.1
	Minimum	0.715	-17.1	-6.28	0.715
	Average	6.17	-2.44	0.0283	9.40
Model 10	Maximum	16.3	1.04	1.04	37.3
	Minimum	-2.00	-18.9	-8.19	-2.00
	Average	4.87	-4.25	-1.64	8.04
All Models	Maximum	29.3	9.17	11.5	48.6
	Minimum	-2.00	-23.5	-11.4	-2.00
	Average	7.69	-0.598	1.77	10.6
	STDEV=	7.05	5.21	3.87	11.4
	r^2 =	0.973	0.995	0.996	0.932

Notes:

1. The Maximum, Minimum, Average, and STDEV are calculated from the % differences between the FEA results and the specific combination methodology. The r^2 is based on a comparison between the FEA and combination methodology calculation.
2. This table was produced on an Excel spreadsheet. The number of significant figures is greater than indicated.

2.6 B31.3-EQ17 Combination Methodology

As discussed earlier, in B31.3 the expression (equation 17 of B31.3) used to evaluate thermal expansion stresses is:

$$S_E = [S_b^2+4S_t^2]^{1/2} \quad \text{(equation 2-7)}$$

where S_b is the resultant bending stress given by:

$$S_b = [(i_iM_i)^2+(i_oM_o)^2]/Z \quad \text{(equation 2-8)}$$

and S_t is the torsional stress given by $M_t/2Z$.

Here, the stresses due to torsion are not intensified. In order to evaluate this approach to combining the effects of the different moments, the equivalent representation would be (using B31.1-EQ17 to represent this approach):

$$\text{B31.1-EQ17} = ((A*S1)^2+(B*S2)^2+(C)^2)^{1/2} \quad \text{(equation 2-9)}$$

The assumption for eq. 2-9 is that A*S1 and B*S2 correspond to an “intensified” stress due to in-plane and out-of-plane moments, where A and B are related to the magnitude of the moment. For torsion, instead of using S3 in the calculations, it is replaced by the value 1.0 (for example, not intensified).

In Tables 2-2, 2-3 and 2-7, the B31.1-EQ17 column lists the values calculated using this approach. The maximum percentage difference is 48.7, the average is 10.6%, the standard deviation is 11.5%, and r^2 = .932. The maximum difference was for model 2, C/B = 1.0, LC-4.

2.7 SQ-SUM Combination Methodology

In this formulation, the effects from the out-of-plane and torsion were added directly. The result would then be “square root sum of the squares” with the in-plane bending effects. The representation is:

$$\text{SQ-SUM} = ((A*S1)^2+(B*S2+C*S3)^2)^{1/2} \quad \text{(equation 2-10)}$$

These results are listed in Tables 2-2 through 2-5 and 2-7. The maximum percentage difference is 23.5% for model 8 which has R = 18 in. The average of the maximum differences for all of the 10 models is -0.58%, the standard deviation is 5.2%, and r^2 = .995.

2.8 SQ-SUM (ADJUSTED) Combination Methodology

This approach is very similar to the SQ-SUM approach except the following adjustment factor is added:

$$a+b(C/B)^n \quad \text{(equation 2-11)}$$

where a, b and n are constants and C/B is the ratio of the magnitude of the torsion to the out-of-plane bending moment at the end of the elbow. The expression is

$$\text{SQ-SUM (ADJUSTED)} = ((A*S1)^2+(a+b(C/B)^n)*(B*S2+C*S3)^2)^{1/2} \qquad \text{(equation 2-12)}$$

If C/B > 1, replace C/B with B/C; see Section 2.9.

The results are also listed in Tables 2-2, 2-3 and 2-7. For the values of the constants given by:

a = 1.0 (equation 2-13)
b = -0.187
n =0.635

the maximum percentage difference is 11.5%, the average of the maximum differences for each of the 10 models is 1.8%, the standard deviation is 0.387, and r^2 is .996.

2.9 Conditions When C/B ≥ 1.0 for SQ-SUM (ADJUSTED) Methodology

The FEAs discussed earlier were for the condition where the applied out-of-plane bending moment was greater than or equal to the torsional moment, for example, C/B ≤ 1.0. Because of the symmetry of the 90° elbow and considering that the torsion on one end results in equal out-of-plane bending on the other (and vice versa) if C/B ≥ 1.0 at the end being evaluated, the same expression can be used to predict the stress intensity by replacing C/B with B/C. In order to confirm this, additional runs were made for model 1. The results are listed in Tables 2-4 and 2-5. The additional cases were for C/B equal to 1.5, 2.0. 4.0, 10.0, 20.0 and 100.0. For C/B equal to 100, the values of A/B were taken to be 4, 10, 30, 60, 100, 200, 500, 1000, and 10,000. The maximum percentage difference for the SQ-SUM (ADJUSTED) combination methodology was 2.84%, which confirms the methodology of using B/C for C/B when C/B ≥ 1.0.

2.10 Elbow Flexibility

Piping system design is based on an analytical determination of displacements, rotations, moments, and reaction forces at various positions along a piping system. The analysis is based on a description of the piping system as an interconnected set of straight and curved beams. Flexibility factors are introduced into the analytical model to correct for the differences in structural behavior between the beam model and the piping system components that make up the real piping system. Adequate characterization of the flexibility of piping components is essential to correctly estimating pipe stresses and support loads. Properly modeling the flexibility of an elbow is at least as significant as the accurate determination of stress intensification factors for the elbows.

The flexibility of an elbow as defined by the Code [1] is 1.65/h, where h is equal to tR/r^2. As stated previously, when using Code Case N-319-2, the flexibility factors provided in the Code Case must be used in pipe stress evaluations. The Code Case uses:

k_y = 1.25/h when the internal pressure is equal to zero. (equation 2-14)

k_z = 1.3/h when internal pressure is equal to zero. (equation 2-15)

Tables 2-8 and 2-9 show the results of FEA analysis of elbow flexibility for four cases with h ranging from .66 to 0.06. The basic model was for D_o = 10 in. (25.4 cm). The equations used in the tables to calculate the flexibility factors from the FEA deflection results were obtained from [5], which gives the background for Code Case N-319-2. The results as calculated from the Code Case equations are also included. These values are close. As can be seen from the tables, the magnitude of the elbow flexibility factors can be significant, especially for thin wall systems.

Table 2-8
In-Plane Flexibility Calculations

Case	t	Ux	Uy	Rz	k_{xz}	k_{yz}	k_{zz}	h	1.3/h
1	0.909	-1.09E-01	-3.52E-01	8.98E-03	2.31	2.15	2.17	0.660	1.97
2	0.196	-2.01E-01	-1.15E+00	2.49E-02	12.48	12.20	12.2	0.122	10.6
3	0.091	-3.11E-01	-2.15E+00	4.50E-02	25.33	25.01	25.0	0.061	21.5
4	0.530	-1.28E-01	-5.05E-01	1.20E-02	4.20	4.01	4.04	0.355	3.67

Notes:

1. My = In-plane moment
2. $k_x = [-\delta_x/(M/EI) - 0.5L^2 - 0.707RL]/(0.571R^2)$
3. $k_y = [-\delta_y/(M/EI) - 1.5L^2 - RL]/[R(1.571L + R)]$
4. $k_z = [\theta_z/(M/EI) - 2L] /(1.571R)$
5. $E = 3*10^7$ psi
6. $I = 0.0491*(D_o^4-(D_o-t_n)^4)$
7. R = 15 in., D_o =10 in.
8. $L = 4*(D_o-t_n)$

Table 2-9
Out-of-Plane Flexibility Calculations

Case	Uz	Rx	Ry	k_{xy}	k_{yy}	k_{zy}	h	1.25/h
1	3.56E-01	5.40E-04	8.92E-03	2.29	2.03	2.04	0.66	1.89
2	7.53E-01	6.39E-03	1.62E-02	13.8	11.3	11.8	0.12	10.2
3	1.24E+00	1.37E-02	2.55E-02	28.4	23.1	24.3	0.06	20.6
4	4.35E-01	1.67E-03	1.03E-02	4.48	3.73	3.86	0.35	3.53

Notes:

1. My = out-of-plane moment
2. $k_x = [\theta_x/(M/EI) + 0.65R]/(0.5R)$
3. $k_y = [\theta_y/(M/EI) - 2.3L - 1.021R]/(0.785R)$
4. $k_z = [\delta_z/(M/EI) - 1.8L^2-2.321RL-0.65R^2] /[R(0.7854L+0.5R)]$
5. $E = 3*10^7$ psi
6. $I = 0.0491*(D_o^4-(D_o-t_n)^4)$
7. R = 15 in., D_o =10 in.
8. $L = 4*(D_o-t_n)$

2.11 Elbow Characteristic "h" Effects

As indicated in Table 2-1, the FEA models used in the evaluation of the methods of combing the effects of different loading conditions had a range of elbow characteristics from 0.036 to 0.626. In order to investigate the effects of h, additional FEA was performed on additional models.

Three models with h values of 0.500, 0.637, and 0.809 were studied. The results are summarized in Table 2-10. As before, the percentage differences from the FEA to the different methods are listed. The results are similar to those listed in Table 2-4.

Table 2-10
Characteristic "h" Effects—Percentage Difference from FEA Results

Model	Do	T	R	h		Expression SRSS	SQ-Sum	SQ- SUM ADJUSTED	B31.3-EQ17
11	4.5	0.531	6	0.809	Maximum	0.53	30.43	17.64	-1.52
					Minimum	-10.2	-9.68	-9.68	-27.5
					Average	-6.93	3.69	0.66	-9.9
12	4.5	0.5	4	0.500	Maximum	-2.77	20.94	9.09	-2.77
(TOP)					Minimum	-17.0	-13.1	-13.1	-34.8
					Average	-11.2	-4.05	-6.21	-14.0
13	4.5	0.438	6	0.637	Maximum	-0.40	27.7	15.2	33.0
(TOP)					Minimum	-10.1	-6.61	-6.61	-28.9
					Average	-4.72	5.7	2.72	-7.81
13	4.5	0.438	6	0.637	Maximum	3.71	16.4	5.32	3.48
(BOTTOM)					Minimum	-17.6	-5.48	-5.48	-33.9
					Average	-6.58	2.66	0.016	-9.11

It was noted that the maximum stresses were located differently than for the models with lower values of h. In general for thin wall elbows, the maximum stress is on the inside of the elbow. However, for thicker elbows, it can be on the outside. The results in Table 2-4 are the "worst case" results from the inside and outside surfaces.

In addition, model 13 was analyzed using thick shell elements to determine if this had any effects. The maximum difference in S1, S2, or S3 was less than 2%.

From this evaluation, it is deemed that the methodology suggested in Section 2.8 is valid for values of h ≤ 0.8.

3
TEST PROGRAM

3.1 Purpose

The purpose of this test program was to obtain some specific data which would provide insight into the effects of the direction of the loading. As discussed earlier, the SIFs presently used are based on both in-plane and out-of-plane tests performed by Markl [6]. However, there are no published results on tests where the loading is a combination of these conditions. Test data for combined loading would serve as a basis for establishing a methodology for evaluating directionality effects.

3.2 Design of Test Specimens

The test specimens consisted of 4 in. NPS schedule 40, A106, GrB long radius elbows. Eight specimens were fabricated by Energy Northwest. Two specimens were fabricated and tested for in-plane bending, two for out-of-plane bending, and four for bending at a 45° angle. While the focus of this investigation is for loadings that are not strictly in-plane or out-of-plane, the tests for in-plane and out-of-plane loads would provide a benchmark for the tests in general.

The effect of the configuration at a 45° is that the loading is equivalent to a combined in-plane and out-of-plane moment loading where the moments are equal. This loading condition is designated “combined 45°” loading.

Figure 3-1 has schematics of the three test configurations. Figure 3-2 shows photographs of the actual test setups.

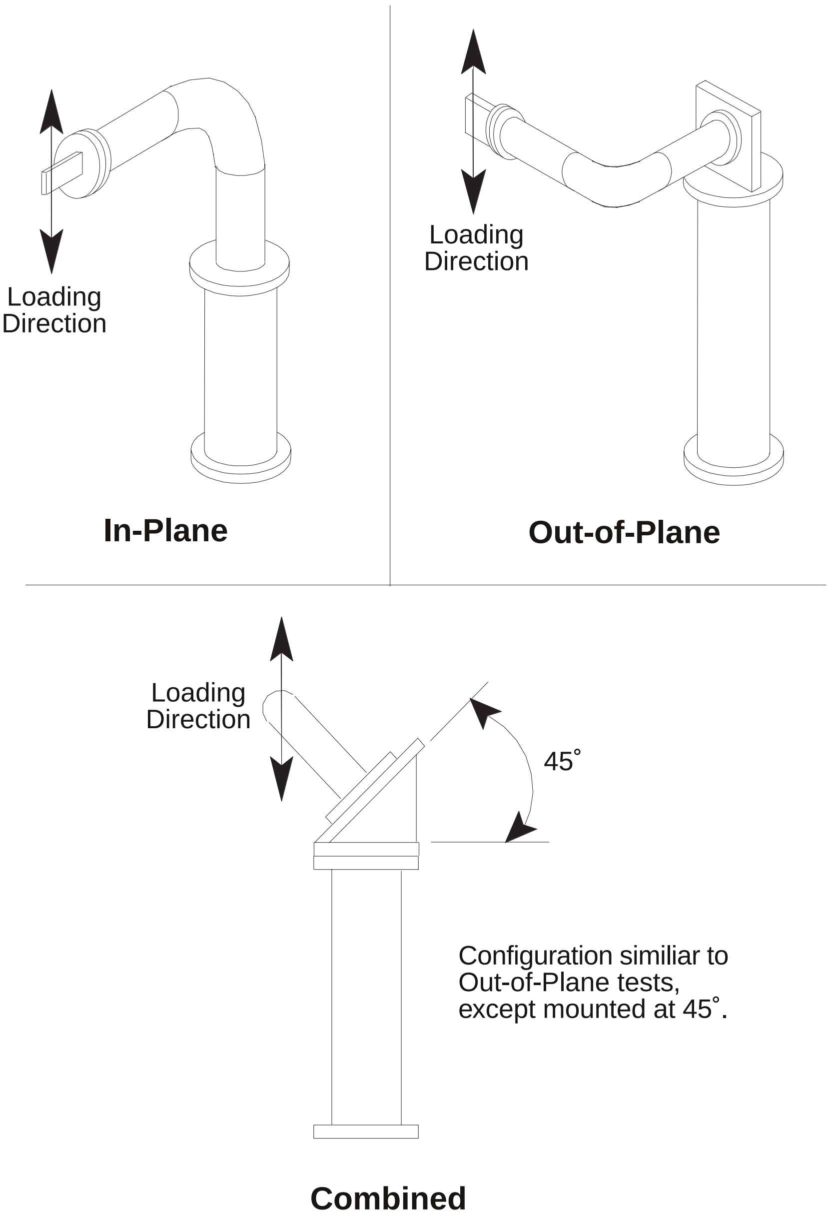
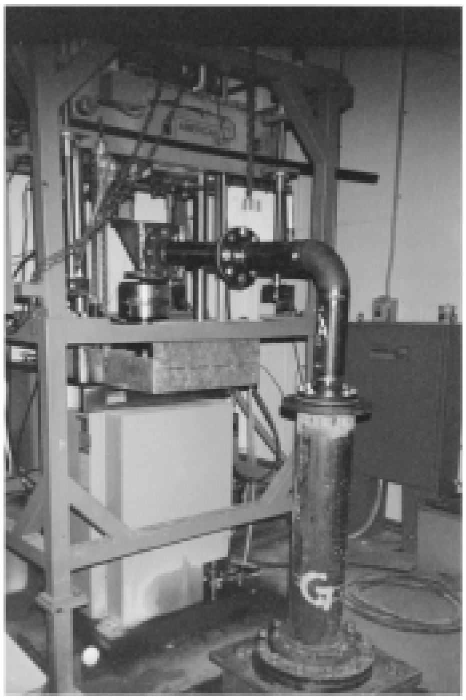
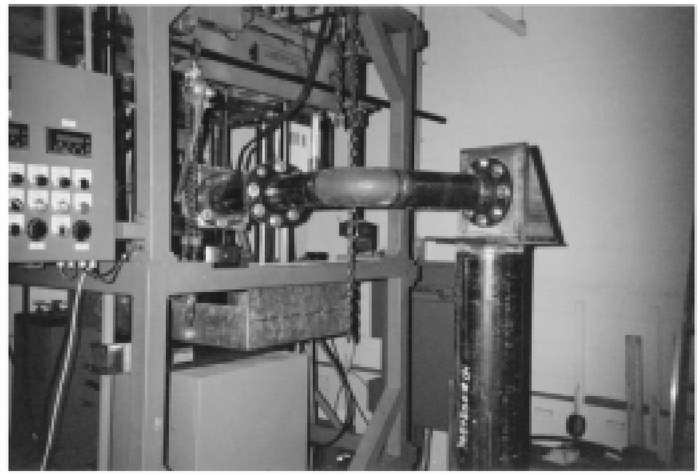


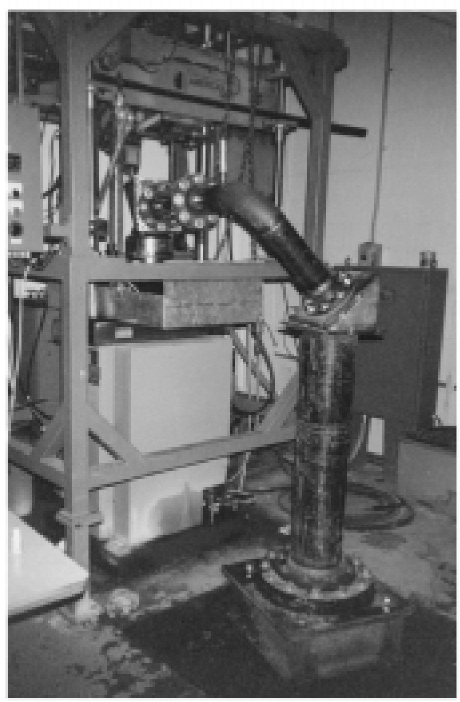
Figure 3-1
Testing Configuration



(a) In-Plane Bending



(b) Out-of-Plane Bending



(c) Combined (45°) Bending

Figure 3-2
Test Setups

3.3 Testing Program

Testing was performed at Ohio State University. The fatigue tests were performed on an MTS Systems Corporation Series 319 dynamically rated Axial/Torsional Load Frame. This unit is designed to accommodate either uniaxial or multiaxial testing. Load Frame capacities are 55,000 lb axial force and 20,000 in-lb torsional moment. A computerized control panel provides local, precise operations of the cross head, hydraulic grips, and actuator. The maximum actuator displacement is six inches. The loading pattern applied to an attached sample is controlled by programmable servo valves.

Built-in loading programs include sinusoidal and triangular waves with the user being able to select, within machine limits, the desired amplitude and frequency. The actual displacement of the actuator is measured by a linear variable differential transformer (LVDT). The output of either the load cell or the LVDT can be selected for closed loop control of the actuator displacement time history. During a test, the number of cycles of applied load is recorded by a digital counter and displayed on the MTS console.

In these tests, the load was sinusoidal at frequencies ranging from 0.3 to 0.5 Hz. Actuator displacement was designated as the test control variable. The selection of displacement as the control parameter meant that actuator movement was used by the MTS system for feedback in the closed loop controls. This resulted in virtually identical cycles of actuator displacement being recorded throughout the duration of each test. The load resulting from the imposition of the specified displacement was measured with fatigue-rated, 5000-lb capacity, tension-comparison, electric load cell manufactured by the Lebow Instrument Company. The output of this load cell was monitored continuously throughout the duration of each test.

Both load and actuator displacements were recorded using a computer program written at OSU, in LabVIEW, specifically for that purpose. LabVIEW is a graphical language developed by National Instruments that allows the user to design in software a test control and data collection system tailored to the requirements of each experimental program. In the LabVIEW application developed for the fatigue tests, the signals from the load and displacement transducers were sampled 30 times per second, and the time histories of each were plotted on the computer screen in real time so that the progress of the test could be readily monitored. By combining the load and displacement time histories, a plot of load vs. displacement at any load cycle desired could be constructed. This too was done in real time so that the changes in the response of the test specimens could be identified while the specimen was still undergoing loading. Any of these presentations of the test data could be printed while the test was still in progress.

Figure 3-1 shows the load application point and direction of loading. Note that the measured distance from the load point to the centerline of the pipe (~49.25 in.) did not vary for the test specimens. The measured distance (L), which is dependent on the installation, is included in the test data.

The test data, results, and other information are provided in Appendix A. The tests were displacement-controlled cantilever bending tests. The tests followed the standard approach corresponding to Markl type tests [6]. Each specimen was first tested to determine the load deflection curve for that particular specimen. The load deflection curve was used to determine the stiffness of each specimen and the load applied to the specimen by a given amount of displacement. The load deflection curves were determined for loading in both positive and negative loading directions (down and up). Each specimen was then fatigue tested by cycling the deflection in both directions of loading by a controlled amount. The cycles to failure were counted to determine the fatigue life. Failure was detected when wall cracks formed and water leaked though the cracks.

The results of Table 3-1 are based on nominal dimensions, (for example, D = 4.5 in. and t = 0.237 in.). In order to determine the actual dimensions, the test specimens were sectioned so that measurements could be taken. The average measurements were OD = 4.58 in. and t = 0.276 in. The distance from the load point to the point of failure was also measured.

Table 3-1
Summary of Test Results

Test	Load Type	F	M	N_{eq}	i	Average i
		lbs.	in. lbs.	Cycles to Failure	Note(2)	for each load type
A	In-plane	2094	103130	2080	1.658	
B	In-plane	1940	95545	2890	1.675	1.667
C	Out-of-plane	2490	122633	2490	1.253	
D	Out-of-plane	2537	124947	2879	1.282	1.268
E	Combined (45^o)	2088	102782	3344	1.512	
F	Combined (45^o)	2105	103671	2917	1.541	
G	Combined (45^o)	2135	105149	2157	1.614	
H	Combined (45^o)	2194	108055	2440	1.533	1.550

Notes:

1. M = F L, where L = 49.25"
2. The value of i is calculated from i = 245,000 $N_{eq}^{-0.2}$/S, where Neq = equivalent cycles to failure, and
   S = M/Z. Where there were more than one loading conditions, Neq was calculated using: Neq = S $(\delta_i/\delta_{max})^5 * N_i$ where δ_{max} is the maximum displacement, δ_i is the "i" th displacement and Ni is the number of cycles associated with the "i"th displacement.
3. Z = 3.215 $in.^3$ Based on nominal dimensions for the elbow.
4. Tests A, B, C and H used two loading conditions. All others used one loading condition.
5. This table was produced on an Excel spreadsheet. The number of significant figures is greater than indicated.

4
ANALYSIS OF TEST RESULTS

4.1 Introduction

In this section, the test results will be compared to the FEA calculations and Code expressions.

4.2 Comparison to FEA

Table 4-1 lists the test results and also the FEA results for model 1 for the same loading. The FEA results are based on nominal dimensions corresponding to the test specimens. The ratio of test SIF to FEA results is also provided. The average ratio of test SIF/FEA is .425.

Table 4-1
Summary of Test Results Based on Nominal Dimensions

TEST	LOAD TYPE	i	FEA	i/FEA
A	In-plane	1.66	4.11	0.403
B	In-plane	1.68	4.11	0.408
C	Out-of-plane	1.25	2.88	0.435
D	Out-of-plane	1.28	2.88	0.445
E	Combined (45^o)	1.51	3.63	0.417
F	Combined (45^o)	1.54	3.63	0.425
G	Combined (45^o)	1.61	3.63	0.445
H	Combined (45^o)	1.53	3.63	0.422
			Average =	0.425

Notes:
1. All calculations are based on nominal dimensions.
2. This table was produced on an Excel spreadsheet. The number of significant figures is greater
than indicated.
3. FEA results are the maximum stress intensity divided by the nominal bending stress in the pipe.

From eq. 1-10:

$$i = C_2K_2/2 \qquad \text{(equation 1-10)}$$

it is expected that since C_2K_2 corresponds to the FEA results, the ratio of SIF/FEA would be about 0.5.

The evaluation of the FEA for model 1 was based on nominal dimensions (D_o = 4.5 in., t_n = 0.237 in.). As noted in Section 3, the actual dimensions were: D_o = 4.58 in. and t_n = 0.276 in. For comparison. the FEA was rerun with actual dimensions for the case with no torsion (C/B = 0). The test SIFs were also recalculated using the measured dimensions and measured distance L to the point of failure. Table 4-2 lists the results and includes the ratio of the SIFs from the test data to the FEA results. As seen from Table 4-2, the average ratio is 0.56 as compared to 0.50 as expected from eq. 1-10.

Table 4-2
Summary of Test Results Based on Actual Dimensions

Test	Load Type	i(test)	FEA	i/FEA	C_2 (N-319-2) (Note 3)	i(test)/C_2	i = 0.9/$h^{2/3}$ or i = 0.75/$h^{2/3}$ (Note 4)	i(test)/i
A	In-plane	2.03	3.73	0.543	3.87	0.524	1.79	1.13
B	In-plane	2.05	3.73	0.549	3.87	0.529	1.79	1.15
C	Out-of-plane	1.55	2.68	0.580	3.04	0.510	1.49	1.04
D	Out-of-plane	1.60	2.68	0.598	3.04	0.526	1.49	1.07
E	Combined (45^o)	1.80	3.31	0.544	3.48	0.518	1.64	1.10
F	Combined (45^o)	1.84	3.31	0.554	3.48	0.527	1.64	1.12
G	Combined (45^o)	1.92	3.31	0.580	3.48	0.553	1.64	1.17
H	Combined (45^o)	1.83	3.31	0.551	3.48	0.525	1.64	1.11
			Average =	0.562	Average =	0.526	Average =	1.11

Notes:

1. All calculations are based on actual dimensions; Do = 4.58", t_n = 0.276", R = 6". This results in h = 0.3576.
2. L is to point of failure.
3. The values for C_2 are based on Code Case N-319-2. See eq. 1-11 and eq. 1-12. For the combined loading, the approach suggested by N-319-2 is followed. (See eq. 1-13.) Since the in-plane and out-of-plane moments are equal, this is equivalent to $0.7071(C_{2Z}^2+C_{2X}^2)^{1/2}$.
4. The values of i for in-plane and out-of-plane loading are based on eq. 1-8 and eq. 1-9: i (in-plane) = $0.9/h^{2/3}$ and i (out-of-plane) = $0.75/h^{2/3}$. For the combined loading, $0.7071((i_i^2+i_o^2)^{1/2}$ is used.
5. This table was produced on an Excel spreadsheet. The number of significant figures is greater than indicated.
6. FEA results are the maximum stress intensity divided by the nominal bending stress in the pipe.

4.3 Comparison to Code Requirements

Table 4-2 also provides a comparison of the test SIFs to C_2 as calculated using Code Case N-319-2. For the combined loading, the “equivalent” C_2 is calculated using the square root sum of the squares approach as suggested by Code Case N-319-2. This is discussed in the notes to

Table 4-2. The average value of the ratio of the test SIFs to C_2 is 0.53 versus 0.50 as suggested by eq. 1-10.

Table 4-2 also includes a comparison to the SIFs as defined in the various Codes. As discussed earlier, ASME Section III provides only one SIF for all loading conditions. B31.3 uses the same expression for in-plane loading and a different one for out-of-plane bending. These expressions are repeated below:

$$i = 0.9/h^{2/3} \text{ for in-plane bending} \qquad \text{(equation 1-1)}$$

$$i = 0.75/h^{2/3} \text{ for out-of-plane bending} \qquad \text{(equation 1-5)}$$

Table 4-2 includes a comparison of equations 1-1 and 1-5 to the test results. The results are very close.

The test loading at 45° was compared to the SRSS of the in-plane and out-of-plane SIFs. This was based on the B31.3 approach to evaluating combined loading conditions. For combined loading, the following expression is used:

$$S_b = [(i_i M_i)^2 + (i_o M_o)^2]^{0.5} / Z \qquad \text{(equation 4-1)}$$

This is discussed in the notes to Table 4-2.

The average ratio of the test SIFs to the calculated SIFs is 1.11.

4.4 Summary

In summary, considering the typical variability in fatigue-related test data and other uncertainties, the results are remarkably accurate and consistent.

5 CONCLUSIONS

The following conclusions, particularly with respect to "conservative" and "unconservative, " are based on the assumption that the moments derived from piping system analyses are accurate. The conclusions arrived at from the analyses and tests discussed in this report are enumerated below

1. Code Case N-319-2 uses the expression $[(C_{2x}M_x)^2+(C_{2y}M_y)^2+(C_{2z}M_z)^2]^{1/2}$ to account for the directionality of the loadings. This approach will normally result in a conservative value as compared to FEA considering the actual loading conditions. For the models studied in this investigation, the conservatism was as high as 29%; the average value was 8%. The only unconservatism was -2%.

2. Additional conservatism exists in the methodology due to the effects of the combinations of the directions of the torsional and out-of-plane moments (see Section 2.5).

3. The method used by ANSI B31.3 to combine stresses (based on SIFs), which includes different SIFs for in-plane and out-of-plane bending, but no intensification for torsion, is apparently unconservative based on a comparison to the FEA. This unconservatism could be as high as -48.6% (model 2, C/B = 1.0, LC-4) based on the loading and models used in this study.

4. The methodology that best predicted the FEA results was the SQ-SUM (ADJUSTED) Combination Methodology. The corresponding methodology for use with SIFs would be:

   $$S = [(i_i\, M_i)^2+(a+b(C/B)^n)^*\,(i_o\, M_o+ i_o\, M_t)^2]^{1/2}/Z \qquad \text{(equation 5-1)}$$

   where

   $a = 1.0$
   $b = -0.187$
   $n = 0.635$
   $i_i = 0.9/h^{2/3}$
   $i_o = 0.75/h^{2/3}$
   C/B is the ratio: M_t/M_o

5. Eq. 5-1 is valid for C/B ≤ 1.0. For the condition when C/B > 1.0, C/B is replaced by B/C in equation 5-1.

6. Eq. 5-1 is valid for 90° elbows or bends with a value of h ≤ 0.86 with no "end effects" created by attachment of the elbow to a flange or other component that would affect the ovalization of the elbow.

The approach discussed above will result in a more accurate evaluation of an elbow.

6
REFERENCES

1. *ASME Boiler and Pressure Vessel Code, Section III, Nuclear Power Plant Components,* American Society of Mechanical Engineers, New York.

2. *American National Standards Institute (ANSI), Code for Pressure Piping, B31.1, Power Piping,* American Society of Mechanical Engineers, New York.

3. *American National Standards Institute (ANSI), Process Piping, B31.3, Power Piping,* American Society of Mechanical Engineers, New York.

4. W. G. Dodge and S. E. Moore, *Stress Indices and Flexibility Factors for Moment Loadings on Elbows and Curved Pipe*, Oak Ridge National Laboratory, ORNL-TM-3658, March 1972.

5. E. C. Rodabaugh, *End Effects on Elbows Subjected to Moment Loadings*, ORNL/Sub-2913/.7, March 1978.

6. A. R. C. Markl, *Fatigue Tests of Piping Components,* ASME Transactions 1952.

7. Leon Beskin, *Bending of Curved Thin Tubes*, Journal of Applied Mechanics, Transactions of the ASME, Vol. 67, New York, 1945.

8. Code Case N-319-2, *Alternate Procedure for Evaluation of Stresses in Butt Welding Elbows in Class 1 Piping, Section III, Division 1*, August 14, 1990.

A
TEST DATA

Overview of Appendix A

The description of the testing is contained in Section 3. Table 3-1 contains a summary of the results. This appendix contains reports of the details regarding the test data for each of the four tests. Each test report contains the following:

1. Load-deflection data sheets for four conditions (=/- directions, loading, and unloading). The sheets are used to determine the linear slope of the load-deflection curves for the four loading conditions.

   The data include loads, deflections, and so on. The columns identified as "modified" are for the case where adjustments are required to the data collection, such as resetting a dial gauge.

2. A summary plot of the load-deflection curve and the four straight lines from the load displacement data (item 1 above). This plot indicated the reasonableness of the slope of the load-deflection curves.

3. The fatigue test data analysis, including the displacement amplitude and number of cycles at each displacement.

Test Data

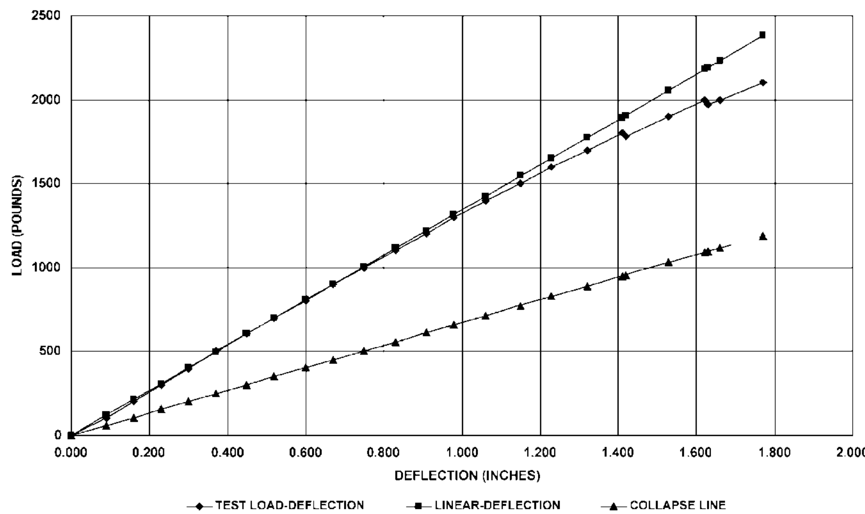
TEST #: **ELBOW - A** TEST TYPE: **IN-PLANE** **FATIGUE - LOAD DEFLECTION CURVE** 11/17/98

POSITIVE LOAD - LOADING CONDITION

F = Fo + m "m" TO BE BASED ON N DATA POINTS, N = 5
THE VALUE OF "m" = 1344 Fo (LBS) = 0

NOMINAL STRESS = M/Z KSI, M=F x L, L(IN) = 49 25 Z(IN^3) = 3.215

DATA POINT #	MEASURED DEFLECTION (INCHES)	MEASURED LOAD F (LBS)	MODIFIED DEFLECTION (INCHES)	MODIFIED LOAD F (LBS)	SLOPE FOR START TO DATA POINT (LBS/INCH)	F BASED ON "m" (LBS)	NOMINAL STRESS (KSI)
1	0	0	0.000	0	N/A	0	
2	0.09	105	0.090	105	1.167	121	1.9
3	0.16	203	0.160	203	1.264	215	3.3
4	0.23	302	0.230	302	1.317	309	4.7
5	0.3	400	0.300	400	1.344	403	6.2
6	0.37	500	0.370	500	1.364	497	7.6
7	0.45	604	0.450	604	1.364	605	9.3
8	0 52	700	0.520	700	1.365	699	10.7
9	0.6	800	0.600	800	1.356	807	12.4
10	0.67	900	0.670	900	1.356	901	13.8
11	0.75	1000	0.750	1000	1.351	1008	15.4
12	0.83	1100	0.830	1100	1.343	1116	17.1
13	0.91	1200	0.910	1200	1.336	1223	18.7
14	0.98	1300	0.980	1300	1.333	1317	20.2
15	1 06	1400	1.060	1400	1.330	1425	21.8
16	1.15	1500	1.150	1500	1.321	1546	23.7
17	1.23	1600	1.230	1600	1.314	1654	25.3
18	1.32	1700	1.320	1700	1.305	1775	27.2
19	1.41	1800	1.410	1800	1.294	1895	29.0
20	1.42	1780	1.420	1780	1.282	1909	29.2
21	1.530	1900	1.530	1900	1.268	2057	31.5
22	1.620	2000	1.620	2000	1.256	2178	33.4
23	1 630	1970	1.630	1970	1.241	2191	33.6
24	1.660	2000	1.660	2000	1.229	2232	34.2
25	1.770	2100	1.770	2100	1.215	2379	36.4



NOTES.
1. Positive load s down.

TEST #: **ELBOW - A** TEST TYPE: **IN-PLANE**

F = Fo + m

"m" TO BE BASED ON N DATA POINTS, N = 6
THE VALUE OF "m" = 1457 Fo (LBS) = 300

NOMINAL STRESS = M/Z KSI, M=F x L, L(IN) = 49.25 Z(IN³) = 3.215

DATA POINT #	MEASURED DEFLECTION (INCHES)	MEASURED LOAD F (LBS)	MODIFIED DEFLECTION (INCHES)	MODIFIED LOAD F (LBS)	SLOPE FOR START TO DATA POINT (LBS/INCH)	F BASED ON "m" (LBS)	NOMINAL STRESS (KSI)
1	1.77	2100	1.770	2100	1,416	2136	32.7
2	1.65	1900	1.650	1900	1,667	1962	30.0
3	1.51	1700	1.510	1700	1,535	1757	26.9
4	1.37	1500	1.370	1500	1,491	1553	23.8
5	1.23	1300	1.230	1300	1,469	1349	20.7
6	1.09	1100	1.090	1100	1,457	1145	17.5
7	0.95	900	0.950	900	1,450	941	14.4
8	0.8	700	0.800	700	1,436	723	11.1
9	0.65	500	0.650	500	1,423	504	7.7
10	0.51	300	0.510	300	1,416	300	4.6
11	0.36	100	0.360	100	1,409	81	1.2
12	0.28	0	0.280	0	1,401	-35	-0.5
13							
14							
15							
16							
17							
18							
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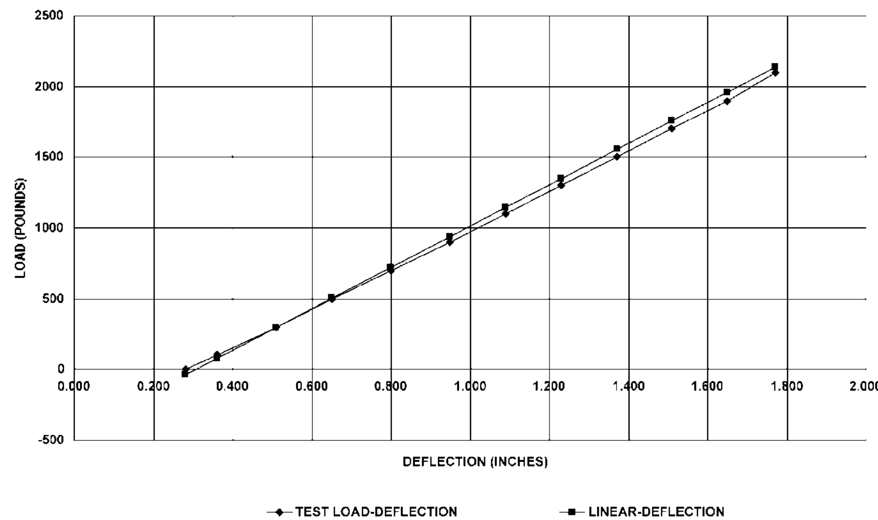
22							
23							
24							
25							

NOTES

FATIGUE - LOAD DEFLECTION CURVE 11/17/98

POSITIVE LOAD - UNLOADING CONDITION



Test Data

TEST #: **ELBOW - A** TEST TYPE: **IN-PLANE**

F = Fo + m "m" TO BE BASED ON N DATA POINTS, N = 5
THE VALUE OF "m" = 1244 Fo (LBS) = 0

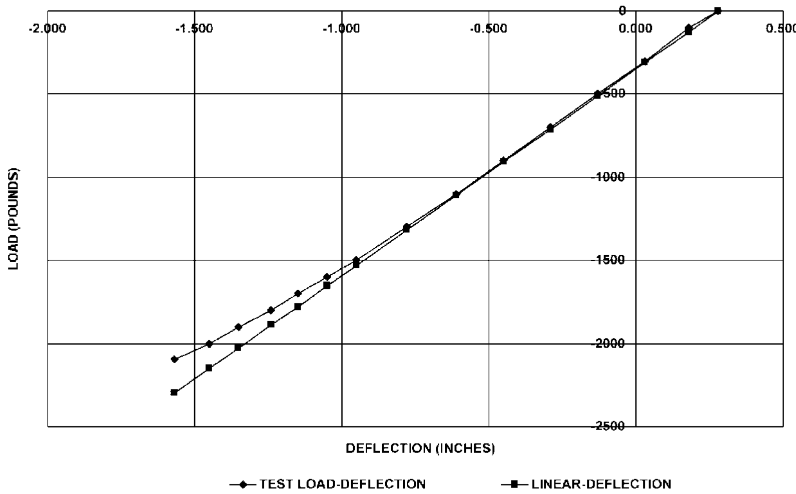
NOMINAL STRESS = M/Z KSI, M=F x L, L(IN) = 49.25 $Z(IN^3)$ = 3.215

DATA POINT #	MEASURED DEFLECTION (INCHES)	MEASURED LOAD F (LBS)	MODIFIED DEFLECTION (INCHES)	MODIFIED LOAD F (LBS)	SLOPE FOR START TO DATA POINT (LBS/INCH)	F BASED ON "m" (LBS)	NOMINAL STRESS (KSI)
1	0.28	0	0.280	0	N/A	0	0.0
2	0.18	-100	0.180	-100	1.000	-124	-1.9
3	0.03	-300	0.030	-300	1.211	-311	-4.8
4	-0.13	-500	-0.130	-500	1.237	-510	-7.8
5	-0.29	-700	-0.290	-700	1.244	-709	-10.9
6	-0.45	-900	-0.450	-900	1.247	-908	-13.9
7	-0.61	-1100	-0.610	-1100	1.248	-1107	-17.0
8	-0.78	-1300	-0.780	-1300	1.242	-1319	-20.2
9	-0.95	-1500	-0.950	-1500	1.234	-1530	-23.4
10	-1.05	-1600	-1.050	-1600	1.223	-1655	-25.3
11	-1.15	-1700	-1.150	-1700	1.210	-1779	-27.3
12	-1.24	-1800	-1.240	-1800	1.200	-1891	-29.0
13	-1.35	-1900	-1.350	-1900	1.187	-2028	-31.1
14	-1.45	-2000	-1.450	-2000	1.175	-2152	-33.0
15	-1.57	-2100	-1.570	-2100	1.160	-2302	-35.3
16							
17							
18							
19							
20							
21							
22							
23							
24							
25							

NOTES:

FATIGUE - LOAD DEFLECTION CURVE

NEGATIVE LOAD - LOADING CONDITION 11/17/98



TEST #: **ELBOW - A** TEST TYPE: **IN-PLANE**

F = Fo + m`. "m" TO BE BASED ON N DATA POINTS, N = 2
THE VALUE OF "m" = 1357 Fo (LBS) = -300

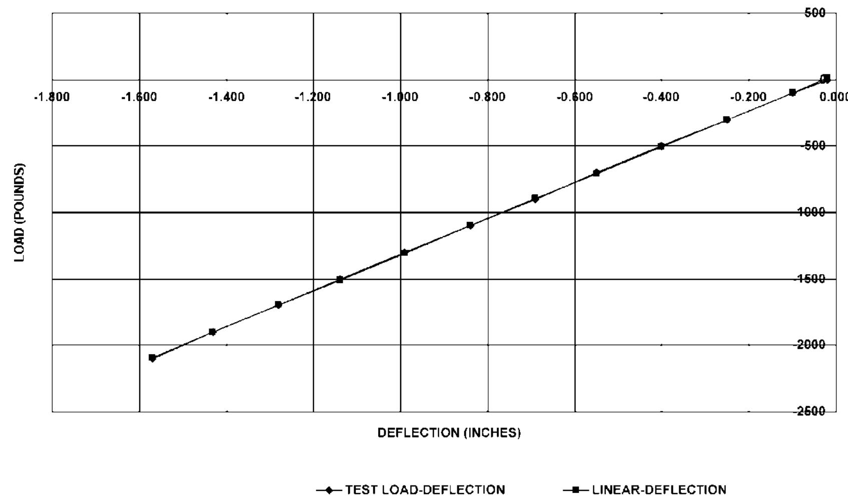
NOMINAL STRESS = M/Z KSI, M=F x L, L(IN) = 49.25 $Z(IN^3)$ = 3.215

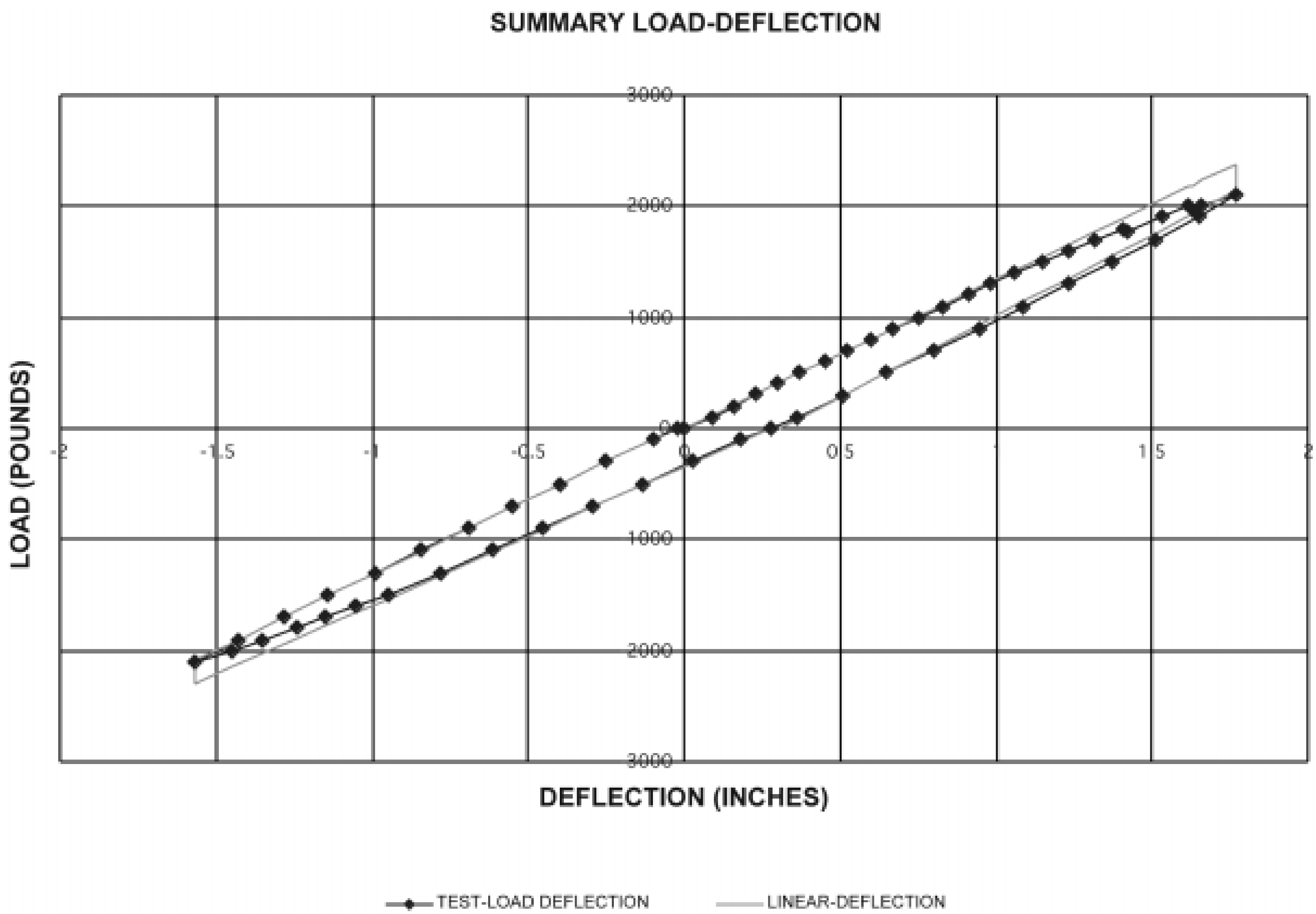
DATA POINT #	MEASURED DEFLECTION (INCHES)	MEASURED LOAD F (LBS)	MODIFIED DEFLECTION (INCHES)	MODIFIED LOAD F (LBS)	SLOPE FOR START TO DATA POINT (LBS/INCH)	F BASED ON "m" (LBS)	NOMINAL STRESS (KSI)
1	-1.57	-2100	-1.570	-2100	1361	-2092	-32.0
2	-1.43	-1900	-1.430	-1900	1357	-1902	-29.1
3	-1.28	-1700	-1 280	-1700	1357	-1698	-26.0
4	-1.14	-1500	-1.140	-1500	1353	-1508	-23.1
5	-0.99	-1300	-0.990	-1300	1356	-1304	-20.0
6	-0.84	-1100	-0.840	-1100	1360	-1101	-16.9
7	-0 69	-900	-0 690	-900	1360	-897	-13 7
8	-0.55	-700	-0.550	-700	1333	-707	-10.8
9	-0.4	-500	-0.400	-500	1333	-504	-7.7
10	-0.25	-300	-0 250	-300	1361	-300	-4.6
11	-0.100	-100	-0.100	-100	1359	-96	-1.5
12	-0.020	0	-0.020	0	1355	12	0.2
13							
14							
15							
16							
17							
18							
19							
20							
21							
22							
23							
24							
25							

NOTES:

FATIGUE - LOAD DEFLECTION CURVE 11/17/98

NEGATIVE LOAD - UNLOADING CONDITION




SUMMARY LOAD-DEFLECTION
3000
2000
1000
0
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
1000
2000
3000
LOAD (POUNDS)
DEFLECTION (INCHES)
TEST-LOAD DEFLECTION
LINEAR-DEFLECTION

FATIGUE TEST DATA ANALYSIS 11/17/98

TEST #: **ELBOW - A** TYPE: **IN-PLANE**

AVERAGE STIFFNESS (lbs/in) = 1351
MOMENT ARM (in)= 47.49

D (in) = 4.5 t (in) = 0.237 Z (in^3) = $0.0982(D^4-(D-2t)^4)/D$= 3.215

TEST DISPLACEMENT/CYCLE DATA:

CONDITION #	DISPLACEMENT AMPLITUDE (+/-) (in.) d_i	EFFECTIVE APPLIED LOAD (lbs)	NOMINAL STRESS (+/-) (psi) S	NUMBER OF TEST CYCLES N_i
1	0.75	1013	14,964	110
2	1.25	1689	24,940	3,645
3	1.40	1891	27,932	345
4	1.55	2094	30,925	626
5	0.00	0	0	0
6	0.00	0	0	0
7	0.00	0	0	0
8	0.00	0	0	0
			TOTAL CYCLES:	4,726

EQUIVALENT NUMBER OF CYCLES, BASED ON δ = **1.55** INCHES

IS: $N_{eq} = SUM(\delta_i/\delta_{max})^5 * N_i$ = 2,080

FOR NOMINAL DIMENSIONS: $i = 245{,}000 * N_{eq}^{(-0.2)}/S$ = **1.719**

FOR Z(IN^3) = 3.215 i = **1.719**

COMMENTS:

1. L = 49.25 to the center of the elbow.
2. Initial deflection 0.75" to 100 cycles. Change to 1.25" completed at 110 cycles.
3. Deflection changed to 1.4" at 3750 cycles. Change completed at 3755 cycles.
4. Deflection changed to 1.55" at 4100 cycles. Change completed at 4107 cycles.
5. Failiure occured on "left" side as a crack along the centerline of the elbow at 45°.
6. Moment arm to point of failure is 47.49.

Test Data

TEST #: **ELBOW - B** TEST TYPE: **IN-PLANE** **FATIGUE - LOAD DEFLECTION CURVE** 11/17/98

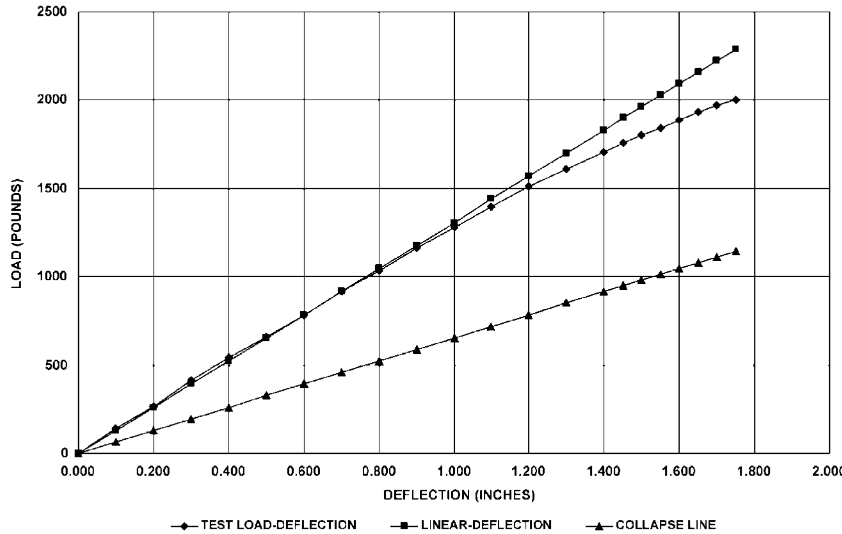
F = Fo + m "m" TO BE BASED ON N DATA POINTS, N = 7
THE VALUE OF "m" = 1308 Fo (LBS) = 0

NOMINAL STRESS = M/Z KSI, M=F x L. L(IN) = 49.25 $Z(IN^3)$ = 3.215

DATA POINT #	MEASURED DEFLECTION (INCHES)	MEASURED LOAD F (LBS)	MODIFIED DEFLECTION (INCHES)	MODIFIED LOAD F (LBS)	SLOPE FOR START TO DATA POINT (LBS/INCH)	F BASED ON "m" (LBS)	NOMINAL STRESS (KSI)
1	0	0	0.000	0	N/A	0	
2	0.1	139	0.100	139	1,390	131	2.0
3	0.2	268	0.200	268	1,340	262	4.0
4	0.3	412	0.300	412	1,365	392	6.0
5	0.4	540	0.400	540	1,353	523	8.0
6	0.5	661	0.500	661	1,329	654	10.0
7	0.6	782	0.600	782	1,308	785	12.0
8	0.7	918	0.700	918	1,303	916	14.0
9	0.8	1032	0.800	1032	1,290	1046	16.0
10	0.9	1161	0.900	1161	1,284	1177	18.0
11	1	1282	1.000	1282	1,277	1308	20.0
12	1.1	1395	1.100	1395	1,267	1439	22.0
13	1.2	1509	1.200	1509	1,257	1569	24.0
14	1.3	1607	1.300	1607	1,243	1700	26.0
15	1.4	1705	1.400	1705	1,227	1831	28.0
16	1.45	1759	1.450	1759	1,215	1896	29.0
17	1.5	1804	1.500	1804	1,204	1962	30.0
18	1.55	1842	1.550	1842	1,193	2027	31.1
19	1.6	1887	1.600	1887	1,182	2093	32.1
20	1.65	1933	1.650	1933	1,172	2158	33.1
21	1.700	1970	1.700	1970	1,162	2223	34.1
22	1.750	2001	1.750	2001	1,151	2289	35.1
23							
24							
25							

NOTES:
1. Positive load is down.

POSITIVE LOAD - LOADING CONDITION



TEST #: **ELBOW - B** TEST TYPE: **IN-PLANE**

F = Fo + m "m" TO BE BASED ON N DATA POINTS, N = 10

THE VALUE OF "m" = 1364 Fo (LBS) = 850

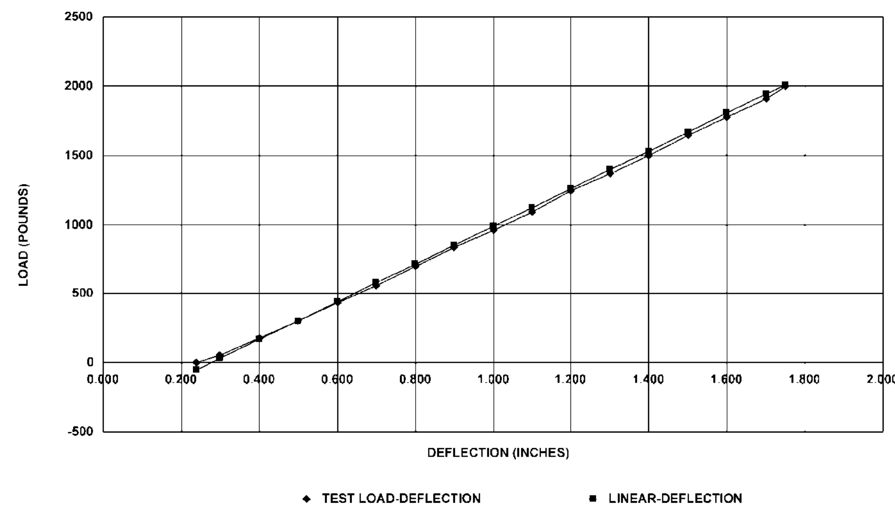
NOMINAL STRESS = M/Z KSI, M=F x L L (IN) = 49.25 Z(IN³) = 3.215

DATA POINT #	MEASURED DEFLECTION (INCHES)	LOAD F (LBS)	MODIFIED DEFLECTION (INCHES)	LOAD F (LBS)	SLOPE FOR START TO DATA POINT (LBS/INCH)	F BASED ON "m" (LBS)	NOMINAL STRESS (KSI)
1	1.75	2001	1.750	2001	N/A	2009	30.8
2	1.7	1910	1.700	1910	1,820	1941	29.7
3	1.6	1774	1.600	1774	1,491	1805	27.6
4	1.5	1645	1.500	1645	1,404	1668	25.6
5	1.4	1494	1.400	1494	1,416	1532	23.5
6	1.3	1365	1.300	1365	1,399	1396	21.4
7	1.2	1244	1.200	1244	1,371	1259	19.3
8	1.1	1092	1.100	1092	1,373	1123	17.2
9	1	957	1.000	957	1,373	986	15.1
10	0.9	835	0.900	835	1,364	850	13.0
11	0.8	699	0.800	699	1,359	714	10.9
12	0.7	555	0.700	555	1,359	577	8.8
13	0.6	434	0.600	434	1,354	441	6.8
14	0.5	305	0.500	305	1,325	304	4.7
15	0.4	177	0.400	177	1,285	168	2.6
16	0.3	56	0.300	56	1,262	32	0.5
17	0.2	0	0.240	0	1,219	-50	-0.8
18							
19							
20							
21							
22							
23							
24							
25							

NOTES:

FATIGUE - LOAD DEFLECTION CURVE 11/17/98

POSITIVE LOAD - UNLOADING CONDITION



Test Data

TEST #: **ELBOW - B** TEST TYPE: **IN-PLANE**

F = Fo + m "m" TO BE BASED ON N DATA POINTS. N = 10

THE VALUE OF "m" = 1209 Fo (LBS) = 0

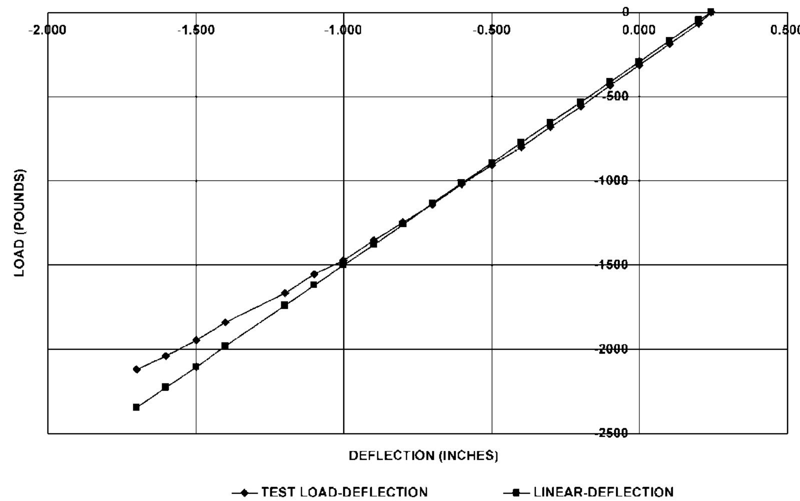
NOMINAL STRESS = M/Z KSI, M=F x L, L(IN) = 49.25 $Z(IN^3)$ = 3.215

DATA POINT #	MEASURED DEFLECTION (INCHES)	MEASURED LOAD F (LBS)	MODIFIED DEFLECTION (INCHES)	MODIFIED LOAD F (LBS)	SLOPE FOR START TO DATA POINT (LBS/INCH)	F BASED ON "m" (LBS)	NOMINAL STRESS (KSI)
1	0.24	0	0.240	0	N/A	0	0.0
2	0.200	-65	0.200	-65	1,625	-48	-0.7
3	0.100	-186	0.100	-186	1,306	-169	-2.6
4	0	-315	0.000	-315	1,291	-290	-4.4
5	-0.1	-435	-0.100	-435	1,268	-411	-6.3
6	-0.2	-557	-0.200	-557	1,254	-532	-8.1
7	-0.3	-678	-0.300	-678	1,245	-653	-10.0
8	-0.4	-799	-0.400	-799	1,238	-774	-11.9
9	-0.5	-905	-0.500	-905	1,222	-895	-13.7
10	-0.6	-1018	-0.600	-1018	1,209	-1016	-15.6
11	-0.7	-1139	-0.700	-1139	1,202	-1137	-17.4
12	-0.8	-1245	-0.800	-1245	1,193	-1257	-19.3
13	-0.9	-1351	-0.900	-1351	1,182	-1378	-21.1
14	-1	-1472	-1.000	-1472	1,177	-1499	-23.0
15	-1.1	-1556	-1.100	-1556	1,165	-1620	-24.8
16	-1.2	-1669	-1.200	-1669	1,156	-1741	-26.7
17	-1.4	-1843	-1.400	-1843	1,137	-1983	-30.4
18	-1.5	-1949	-1.500	-1949	1,124	-2104	-32.2
19	-1.6	-2040	-1.600	-2040	1,111	-2225	-34.1
20	-1.7	-2123	-1.700	-2123	1,098	-2346	-35.9
21							
22							
23							
24							
25							

NOTES.

FATIGUE - LOAD DEFLECTION CURVE 11/17/98

NEGATIVE LOAD - LOADING CONDITION



TEST #: **ELBOW - B** TEST TYPE: **IN-PLANE**

F = Fo + m.: "m" TO BE BASED ON N DATA POINTS, N = 2

THE VALUE OF "m" = 1293 Fo (LBS) = -912

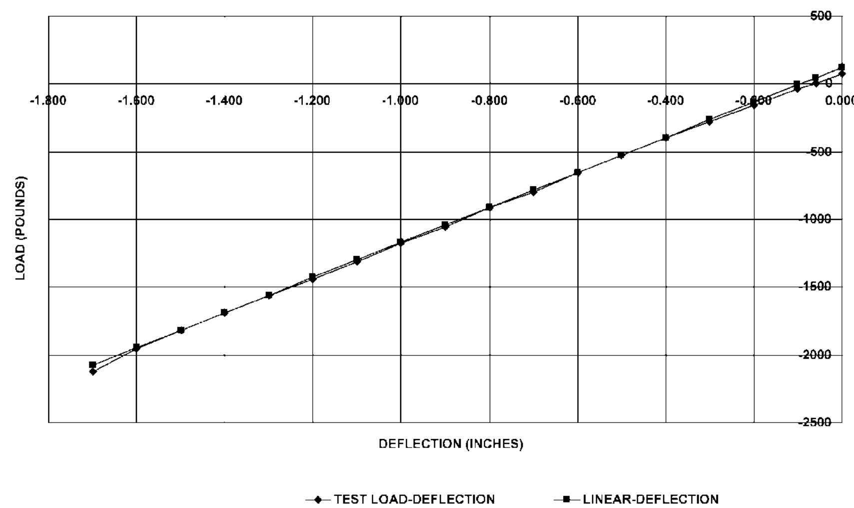
NOMINAL STRESS – M/Z KSI, M–F x L, L(IN) – 49.25 Z(IN³) = 3.215

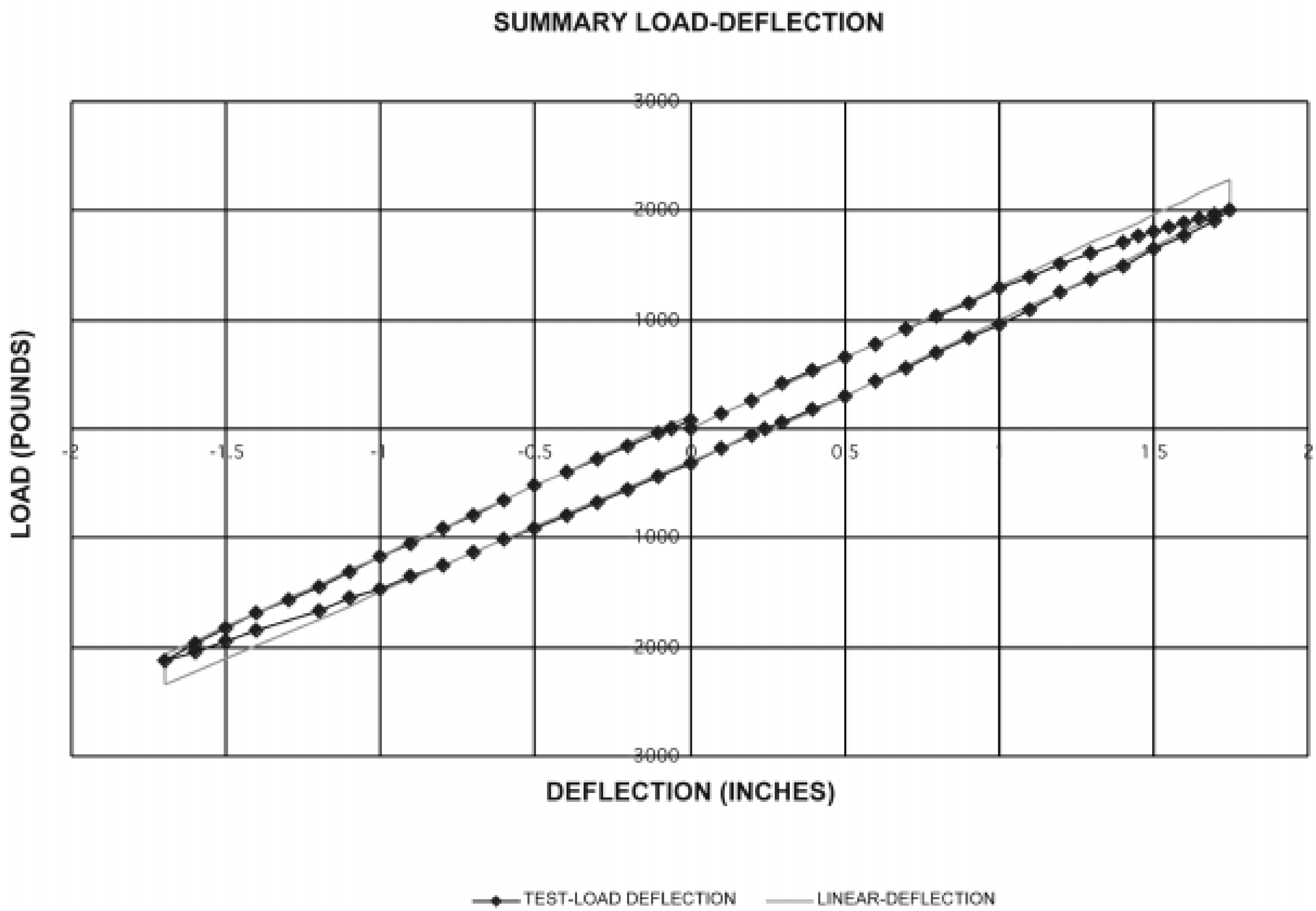
DATA POINT #	MEASURED DEFLECTION (INCHES)	MEASURED LOAD F (LBS)	MODIFIED DEFLECTION (INCHES)	MODIFIED LOAD F (LBS)	SLOPE FOR START TO DATA POINT (LBS/INCH)	F BASED ON "m" (LBS)	NOMINAL STRESS (KSI)
1	-1.7	-2123	-1.700	-2123	N/A	-2075	-31.8
2	-1.6	-1957	-1.600	-1957	1293	-1946	-29.8
3	-1.5	-1821	-1.500	-1821	1289	-1817	-27.8
4	-1.4	-1692	-1.400	-1692	1293	-1688	-25.8
5	-1.3	-1563	-1.300	-1563	1300	-1558	-23.9
6	-1.2	-1442	-1.200	-1442	1317	-1429	-21.9
7	-1.1	-1313	-1.100	-1313	1324	-1300	-19.9
8	-1	-1177	-1.000	-1177	1325	-1171	-17.9
9	-0.9	-1056	-0.900	-1056	1440	-1041	-15.9
10	-0.8	-912	-0.800	-912	1314	-912	-14.0
11	0.700	799	0.700	799	1307	783	12.0
12	-0.600	-655	-0.600	-655	1308	-654	-10.0
13	-0.500	-526	-0.500	-526	1308	-524	-8.0
14	-0.400	-398	-0.400	-398	1307	-395	-6.1
15	-0.300	-277	-0.300	-277	1304	-266	-4.1
16	-0.200	-155	-0.200	-155	1300	-137	-2.1
17	0.100	34	0.100	34	1296	7	0.1
18	-0.060	0	-0.060	0	1290	44	0.7
19	0.000	78	0.000	78	1286	122	1.9
20							
21							
22							
23							
24							
25							

NOTES:

FATIGUE - LOAD DEFLECTION CURVE 11/17/98

NEGATIVE LOAD - UNLOADING CONDITION




SUMMARY LOAD-DEFLECTION
LOAD (POUNDS)
DEFLECTION (INCHES)
TEST-LOAD DEFLECTION
LINEAR-DEFLECTION

FATIGUE TEST DATA ANALYSIS 11/17/98

TEST #: **ELBOW - B** TYPE: **IN-PLANE**

AVERAGE STIFFNESS (lbs/in) = 1293
MOMENT ARM (in)= 47.49

D (in) = 4.5 t (in) = 0.237 $Z\ (in^3) = 0.0982(D^4\text{-}(D\text{-}2t)^4)/D=$ 3.215

TEST DISPLACEMENT/CYCLE DATA:

CONDITION #	DISPLACEMENT AMPLITUDE (+/-) (in.) d_i	EFFECTIVE APPLIED LOAD (lbs)	NOMINAL STRESS (+/-) (psi) S	NUMBER OF TEST CYCLES N_i
1	1.45	1875	27,699	2,685
2	1.50	1940	28,654	624
3	0.00	0	0	0
4	0.00	0	0	0
5	0.00	0	0	0
6	0.00	0	0	0
7	0.00	0	0	0
8	0.00	0	0	0
			TOTAL CYCLES:	3,309

EQUIVALENT NUMBER OF CYCLES, BASED ON δ = **1.5** INCHES

IS: $N_{eq} = SUM(\delta_i/\delta_{max})^5 * N_i =$ 2,890

FOR NOMINAL DIMENSIONS: $i = 245{,}000 * N_{eq}^{(-0.2)}/S =$ **1.737**

FOR $Z(IN^3) =$ 3.215 i = **1.737**

COMMENTS:

1. L = 49.25 to the center of the elbow.
2. 2 cycles to measure deflection.
3. Deflection cahnged to 1.5 inches at 2680 cycles. Change complete at 2685 cycles.
4. Failure occured on "left" side as a crack along the centerline of the elbow at 45°.
5. Moment arm to point 0f failure is 47.49

Test Data

TEST #: **ELBOW - C** TEST TYPE: **OUT-OF-PLANE** **FATIGUE - LOAD DEFLECTION CURVE** 11/18/98

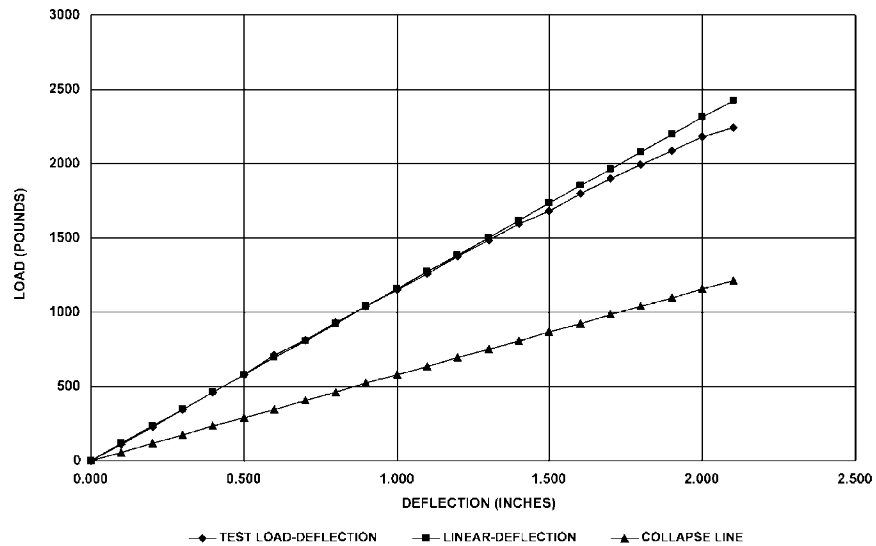
F = Fo + m "m" TO BE BASED ON N DATA POINTS, N = 5
THE VALUE OF "m" = 1155 Fo (LBS) = 0

NOMINAL STRESS = M/Z KSI, M=F x L, L(IN) = 49.25 $Z(IN^3)$ = 3.215

DATA POINT #	MEASURED DEFLECTION (INCHES)	LOAD F (LBS)	MODIFIED DEFLECTION (INCHES)	LOAD F (LBS)	SLOPE FOR START TO DATA POINT (LBS/INCH)	F BASED ON "m" (LBS)	NOMINAL STRESS (KSI)
1	0	0	0.000	0	N/A	0	
2	0.1	111	0.100	111	1,110	116	1.8
3	0.2	225	0.200	225	1,125	231	3.5
4	0.3	346	0.300	346	1,152	347	5.3
5	0.4	460	0.400	460	1,155	462	7.1
6	0.5	581	0.500	581	1,164	578	8.8
7	0.6	709	0.600	709	1,179	693	10.6
8	0.7	815	0.700	815	1,176	808	12.4
9	0.8	929	0.800	929	1,172	924	14.2
10	0.9	1042	0.900	1042	1,168	1040	15.9
11	1	1148	1.000	1148	1,160	1155	17.7
12	1.1	1254	1.100	1254	1,152	1271	19.5
13	1.2	1375	1.200	1375	1,149	1386	21.2
14	1.3	1481	1.300	1481	1,145	1502	23.0
15	1.4	1595	1.400	1595	1,142	1617	24.8
16	1.5	1678	1.500	1678	1,133	1733	26.5
17	1.6	1799	1.600	1799	1,128	1848	28.3
18	1.7	1898	1.700	1898	1,123	1964	30.1
19	1.8	1996	1.800	1996	1,116	2079	31.8
20	1.9	2087	1.900	2087	1,109	2195	33.6
21	2	2178	2.000	2178	1,101	2310	35.4
22	2.1	2246	2.100	2246	1,090	2426	37.2
23							
24							
25							

NOTES:
1. Positive load is down.

POSITIVE LOAD - LOADING CONDITION



TEST #: **ELBOW - C** TEST TYPE: **OUT-OF-PLANE** **FATIGUE - LOAD DEFLECTION CURVE** 11/18/98

F = Fo – m

"m" TO BE BASED ON N DATA POINTS, N = 15

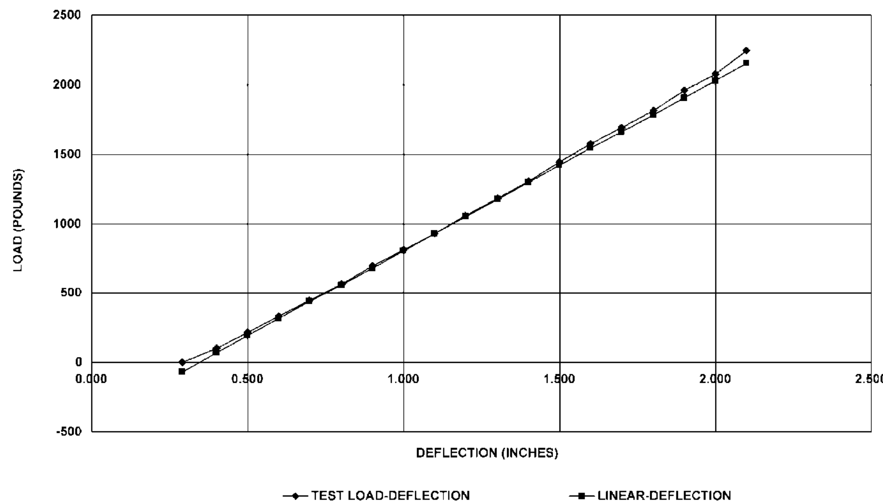
THE VALUE OF "m" – 1225 Fo (LBS) – 1050

NOMINAL STRESS = M/Z KSI, M=F x L. L(IN) = 49.25 Z(IN^3) = 3.215

DATA POINT #	MEASURED DEFLECTION (INCHES)	MEASURED LOAD F (LBS)	MODIFIED DEFLECTION (INCHES)	MODIFIED LOAD F (LBS)	SLOPE FOR START TO DATA POINT (LBS/INCH)	F BASED ON "m" (LBS)	NOMINAL STRESS (KSI)
1	2.1	2246	2.100	2246	N/A	2153	33.0
2	2	2079	2.000	2079	1,670	2030	31.1
3	1.9	1958	1.900	1958	1,440	1908	29.2
4	1.8	1814	1.800	1814	1,417	1785	27.3
5	1.7	1693	1.700	1693	1,371	1663	25.5
6	1.6	1572	1.600	1572	1,335	1540	23.6
7	1.5	1444	1.500	1444	1,316	1418	21.7
8	1.4	1307	1.400	1307	1,313	1295	19.8
9	1.3	1179	1.300	1179	1,309	1173	18.0
10	1.2	1058	1.200	1058	1,302	1050	16.1
11	1.1	929	1.100	929	1,297	928	14.2
12	1	808	1.000	808	1,291	805	12.3
13	0.9	697	0.900	697	1,282	683	10.5
14	0.8	566	0.800	566	1,216	560	8.6
15	0.7	452	0.700	452	1,225	438	6.7
16	0.6	331	0.600	331	1,212	315	4.8
17	0.5	217	0.500	217	1,195	193	2.9
18	0.4	104	0.400	104	1,181	70	1.1
19	0.29	0	0.290	0	1,148	-65	-1.0
20							
21							
22							
23							
24							
25							

NOTES:

POSITIVE LOAD - UNLOADING CONDITION



Test Data

TEST #: **ELBOW - C** TEST TYPE: **OUT-OF-PLANE**

FATIGUE - LOAD DEFLECTION CURVE 11/18/98

F = Fo + m "m" TO BE BASED ON N DATA POINTS, N = 10

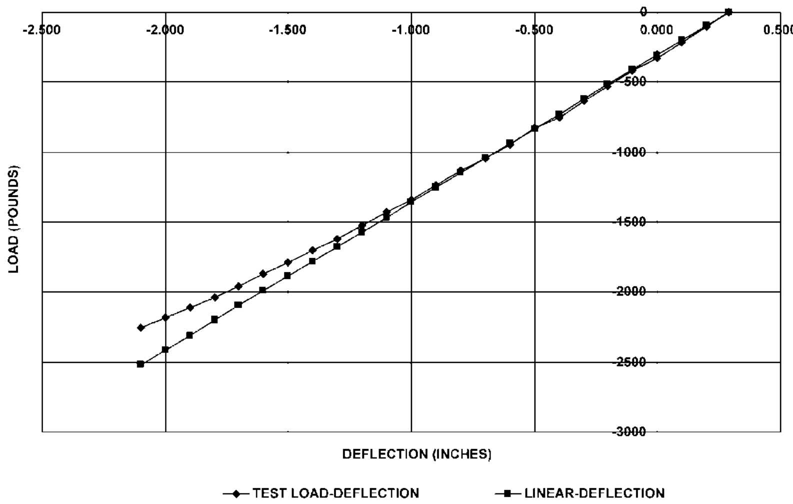
THE VALUE OF 'm' = 1053 Fo (LBS) = 0

NOMINAL STRESS = M/Z KSI, M=F x L, L(IN) = 49.25 Z(IN³) = 3.215

DATA POINT #	MEASURED DEFLECTION (INCHES)	MEASURED LOAD F (LBS)	MODIFIED DEFLECTION (INCHES)	MODIFIED LOAD F (LBS)	SLOPE FOR START TO DATA POINT (LBS/INCH)	F BASED ON "m" (LBS)	NOMINAL STRESS (KSI)
1	0.29	0	0.290	0	N/A	0	0.0
2	0.200	-107	0.200	-107	1,189	-95	-1.5
3	0.100	-213	0.100	-213	1,120	-200	-3.1
4	0	-326	0.000	-326	1,117	-305	-4.7
5	-0.100	-417	-0.100	-417	1,074	-411	-6.3
6	-0.200	-531	-0.200	-531	1,071	-516	-7.9
7	-0.3	-637	-0.300	-637	1,069	-621	-9.5
8	-0.400	-750	-0.400	-750	1,074	-727	-11.1
9	-0.500	-826	-0.500	-826	1,055	-832	-12.7
10	-0.6	-947	-0.600	-947	1,053	-938	-14.4
11	0.700	1045	0.700	1045	1,049	1043	16.0
12	-0.800	-1129	-0.800	-1129	1,039	-1148	-17.6
13	-0.9	-1235	-0.900	-1235	1,033	-1254	-19.2
14	-1.000	-1341	-1.000	-1341	1,031	-1359	-20.8
15	-1.100	-1424	-1.100	-1424	1,024	-1464	-22.4
16	-1.2	-1522	-1.200	-1522	1,018	-1570	-24.0
17	-1.300	-1621	-1.300	-1621	1,014	-1675	-25.7
18	-1.400	-1704	-1.400	-1704	1,008	-1780	-27.3
19	-1.5	-1787	-1.500	-1787	1,000	-1886	-28.9
20	-1.600	-1870	-1.600	-1870	993	-1991	-30.5
21	-1.700	-1954	-1.700	-1954	985	-2096	-32.1
22	-1.8	-2037	-1.800	-2037	977	-2202	-33.7
23	-1.900	-2113	-1.900	-2113	969	-2307	-35.3
24	-2.000	-2181	-2.000	-2181	960	-2412	-36.9
25	-2.100	-2256	-2.100	-2256	951	-2518	-38.6

NOTES:

NEGATIVE LOAD - LOADING CONDITION



TEST #: **ELBOW - C** TEST TYPE: **OUT-OF-PLANE**

F = Fo − m "m" TO BE BASED ON N DATA POINTS, N = 7
THE VALUE OF "m" = 1093 Fo (LBS) = -387

NOMINAL STRESS = M/Z KSI, M=F x L, L(IN) = 49.25 Z(IN³) = 3.215

DATA POINT #	MEASURED DEFLECTION (INCHES)	MEASURED LOAD F (LBS)	MODIFIED DEFLECTION (INCHES)	MODIFIED LOAD F (LBS)	SLOPE FOR START TO DATA POINT (LBS/INCH)	F BASED ON "m" (LBS)	NOMINAL STRESS (KS)
1	-2.1	-2256	-2.100	-2256	N/A	-2246	-34.4
2	-2	-2128	-2.000	-2128	1280	-2136	-32.7
3	-1.8	-1923	-1.800	-1923	1098	-1918	-29.4
4	-1.6	-1704	-1.600	-1704	1090	-1699	-26.0
5	-1.4	-1484	-1.400	-1484	1091	-1480	-22.7
6	-1.2	-1265	-1.200	-1265	1092	-1262	-19.3
7	-1	-1045	-1.000	-1045	1093	-1043	-16.0
8	-0.8	-818	-0.800	-818	1097	-824	-12.6
9	-0.6	-599	-0.600	-599	1099	-606	-9.3
10	-0.4	-387	-0.400	-387	1098	-387	-5.9
11	0.200	175	0.200	175	1095	168	2.6
12	0.000	51	0.000	51	1095	50	0.8
13							
14							
15							
16							
17							
18							
19							
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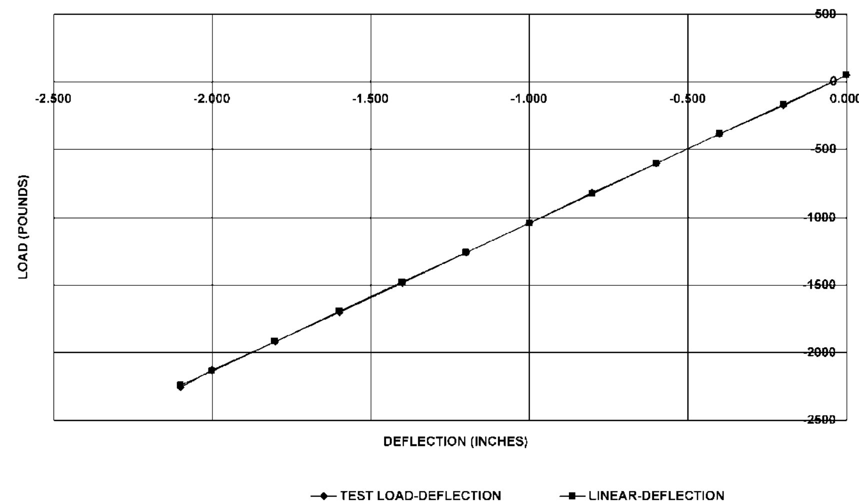
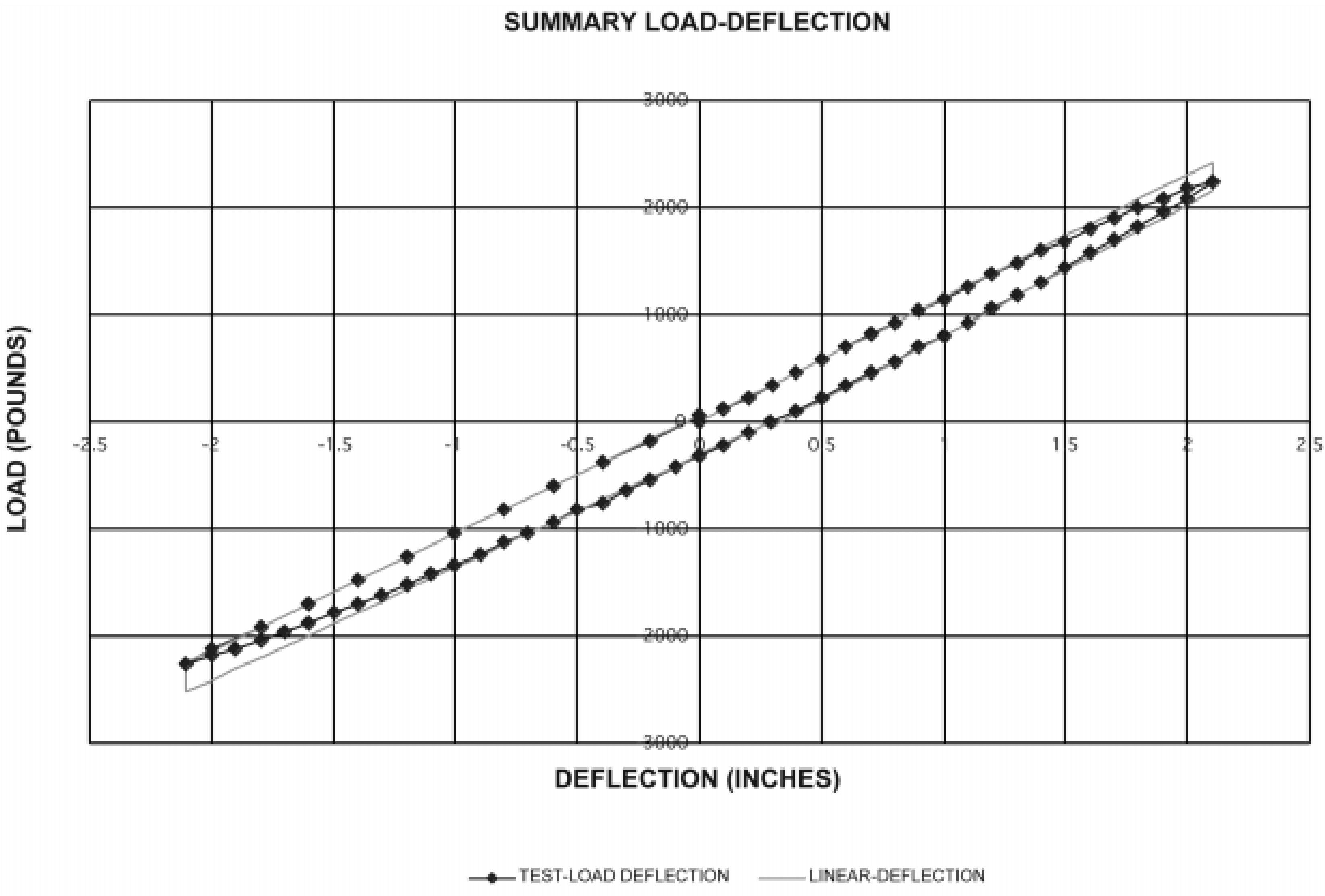
25							

NOTES

FATIGUE - LOAD DEFLECTION CURVE 11/18/98

NEGATIVE LOAD - UNLOADING CONDITION




SUMMARY LOAD-DEFLECTION
3000
2000
1000
0
-1000
-2000
-3000
-2.5
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
2.5
LOAD (POUNDS)
DEFLECTION (INCHES)
TEST-LOAD DEFLECTION
LINEAR-DEFLECTION

FATIGUE TEST DATA ANALYSIS 11/18/98

TEST #: **ELBOW - C** TYPE: **OUT-OF-PLANE**

AVERAGE STIFFNESS (lbs/in) = 1132
MOMENT ARM (in)= 49.25

D (in) = 4.5 t (in) = 0.237 $Z\ (in^3) = 0.0982(D^4-(D-2t)^4)/D=$ 3.215

TEST DISPLACEMENT/CYCLE DATA:

CONDITION #	DISPLACEMENT AMPLITUDE (+/-) (in.) d_i	EFFECTIVE APPLIED LOAD (lbs)	NOMINAL STRESS (+/-) (psi) S	NUMBER OF TEST CYCLES N_i
1	2.15	2433	37,268	3,820
2	2.20	2490	38,135	138
3	0.00	0	0	0
4	0.00	0	0	0
5	0.00	0	0	0
6	0.00	0	0	0
7	0.00	0	0	0
8	0.00	0	0	0
			TOTAL CYCLES:	3,958

EQUIVALENT NUMBER OF CYCLES, BASED ON δ = **2.2** INCHES

IS: $N_{eq} = SUM(\delta_i/\delta_{max})^5 * N_i =$ 3,543

FOR NOMINAL DIMENSIONS: $i = 245{,}000 * N_{eq}^{(-0.2)}/S =$ **1.253**

FOR $Z(IN^3) =$ 3.215 i = **1.253**

COMMENTS:

1. L = 49.25 to the center of the elbow.
2. Deflection started at 1.75". Changed to 2.1" in 8 cycles.
3. Loading rate: 16 cycles/min.
4. At 3665 changed deflection to 2.5. Bottomed out at 3675. Restarted and reached 2.2 at 3690. Assume changed to 2.2 at 3665.

Test Data

TEST #: **ELBOW - D** TEST TYPE: **OUT-OF-PLANE** **FATIGUE - LOAD DEFLECTION CURVE** 11/19/98

F = Fo + m "m" TO BE BASED ON N DATA POINTS, N = 10

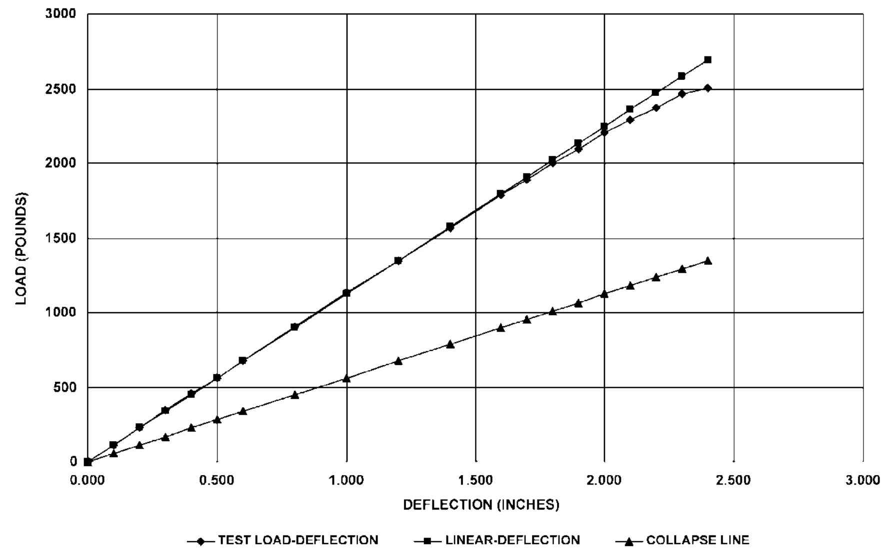
THE VALUE OF "m" = 1123 Fo (LBS) = 0

NOMINAL STRESS = M/Z KSI, M=F x L, L(IN) = 49.25 $Z(IN^3)$ = 3.215

DATA POINT #	MEASURED DEFLECTION (INCHES)	MEASURED LOAD F (LBS)	MODIFIED DEFLECTION (INCHES)	MODIFIED LOAD F (LBS)	SLOPE FOR START TO DATA POINT (LBS/INCH)	F BASED ON "m" (LBS)	NOMINAL STRESS (KSI)
1	0.00	0	0.000	0	N/A	0	
2	0.10	109	0.100	109	1,090	112	1.7
3	0.20	230	0.200	230	1,150	225	3.4
4	0.30	344	0.300	344	1,153	337	5.2
5	0.40	457	0.400	457	1,149	449	6.9
6	0.50	556	0.500	556	1,125	562	8.6
7	0.60	677	0.600	677	1,126	674	10.3
8	0.80	904	0.800	904	1,128	898	13.8
9	1.00	1131	1.000	1131	1,129	1123	17.2
10	1.20	1343	1.200	1343	1,123	1348	20.6
11	1.40	1570	1.400	1570	1,121	1572	24.1
12	1.60	1789	1.600	1789	1,119	1797	27.5
13	1.70	1888	1.700	1888	1,115	1909	29.2
14	1.80	2001	1.800	2001	1,112	2021	31.0
15	1.90	2092	1.900	2092	1,108	2134	32.7
16	2.00	2206	2.000	2206	1,105	2246	34.4
17	2.10	2289	2.100	2289	1,100	2358	36.1
18	2.20	2372	2.200	2372	1,093	2471	37.8
19	2.30	2463	2.300	2463	1,086	2583	39.6
20	2.40	2501	2.400	2501	1,074	2695	41.3
21							
22							
23							
24							
25							

NOTES:
1. Positive load is down.

POSITIVE LOAD - LOADING CONDITION



TEST #: **ELBOW - D** TEST TYPE: **OUT-OF-PLANE**

F = Fo + m "m" TO BE BASED ON N DATA POINTS, N = 12
THE VALUE OF "m" = 1194 Fo (LBS) = 300

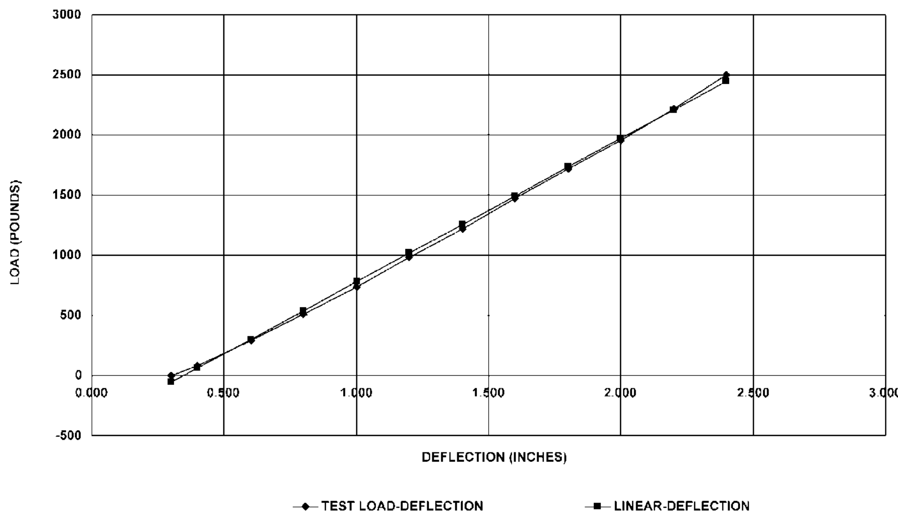
NOMINAL STRESS = M/Z KSI, M=F x L, L(IN) = 49.25 $Z(IN^3)$ = 3.215

DATA POINT #	MEASURED DEFLECTION (INCHES)	MEASURED LOAD F (LBS)	MODIFIED DEFLECTION (INCHES)	MODIFIED LOAD F (LBS)	SLOPE FOR START TO DATA POINT (LBS/INCH)	F BASED ON "m" (LBS)	NOMINAL STRESS (KSI)
1	2.40	2501	2.400	2501	N/A	2450	37.5
2	2.20	2221	2.200	2221	1,400	2211	33.9
3	2.00	1956	2.000	1956	1,362	1972	30.2
4	1.80	1721	1.800	1721	1,302	1733	26.5
5	1.60	1472	1.600	1472	1,279	1494	22.9
6	1.40	1214	1.400	1214	1,274	1255	19.2
7	1.20	980	1.200	980	1,261	1017	15.6
8	1.00	737	1.000	737	1,252	778	11.9
9	0.80	510	0.800	510	1,240	539	8.3
10	0.60	291	0.600	291	1,226	300	4.6
11	0.40	79	0.400	79	1,210	61	0.9
12	0.30	0	0.300	0	1,194	-58	-0.9
13							
14							
15							
16							
17							
18							
19							
20							
21							
22							
23							
24							
25							

NOTES:

FATIGUE - LOAD DEFLECTION CURVE 11/19/98

POSITIVE LOAD - UNLOADING CONDITION



Test Data

TEST #: **ELBOW - D** TEST TYPE: **OUT-OF-PLANE**

F = Fo + m "m" TO BE BASED ON N DATA POINTS, N = 10
THE VALUE OF "m" = 966 Fo (LBS) = 0

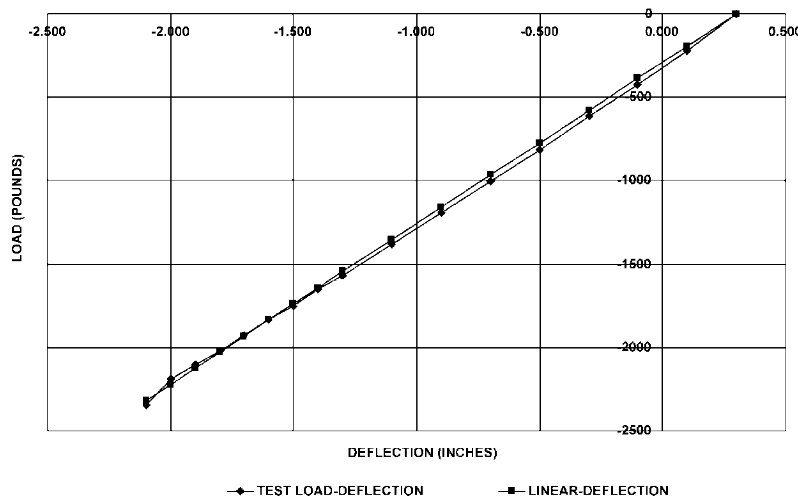
NOMINAL STRESS = M/Z KSI, M=F x L, L(IN) = 49.25 $Z(IN^3)$ = 3.215

DATA POINT #	MEASURED DEFLECTION (INCHES)	MEASURED LOAD F (LBS)	MODIFIED DEFLECTION (INCHES)	MODIFIED LOAD F (LBS)	SLOPE FOR START TO DATA POINT (LBS/INCH)	F BASED ON "m" (LBS)	NOMINAL STRESS (KSI)
1	0.300	0	0.300	0	N/A	0	0.0
2	0.100	-223	0.100	-223	1,115	-193	-3.0
3	-0.100	-427	-0.100	-427	1,068	-386	-5.9
4	-0.300	-616	-0.300	-616	1,026	-580	-8.9
5	-0.500	-813	-0.500	-813	1,010	-773	-11.8
6	-0.700	-1002	-0.700	-1002	996	-966	-14.8
7	-0.900	-1192	-0.900	-1192	986	-1159	-17.8
8	-1.100	-1381	-1.100	-1381	978	-1352	-20.7
9	-1.300	-1570	-1.300	-1570	973	-1546	-23.7
10	-1.400	-1653	-1.400	-1653	966	-1642	-25.2
11	-1.500	-1752	-1.500	-1752	963	-1739	-26.6
12	1.600	1835	1.600	1835	959	1835	28.1
13	-1.700	-1926	-1.700	-1926	955	-1932	-29.6
14	-1.800	-2024	-1.800	-2024	953	-2029	-31.1
15	-1.900	-2100	-1.900	-2100	948	-2125	-32.6
16	-2.000	-2191	-2.000	-2191	945	-2222	-34.0
17	-2.100	-2342	-2.100	-2342	948	-2319	-35.5
18							
19							
20							
21							
22							
23							
24							
25							

NOTES:

FATIGUE - LOAD DEFLECTION CURVE 11/19/98

NEGATIVE LOAD - LOADING CONDITION



TEST #: **ELBOW - D** TEST TYPE: **OUT-OF-PLANE**

F = Fo + m'Δ "m" TO BE BASED ON N DATA POINTS. N = 12
THE VALUE OF "m" = 1128 Fo (LBS) = -321

NOMINAL STRESS = M/Z KSI, M=F x L, L(IN) = 49 25 $Z(IN^3)$ = 3.215

DATA POINT #	MEASURED DEFLECTION (INCHES)	LOAD F (LBS)	MODIFIED DEFLECTION (INCHES)	LOAD F (LBS)	SLOPE FOR START TO DATA POINT (LBS/INCH)	F BASED ON "m" (LBS)	NOMINAL STRESS (KSI)
1	-2.10	-2342	-2.100	-2342	N/A	-2239	-34.3
2	-2.00	-2100	-2.000	-2100	2420	-2127	-32.6
3	-1.80	-1873	-1.800	-1873	1502	-1901	-29.1
4	-1.60	-1646	-1.600	-1646	1331	-1675	-25.7
5	-1.40	-1419	-1.400	-1419	1260	-1449	-22.2
6	-1.20	-1184	-1.200	-1184	1229	-1224	-18.7
7	-1.00	-965	-1.000	-965	1204	-998	-15.3
8	-0.80	-745	-0.800	-745	1184	-772	-11.8
9	-0.60	-526	-0.600	-526	1169	-547	-8.4
10	-0.40	-321	-0.400	-321	1154	-321	-4.9
11	-0.20	-109	-0.200	-109	1141	-95	-1.5
12	-0.08	0	-0.080	0	1128	40	0.6
13							
14							
15							
16							
17							
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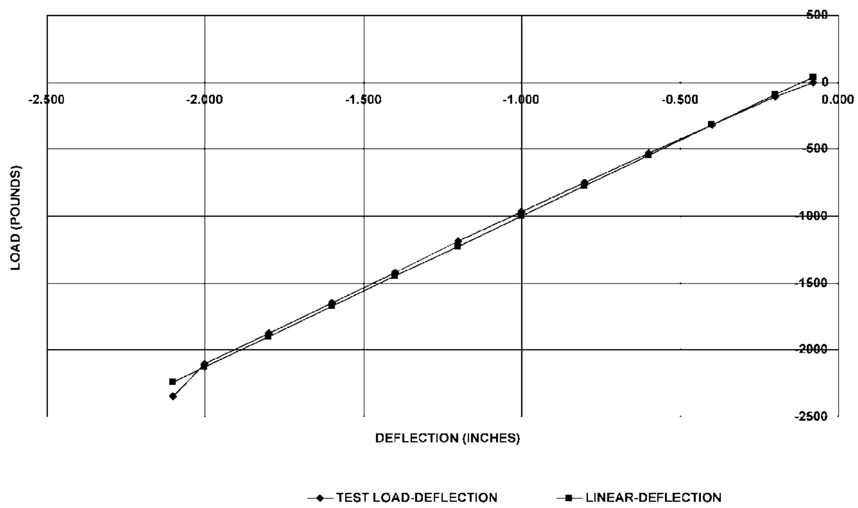
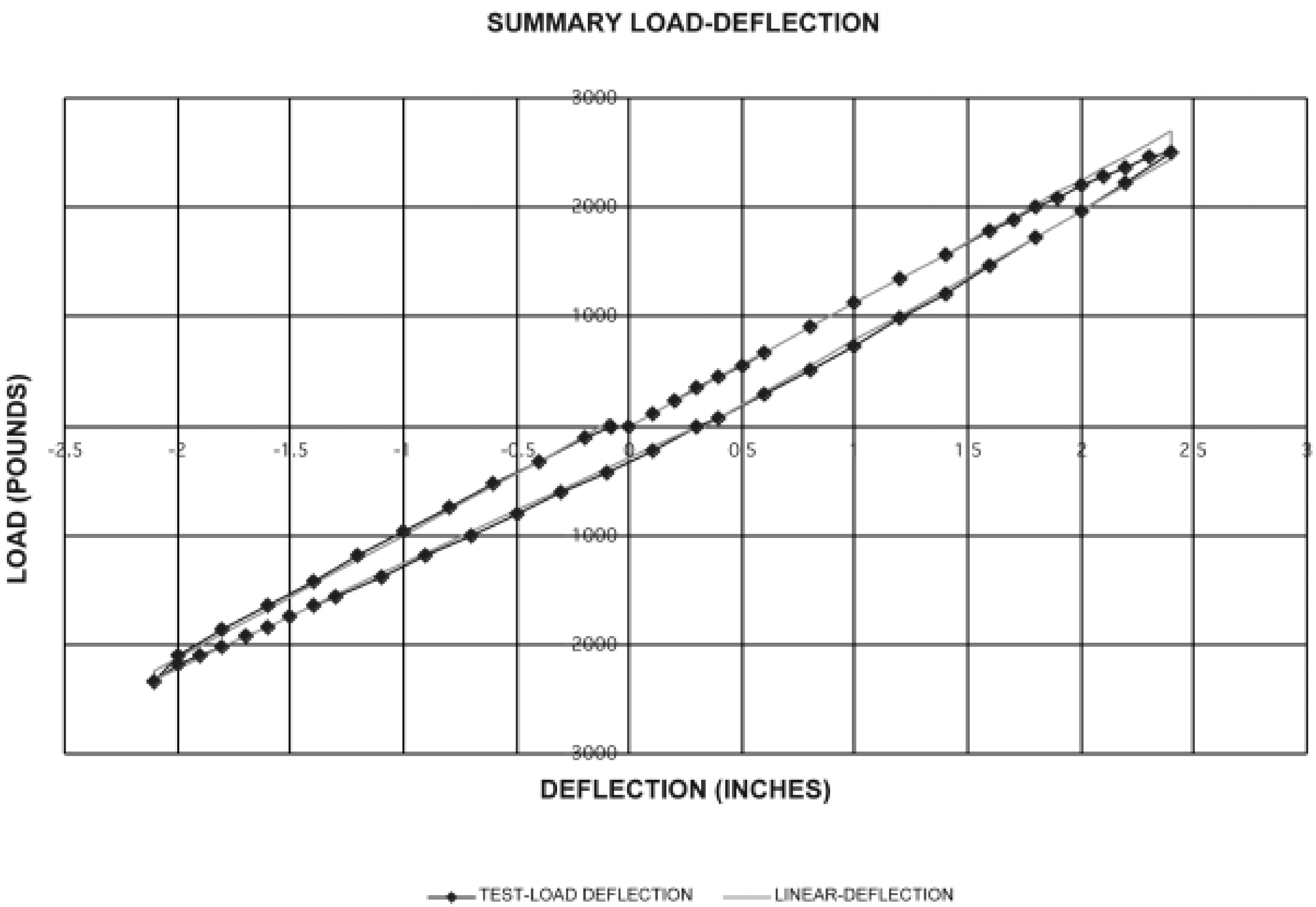
NOTES:

FATIGUE - LOAD DEFLECTION CURVE 11/19/98

NEGATIVE LOAD - UNLOADING CONDITION




SUMMARY LOAD-DEFLECTION
3000
2000
1000
1000
2000
3000
-2.5
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
2.5
3
LOAD (POUNDS)
DEFLECTION (INCHES)
TEST-LOAD DEFLECTION
LINEAR-DEFLECTION

FATIGUE TEST DATA ANALYSIS 11/19/98

TEST #: **ELBOW - D** TYPE: **OUT-OF-PLANE**

AVERAGE STIFFNESS (lbs/in) = 1103
MOMENT ARM (in)= 49.25

D (in) = 4.5 t (in) = 0.237 Z (in^3) = 0.0982(D^4-(D-2t)^4)/D= 3.215

TEST DISPLACEMENT/CYCLE DATA:

CONDITION #	DISPLACEMENT AMPLITUDE (+/-) (in.) d_i	EFFECTIVE APPLIED LOAD (lbs)	NOMINAL STRESS (+/-) (psi) S	NUMBER OF TEST CYCLES N_i
1	2.30	2537	38,857	2,879
2	0.00	0	0	0
3	0.00	0	0	0
4	0.00	0	0	0
5	0.00	0	0	0
6	0.00	0	0	0
7	0.00	0	0	0
8	0.00	0	0	0
			TOTAL CYCLES:	2,879

EQUIVALENT NUMBER OF CYCLES, BASED ON δ = **2.3** INCHES

IS: $N_{eq} = SUM(\delta_i/\delta_{max})^5 * N_i =$ 2,879

FOR NOMINAL DIMENSIONS: $i = 245{,}000 * N_{eq}^{(-0.2)}/S =$ **1.282**

FOR Z(IN^3) = 3.215 i = **1.282**

COMMENTS:

1. L = 49.25 to the center of the elbow.

TEST #: **ELBOW - E** TEST TYPE: **COMBINED-45**

F = Fo + m "m" TO BE BASED ON N DATA POINTS, N = 7

THE VALUE OF "m" = 1068 Fo (LBS) = 0

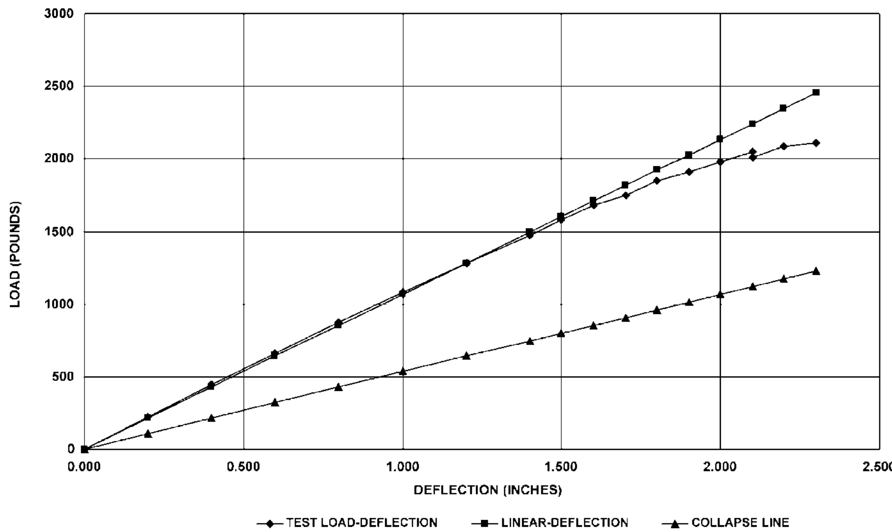
NOMINAL STRESS = M/Z KSI, M=F x L, L(IN) = 49.25 Z(IN³) = 3.215

DATA POINT #	MEASURED DEFLECTION (INCHES)	LOAD F (LBS)	MODIFIED DEFLECTION (INCHES)	LOAD F (LBS)	SLOPE FOR START TO DATA POINT (LBS/INCH)	F BASED ON "m" (LBS)	NOMINAL STRESS (KSI)
1	0.00	0	0.000	0	N/A	0	
2	0.20	226	0.200	226	1,130	214	3.3
3	0.40	446	0.400	446	1,115	427	6.5
4	0.60	659	0.600	659	1,099	641	9.8
5	0.80	877	0.800	877	1,094	854	13.1
6	1.00	1082	1.000	1082	1,082	1068	16.4
7	1.20	1279	1.200	1279	1,068	1281	19.6
8	1.40	1475	1.400	1475	1,055	1495	22.9
9	1.50	1581	1.500	1581	1,049	1602	24.5
10	1.60	1684	1.600	1684	1,045	1709	26.2
11	1.70	1748	1.700	1748	1,034	1815	27.8
12	1.80	1846	1.800	1846	1,026	1922	29.4
13	1.90	1914	1.900	1914	1,015	2029	31.1
14	2.00	1982	2.000	1982	1,002	2136	32.7
15	2.10	2050	2.100	2050	988	2243	34.3
16	2.10	2010	2.100	2010	974	2243	34.3
17	2.20	2088	2.200	2088	960	2349	36.0
18	2.30	2111	2.300	2111	942	2456	37.6
19							
20							
21							
22							
23							
24							
25							

NOTES:
1. Positive load is down

FATIGUE - LOAD DEFLECTION CURVE 11/19/98

POSITIVE LOAD - LOADING CONDITION



TEST #: **ELBOW - E** TEST TYPE: **COMBINED-45**

F = Fo + m "m" TO BE BASED ON N DATA POINTS, N = 10
THE VALUE OF "m" = 1106 Fo (LBS) = 100

NOMINAL STRESS = M/Z KSI, M=F x L, L(IN) = 49.25 $Z(IN^3)$ = 3.215

DATA POINT #	MEASURED DEFLECTION (INCHES)	MEASURED LOAD F (LBS)	MODIFIED DEFLECTION (INCHES)	MODIFIED LOAD F (LBS)	SLOPE FOR START TO DATA POINT (LBS/INCH)	F BASED ON "m" (LBS)	NOMINAL STRESS (KSI)
1	2.30	2111	2.300	2111	N/A	2091	32.0
2	2.10	1869	2.100	1869	1,210	1870	28.6
3	1.90	1626	1.900	1626	1,213	1649	25.3
4	1.70	1399	1.700	1399	1,189	1427	21.9
5	1.50	1180	1.500	1180	1,166	1206	18.5
6	1.30	945	1.300	945	1,161	985	15.1
7	1.10	733	1.100	733	1,148	764	11.7
8	0.90	529	0.900	529	1,132	542	8.3
9	0.70	317	0.700	317	1,120	321	4.9
10	0.50	120	0.500	120	1,106	100	1.5
11	0.39	0	0.390	0	1,099	-22	-0.3
12							
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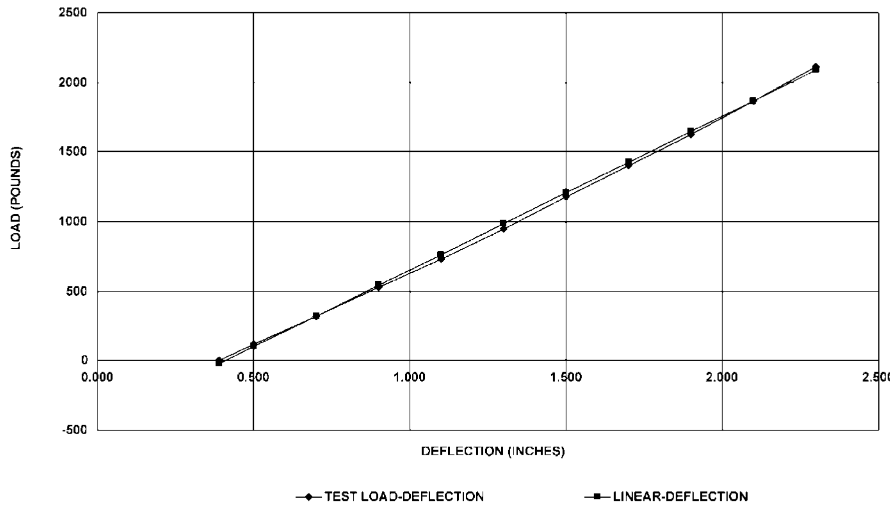
NOTES:

FATIGUE - LOAD DEFLECTION CURVE 11/19/98

POSITIVE LOAD - UNLOADING CONDITION



Test Data

TEST #: **ELBOW - E** TEST TYPE: **COMBINED-45**

F = Fo + m "m" TO BE BASED ON N DATA POINTS, N = 10
THE VALUE OF "m" = 888 Fo (LBS) = 0

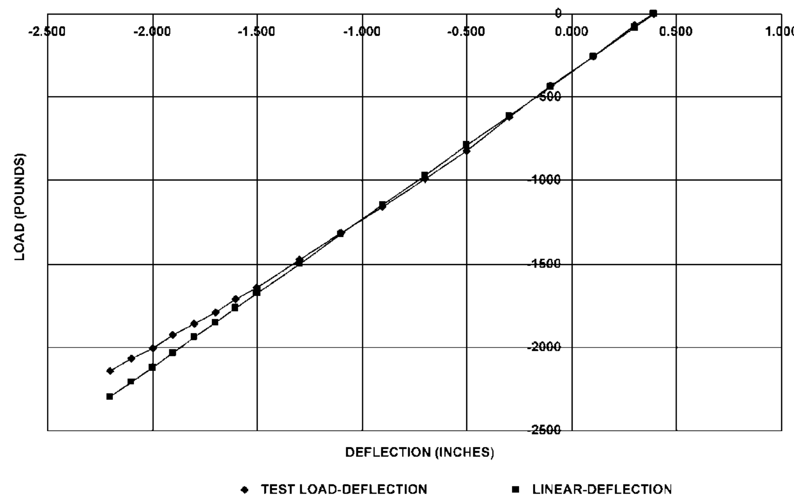
NOMINAL STRESS = M/Z KSI, M=F x L, L(IN) = 49.25 Z(IN^3) = 3.215

DATA POINT #	MEASURED DEFLECTION (INCHES)	LOAD F (LBS)	MODIFIED DEFLECTION (INCHES)	LOAD F (LBS)	SLOPE FOR START TO DATA POINT (LBS/INCH)	F BASED ON "m" (LBS)	NOMINAL STRESS (KSI)
1	0.390	0	0.390	0	N/A	0	0.0
2	0.300	-68	0.300	-68	756	-80	-1.2
3	0.100	-257	0.100	-257	896	-257	-3.9
4	-0.100	-431	-0.100	-431	891	-435	-6.7
5	-0.300	-620	-0.300	-620	903	-612	-9.4
6	-0.500	-825	-0.500	-825	925	-790	-12.1
7	-0.700	-991	-0.700	-991	921	-968	-14.8
8	-0.900	-1158	-0.900	-1158	912	-1145	-17.5
9	-1.100	-1317	-1.100	-1317	900	-1323	-20.3
10	-1.300	-1476	-1.300	-1476	888	-1500	-23.0
11	-1.500	-1642	-1.500	-1642	878	-1678	-25.7
12	-1.600	-1710	-1.600	-1710	870	-1766	-27.1
13	-1.700	-1793	-1.700	-1793	864	-1855	-28.4
14	-1.800	-1862	-1.800	-1862	857	-1944	-29.8
15	-1.900	-1930	-1.900	-1930	851	-2033	-31.1
16	-2.000	-2005	-2.000	-2005	845	-2121	-32.5
17	-2.100	-2066	-2.100	-2066	838	-2210	-33.9
18	-2.200	-2142	-2.200	-2142	833	-2299	-35.2
19							
20							
21							
22							
23							
24							
25							

NOTES:

FATIGUE - LOAD DEFLECTION CURVE 11/19/98

NEGATIVE LOAD - LOADING CONDITION



TEST #: **ELBOW - E** TEST TYPE: **COMBINED-45**

F = Fo + m "m" TO BE BASED ON N DATA POINTS, N = 12
THE VALUE OF "m" = 1012 Fo (LBS) = -280

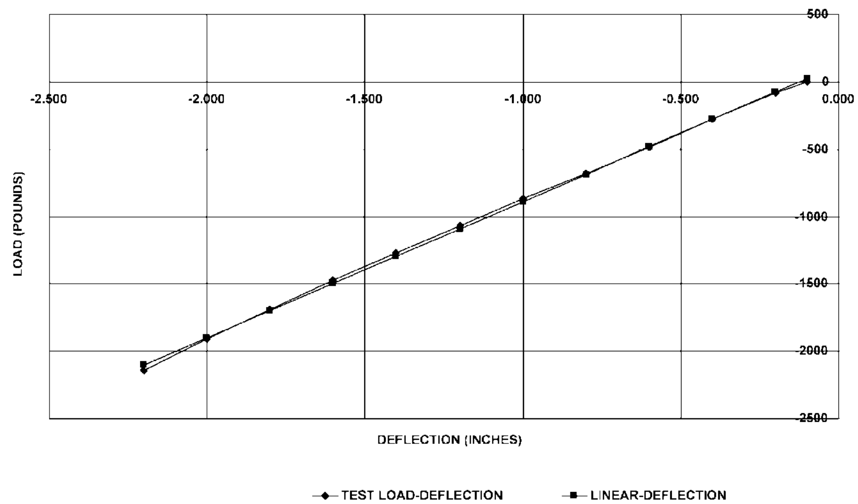
NOMINAL STRESS = M/Z KSI, M=F x L, L (IN) = 49.25 Z(IN³) = 3.215

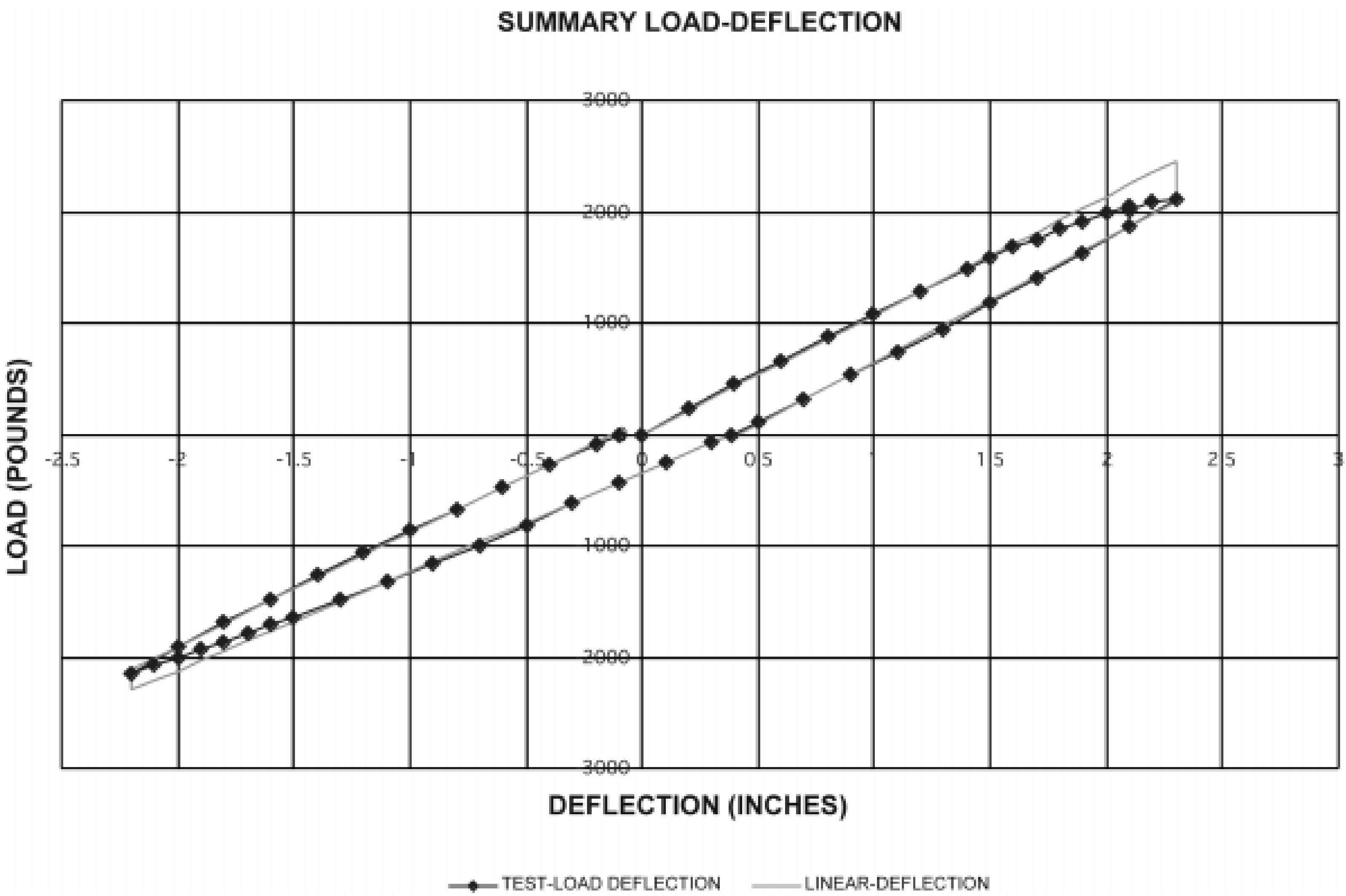
DATA POINT #	MEASURED DEFLECTION (INCHES)	MEASURED LOAD F (LBS)	MODIFIED DEFLECTION (INCHES)	MODIFIED LOAD F (LBS)	SLOPE FOR START TO DATA POINT (LBS/INCH)	F BASED ON "m" (LBS)	NOMINAL STRESS (KSI)
1	-2.20	-2142	-2.200	-2142	N/A	-2102	-32.2
2	-2.00	-1907	-2.000	-1907	1175	-1900	-29.1
3	-1.80	-1688	-1.800	-1688	1135	-1697	-26.0
4	-1.60	-1476	-1.600	-1476	1109	-1495	-22.9
5	-1.40	-1271	-1.400	-1271	1087	-1292	-19.8
6	-1.20	-1067	-1.200	-1067	1071	-1090	-16.7
7	-1.00	-863	-1.000	-863	1060	-887	-13.6
8	-0.80	-681	-0.800	-681	1043	-685	-10.5
9	-0.60	-484	-0.600	-484	1031	-482	-7.4
10	0.40	280	0.400	280	1024	280	4.3
11	-0.20	-83	-0.200	-83	1019	-78	-1.2
12	-0.10	0	-0.100	0	1012	24	0.4
13							
14							
15							
16							
17							
18							
19							
20							
21							
22							
23							
24							
25							

NOTES:

FATIGUE - LOAD DEFLECTION CURVE 11/19/98

NEGATIVE LOAD - UNLOADING CONDITION




SUMMARY LOAD-DEFLECTION
LOAD (POUNDS)
DEFLECTION (INCHES)
3000
2000
1000
1000
2000
3000
-2.5
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
2.5
3
TEST-LOAD DEFLECTION
LINEAR-DEFLECTION

FATIGUE TEST DATA ANALYSIS 11/19/98

TEST #: **ELBOW - E** TYPE: **COMBINED-45**

AVERAGE STIFFNESS (lbs/in) = 1018
MOMENT ARM (in)= 49.25

D (in) = 4.5 t (in) = 0.237 $Z\ (in^3) = 0.0982(D^4-(D-2t)^4)/D=$ 3.215

TEST DISPLACEMENT/CYCLE DATA:

CONDITION #	DISPLACEMENT AMPLITUDE (+/-) (in.) d_i	EFFECTIVE APPLIED LOAD (lbs)	NOMINAL STRESS (+/-) (psi) S	NUMBER OF TEST CYCLES N_i
1	2.05	2088	31,981	3,344
2	0.00	0	0	0
3	0.00	0	0	0
4	0.00	0	0	0
5	0.00	0	0	0
6	0.00	0	0	0
7	0.00	0	0	0
8	0.00	0	0	0
			TOTAL CYCLES:	3,344

EQUIVALENT NUMBER OF CYCLES, BASED ON δ = **2.05** INCHES

IS: $N_{eq} = SUM(\delta_i/\delta_{max})^5 * N_i =$ 3,344

FOR NOMINAL DIMENSIONS: $i = 245{,}000 * N_{eq}^{(-0.2)}/S =$ **1.512**

FOR $Z(IN^3) =$ 3.215 i = **1.512**

COMMENTS:

1. L = 49.25 to the center of the elbow.
2. Tests stopped at about 2600 cycles. Then restarted.

Test Data

TEST #: **ELBOW - F** TEST TYPE: **COMBINED-45**

F = Fo + m "m" TO BE BASED ON N DATA POINTS, N = 10
THE VALUE OF "m" = 1114 Fo (LBS) = 0

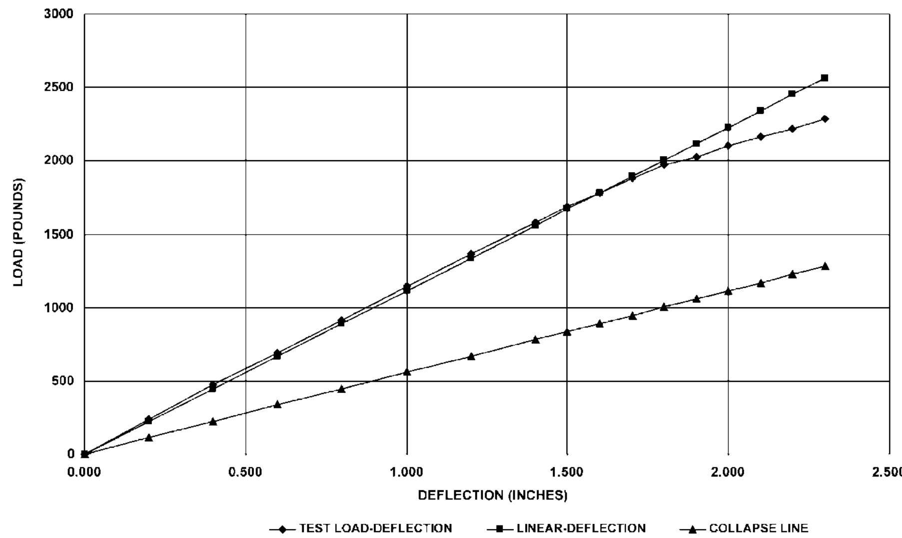
NOMINAL STRESS = M/Z KSI, M=F x L, L(IN) = 49.25 Z(IN³) = 3.215

DATA POINT #	MEASURED DEFLECTION (INCHES)	LOAD F (LBS)	MODIFIED DEFLECTION (INCHES)	LOAD F (LBS)	SLOPE FOR START TO DATA POINT (LBS/INCH)	F BASED ON "m" (LBS)	NOMINAL STRESS (KSI)
1	0.00	0	0.000	0	N/A	0	
2	0.20	237	0.200	237	1,185	223	3.4
3	0.40	479	0.400	479	1,198	446	6.8
4	0.60	691	0.600	691	1,158	669	10.2
5	0.80	911	0.800	911	1,138	891	13.7
6	1.00	1145	1.000	1145	1,137	1114	17.1
7	1.20	1365	1.200	1365	1,133	1337	20.5
8	1.40	1577	1.400	1577	1,125	1560	23.9
9	1.50	1690	1.500	1690	1,122	1671	25.6
10	1.60	1781	1.600	1781	1,114	1783	27.3
11	1.70	1880	1.700	1880	1,107	1894	29.0
12	1.80	1970	1.800	1970	1,099	2006	30.7
13	1.90	2023	1.900	2023	1,083	2117	32.4
14	2.00	2099	2.000	2099	1,068	2229	34.1
15	2.10	2167	2.100	2167	1,051	2340	35.8
16	2.20	2220	2.200	2220	1,032	2451	37.5
17	2.30	2288	2.300	2288	1,014	2563	39.3
18							
19							
20							
21							
22							
23							
24							
25							

NOTES:
1. Positive load is down.

FATIGUE - LOAD DEFLECTION CURVE 11/19/98

POSITIVE LOAD - LOADING CONDITION



TEST #: **ELBOW - F** TEST TYPE: **COMBINED-45**

F = Fo - m "m" TO BE BASED ON N DATA POINTS, N = 9
THE VALUE OF "m" = 1225 Fo (LBS) = 50

NOMINAL STRESS = M/Z KSI, M=F x L, L(IN) = 49.25 $Z(IN^3)$ = 3.215

DATA POINT #	MEASURED DEFLECTION (INCHES)	MEASURED LOAD F (LBS)	MODIFIED DEFLECTION (INCHES)	MODIFIED LOAD F (LBS)	SLOPE FOR START TO DATA POINT (LBS/INCH)	F BASED ON "m" (LBS)	NOMINAL STRESS (KSI)
1	2.30	2288	2.300	2288	N/A	2255	34.5
2	2.10	1993	2.100	1993	1,475	2010	30.8
3	1.90	1728	1.900	1728	1,400	1765	27.0
4	1.70	1486	1.700	1486	1,336	1520	23.3
5	1.50	1244	1.500	1244	1,298	1275	19.5
6	1.30	1002	1.300	1002	1,274	1030	15.8
7	1.10	767	1.100	767	1,255	785	12.0
8	0.90	540	0.900	540	1,237	540	8.3
9	0.70	305	0.700	305	1,225	295	4.5
10	0.50	93	0.500	93	1,209	50	0.8
11	0.41	0	0.410	0	1,198	60	0.9
12							
13							
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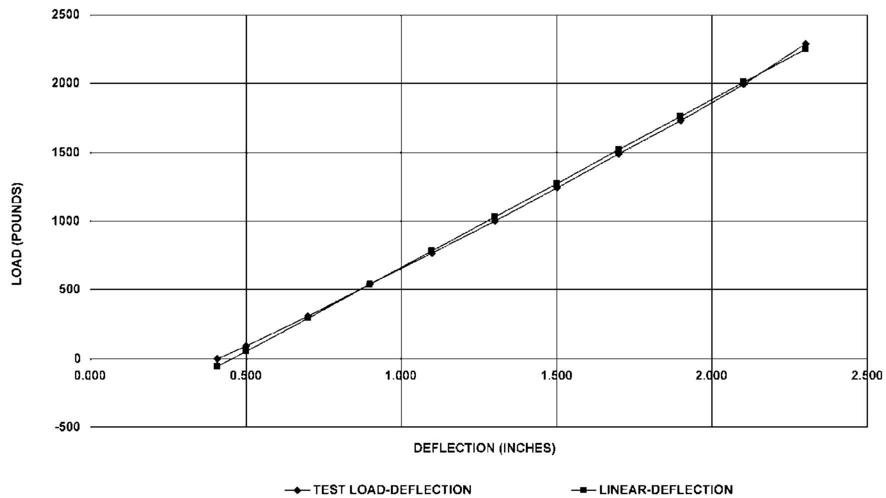
NOTES:

FATIGUE - LOAD DEFLECTION CURVE 11/19/98

POSITIVE LOAD - UNLOADING CONDITION



Test Data

TEST #: **ELBOW - F** TEST TYPE: **COMBINED-45**

F = Fo + m "m" TO BE BASED ON N DATA POINTS, N = 8
THE VALUE OF "m" = 973 Fo (LBS) = 0

NOMINAL STRESS = M/Z KSI, M=F x L, L(IN) = 49.25 Z(IN^3) = 3.215

DATA POINT #	MEASURED DEFLECTION (INCHES)	LOAD F (LBS)	MODIFIED DEFLECTION (INCHES)	LOAD F (LBS)	SLOPE FOR START TO DATA POINT (LBS/INCH)	F BASED ON "m" (LBS)	NOMINAL STRESS (KSI)
1	0.410	0	0.410	0	N/A	0	0.0
2	0.300	-87	0.300	-87	791	-107	-1.6
3	0.100	-307	0.100	-307	1,004	-302	-4.6
4	-0.100	-504	-0.100	-504	1,006	-496	-7.6
5	-0.300	-693	-0.300	-693	992	-691	-10.6
6	-0.500	-897	-0.500	-897	993	-886	-13.6
7	-0.700	-1079	-0.700	-1079	984	-1080	-16.6
8	-0.900	-1260	-0.900	-1260	973	-1275	-19.5
9	-1.100	-1442	-1.100	-1442	964	-1470	-22.5
10	-1.300	-1616	-1.300	-1616	954	-1665	-25.5
11	-1.500	-1775	-1.500	-1775	941	-1859	-28.5
12	-1.600	-1856	-1.600	-1856	932	-1957	-30.0
13	-1.700	-1951	-1.700	-1951	927	-2054	-31.5
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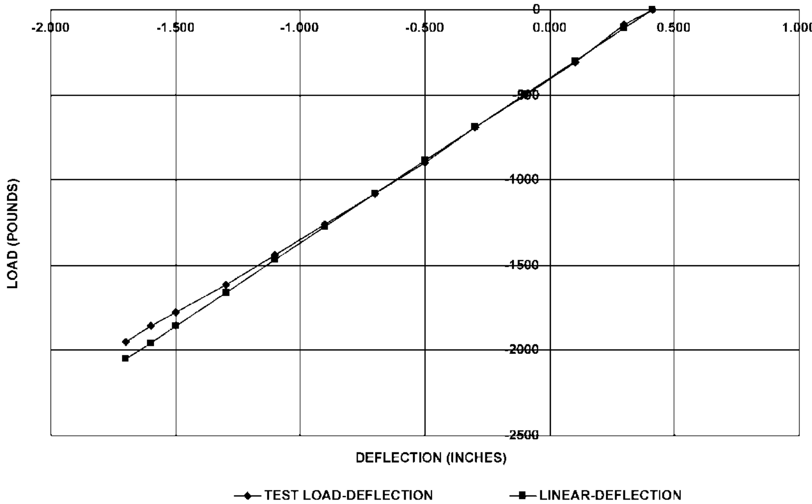
NOTES:

FATIGUE - LOAD DEFLECTION CURVE 11/19/98

NEGATIVE LOAD - LOADING CONDITION



TEST #: **ELBOW - F** TEST TYPE: **COMBINED-45**

F = Fo + m

"m" TO BE BASED ON N DATA POINTS, N = 12

THE VALUE OF "m" = 1118 Fo (LBS) = -1200

NOMINAL STRESS = M/Z KS , M=F x L, L(IN) = 49.25 Z(N³) = 3.215

DATA POINT #	MEASURED DEFLECTION (INCHES)	MEASURED LOAD F (LBS)	MODIFIED DEFLECTION (INCHES)	MODIFIED LOAD F (LBS)	SLOPE FOR START TO DATA POINT (LBS/INCH)	F BASED ON "m" (LBS)	NOMINAL STRESS (KSI)
1	-1.70	-1951	-1.700	-1951	N/A	-1200	-18.4
2	-1.73	-1866	-1.730	-1866	-2833	-1234	-18.9
3	-2.37	-1862	-2.370	-1862	-75	-1949	-29.9
4	-2.13	-1597	-2.130	-1597	-207	-1681	-25.7
5	-2.08	-1619	-2.080	-1619	-250	-1625	-24.9
6	-2.00	-1506	-2.000	-1506	-249	-1536	-23.5
7	-1.80	-1279	-1.800	-1279	-5	-1312	-20.1
8	-1.60	-1067	-1.600	-1067	405	-1088	-16.7
9	-1.40	-855	-1.400	-855	744	-864	-13.2
10	-1.20	-620	-1.200	-620	954	-641	-9.8
11	-1.00	-401	-1.000	-401	1064	-417	-6.4
12	-0.80	-181	-0.800	-181	1118	-193	-3.0
13	-0.62	0	-0.620	0	1141	8	0.1
14							
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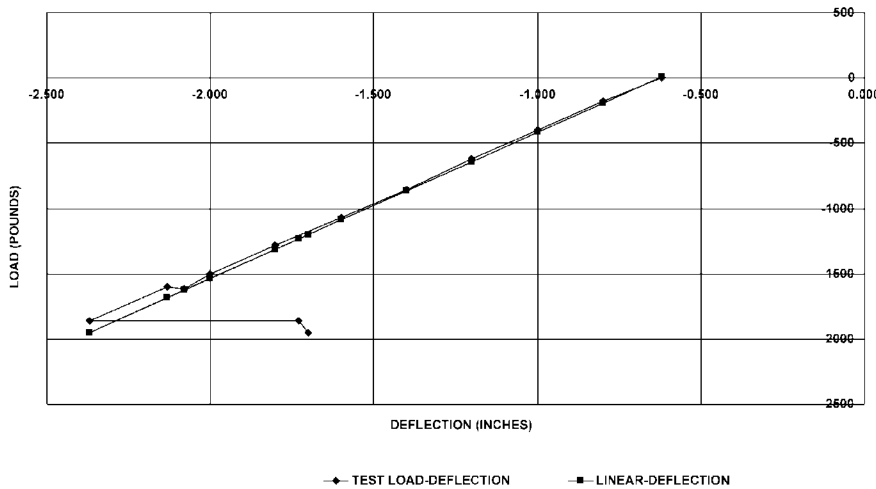
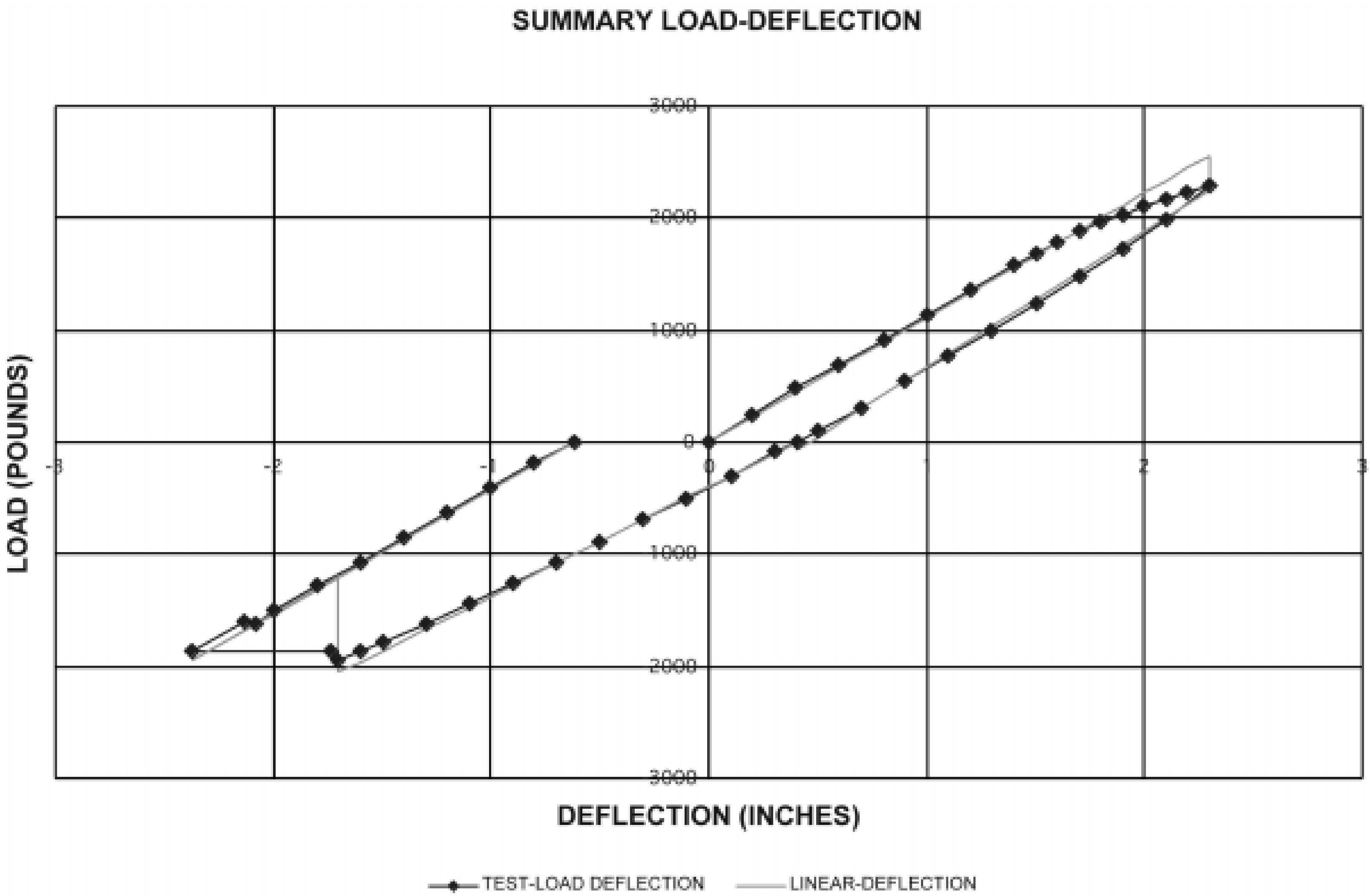
FATIGUE - LOAD DEFLECTION CURVE 11/19/98

NEGATIVE LOAD - UNLOADING CONDITION



NOTES:
1. At the beginning of the down oad, there was a problem with the software which required a shut down and restart. When restarted, the "offset" displacement was incorrect. The change in displacement and change in loads were correct.


SUMMARY LOAD-DEFLECTION
3000
2000
1000
0
-1000
-2000
-3000
-3
-2
-1
0
1
2
3
LOAD (POUNDS)
DEFLECTION (INCHES)
TEST-LOAD DEFLECTION
LINEAR-DEFLECTION

FATIGUE TEST DATA ANALYSIS 11/19/98

TEST #: **ELBOW - F** TYPE: **COMBINED-45**

AVERAGE STIFFNESS (lbs/in) = 1108
MOMENT ARM (in)= 49.25

D (in) = 4.5 t (in) = 0.237 Z (in^3) = $0.0982(D^4-(D-2t)^4)/D$= 3.215

TEST DISPLACEMENT/CYCLE DATA:

CONDITION #	DISPLACEMENT AMPLITUDE (+/-) (in.) d_i	EFFECTIVE APPLIED LOAD (lbs)	NOMINAL STRESS (+/-) (psi) S	NUMBER OF TEST CYCLES N_i
1	1.90	2105	32,238	2,917
2	0.00	0	0	0
3	0.00	0	0	0
4	0.00	0	0	0
5	0.00	0	0	0
6	0.00	0	0	0
7	0.00	0	0	0
8	0.00	0	0	0
			TOTAL CYCLES:	2,917

EQUIVALENT NUMBER OF CYCLES, BASED ON δ = **1.9** INCHES

IS: $N_{eq} = SUM(\delta_i/\delta_{max})^5 * N_i$ = 2,917

FOR NOMINAL DIMENSIONS: $i = 245{,}000 * N_{eq}^{(-0.2)}/S$ = **1.541**

FOR Z(IN^3) = 3.215 i = **1.541**

COMMENTS:

1. L = 49.25 to the center of the elbow.
2. Bolt replaced at 1245 cycles.

Test Data

TEST #: **ELBOW - G** TEST TYPE: **COMBINED-45**

FATIGUE - LOAD DEFLECTION CURVE 11/19/98

POSITIVE LOAD - LOADING CONDITION

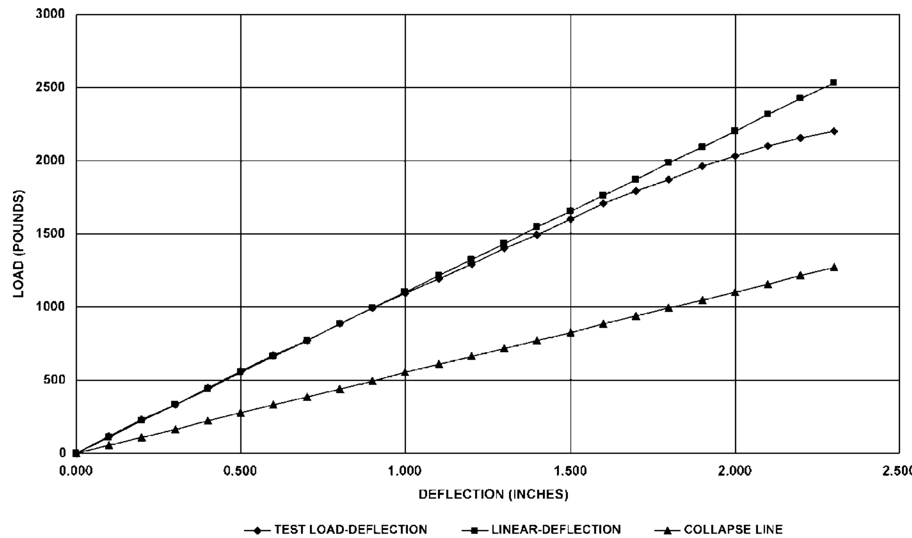
F = Fo + m "m" TO BE BASED ON N DATA POINTS, N = 10

THE VALUE OF "m" = 1102 Fo (LBS) = 0

NOMINAL STRESS = M/Z KSI, M=F x L, L(IN) = 49.25 Z(IN^3) = 3.215

DATA POINT #	MEASURED DEFLECTION (INCHES)	MEASURED LOAD F (LBS)	MODIFIED DEFLECTION (INCHES)	MODIFIED LOAD F (LBS)	SLOPE FOR START TO DATA POINT (LBS/INCH)	F BASED ON 'm" (LBS)	NOMINAL STRESS (KSI)
1	0.00	0	0.000	0	N/A	0	
2	0.10	115	0.100	115	1.150	110	1.7
3	0.20	228	0.200	228	1.140	220	3.4
4	0.30	334	0.300	334	1.115	331	5.1
5	0.40	448	0.400	448	1.115	441	6.8
6	0.50	561	0.500	561	1.117	551	8.4
7	0.60	667	0.600	667	1.112	661	10.1
8	0.70	773	0.700	773	1.105	771	11.8
9	0.80	887	0.800	887	1.105	881	13.5
10	0.90	993	0.900	993	1.102	992	15.2
11	1.00	1091	1.000	1091	1.095	1102	16.9
12	1.10	1190	1.100	1190	1.087	1212	18.6
13	1.20	1296	1.200	1296	1.081	1322	20.3
14	1.30	1401	1.300	1401	1.076	1432	21.9
15	1.40	1492	1.400	1492	1.069	1542	23.6
16	1.50	1598	1.500	1598	1.064	1653	25.3
17	1.60	1704	1.600	1704	1.061	1763	27.0
18	1.70	1795	1.700	1795	1.056	1873	28.7
19	1.80	1871	1.800	1871	1.047	1983	30.4
20	1.90	1962	1.900	1962	1.039	2093	32.1
21	2.00	2030	2.000	2030	1.029	2203	33.8
22	2.10	2098	2.100	2098	1.017	2314	35.4
23	2.20	2151	2.200	2151	1.002	2424	37.1
24	2.30	2198	2.300	2198	986	2534	38.8
25							

NOTES:
1. Positive load is down.



TEST #: **ELBOW - G** TEST TYPE: **COMBINED-45**

F = Fo + m "m" TO BE BASED ON N DATA POINTS, N = 12
THE VALUE OF "m" = 1121 Fo (LBS) = 200

NOMINAL STRESS = M/Z KSI, M=F x L, L(IN) = 49.25 Z(IN³) = 3.215

DATA POINT #	MEASURED DEFLECTION (INCHES)	MEASURED LOAD F (LBS)	MODIFIED DEFLECTION (INCHES)	MODIFIED LOAD F (LBS)	SLOPE FOR START TO DATA POINT (LBS/INCH)	F BASED ON "m" (LBS)	NOMINAL STRESS (KSI)
1	2.30	2198	2.300	2198	N/A	2106	32.3
2	2.10	1939	2.100	1939	1,295	1882	28.8
3	2.00	1825	2.000	1825	1,251	1770	27.1
4	1.80	1591	1.800	1591	1,211	1546	23.7
5	1.60	1349	1.600	1349	1,204	1321	20.2
6	1.40	1137	1.400	1137	1,178	1097	16.8
7	1.20	910	1.200	910	1,164	873	13.4
8	1.00	682	1.000	682	1,157	649	9.9
9	0.80	463	0.800	463	1,149	424	6.5
10	0.60	251	0.600	251	1,140	200	3.1
11	0.40	39	0.400	39	1,131	-24	-0.4
12	0.34	0	0.340	0	1,121	-92	-1.4
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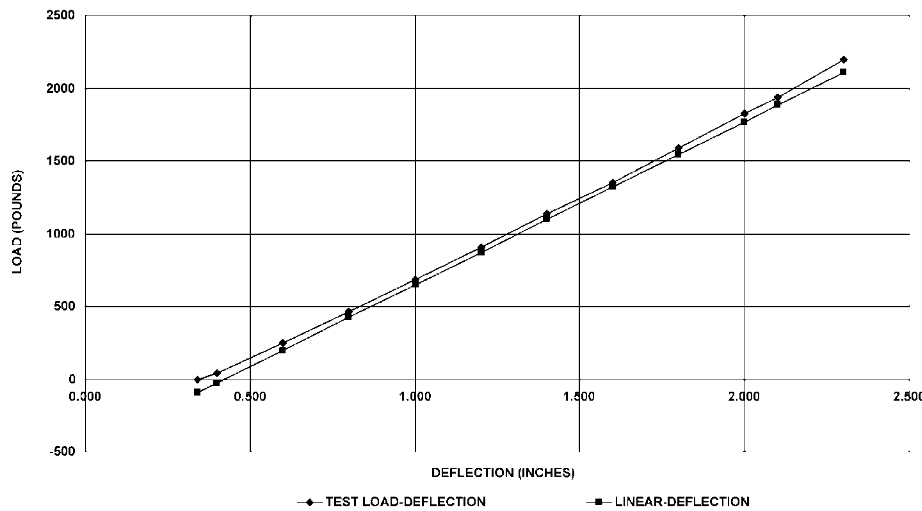
NOTES:

FATIGUE - LOAD DEFLECTION CURVE 11/19/98

POSITIVE LOAD - UNLOADING CONDITION



Test Data

TEST #: **ELBOW - G** TEST TYPE: **COMBINED-45** **FATIGUE - LOAD DEFLECTION CURVE** 11/19/98

NEGATIVE LOAD - LOADING CONDITION

F = Fo + m "m" TO BE BASED ON N DATA POINTS, N = 8
THE VALUE OF "m" = 964 Fo (LBS) = 0

NOMINAL STRESS = M/Z KSI, M=F x L, L(IN) = 49.25 $Z(IN^3)$ = 3.215

DATA POINT #	MEASURED DEFLECTION (INCHES)	MEASURED LOAD F (LBS)	MODIFIED DEFLECTION (INCHES)	MODIFIED LOAD F (LBS)	SLOPE FOR START TO DATA POINT (LBS/INCH)	F BASED ON "m" (LBS)	NOMINAL STRESS (KSI)
1	0.34	0	0.34	0	N/A	0	0.0
2	0.20	-141	0.20	-141	1,007	-135	-2.1
3	0.00	-346	0.00	-346	1,018	-328	-5.0
4	-0.20	-527	-0.20	-527	980	-521	-8.0
5	-0.40	-724	-0.40	-724	975	-713	-10.9
6	-0.60	-921	-0.60	-921	975	-906	-13.9
7	-0.80	-1118	-0.80	-1118	976	-1099	-16.8
8	-1.00	-1284	-1.00	-1284	964	-1292	-19.8
9	-1.10	-1368	-1.10	-1368	955	-1388	-21.3
10	-1.20	-1451	-1.20	-1451	946	-1485	-22.7
11	-1.30	-1557	-1.30	-1557	944	-1581	-24.2
12	-1.40	-1617	-1.40	-1617	936	-1677	-25.7
13	-1.50	-1706	-1.50	-1706	929	-1774	-27.2
14	-1.60	-1776	-1.60	-1776	921	-1870	-28.6
15	-1.70	-1844	-1.70	-1844	912	-1967	-30.1
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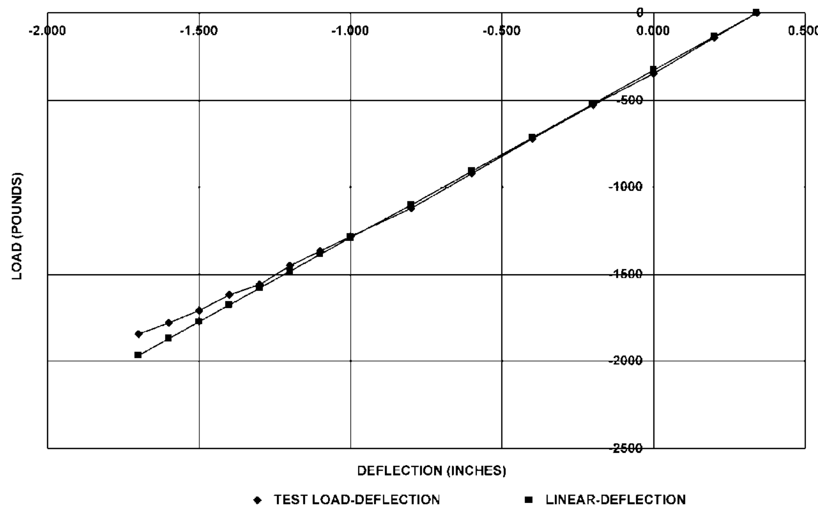
NOTES:



TEST #: **ELBOW - G** TEST TYPE: **COMBINED-45** **FATIGUE - LOAD DEFLECTION CURVE** 11/19/98

NEGATIVE LOAD - UNLOADING CONDITION

F = Fo + m "m" TO BE BASED ON N DATA POINTS, N = 10
THE VALUE OF "m" = 1030 Fo (LBS) = -1800

NOMINAL STRESS = M/Z KSI, M=F x L, L(IN) = 49.25 Z(IN³) = 3.215

DATA POINT #	MEASURED DEFLECTION (INCHES)	MEASURED LOAD F (LBS)	MODIFIED DEFLECTION (INCHES)	MODIFIED LOAD F (LBS)	SLOPE FOR START TO DATA POINT (LBS/INCH)	F BASED ON "m" (LBS)	NOMINAL STRESS (KSI)
1	1.70	1844	1.700	1844	N/A	1800	27.6
2	-1.60	-1655	-1.600	-1655	1890	-1697	-26.0
3	-1.40	-1458	-1.400	-1458	1244	-1491	-22.8
4	-1.20	-1239	-1.200	-1239	1164	-1285	-19.7
5	-1.00	-1049	-1.000	-1049	1103	-1079	-16.5
6	-0.80	-845	-0.800	-845	1074	-873	-13.4
7	-0.60	-641	-0.600	-641	1059	-667	-10.2
8	-0.40	-444	-0.400	-444	1046	-461	-7.1
9	-0.20	-247	-0.200	-247	1036	-255	-3.9
10	0.00	-43	0.000	-43	1030	-49	-0.7
11	0.05	0	0.050	0	1025	3	0.0
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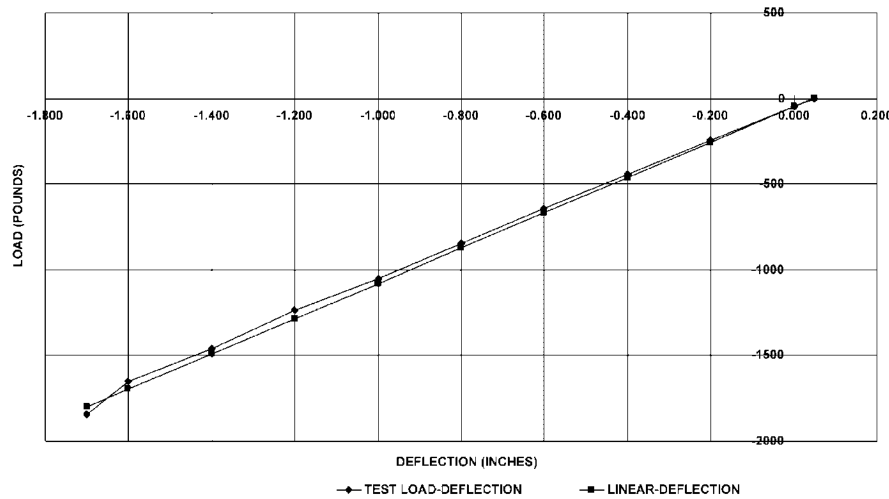
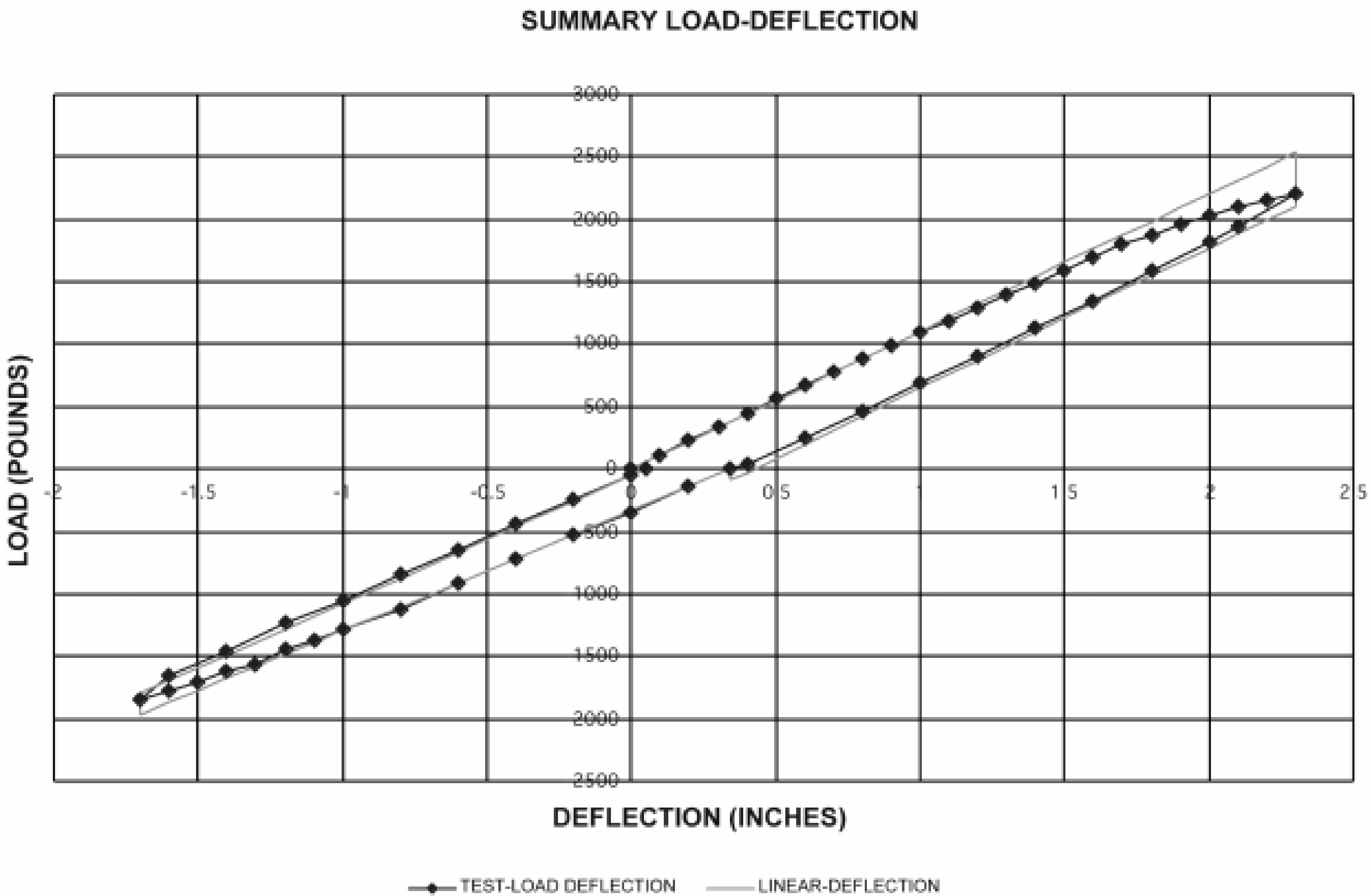


NOTES:
1. At the beginning of the download, there was a problem with the software which required a shut down and restart. When restarted, the "offset" displacement was incorrect. The change in displacement and change in loads were correct.


SUMMARY LOAD-DEFLECTION
3000
2500
2000
1500
1000
500
0
-500
-1000
-1500
-2000
-2500
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
2.5
LOAD (POUNDS)
DEFLECTION (INCHES)
TEST-LOAD DEFLECTION
LINEAR-DEFLECTION

FATIGUE TEST DATA ANALYSIS 11/19/98

TEST #: **ELBOW - G** TYPE: **COMBINED-45**

AVERAGE STIFFNESS (lbs/in) = 1054
MOMENT ARM (in)= 49.25

D (in) = 4.5 t (in) = 0.237 Z (in^3) = $0.0982(D^4-(D-2t)^4)/D=$ 3.215

TEST DISPLACEMENT/CYCLE DATA:

CONDITION #	DISPLACEMENT AMPLITUDE (+/-) (in.) d_i	EFFECTIVE APPLIED LOAD (lbs)	NOMINAL STRESS (+/-) (psi) S	NUMBER OF TEST CYCLES N_i
1	2.03	2135	32,703	2,157
2	0.00	0	0	0
3	0.00	0	0	0
4	0.00	0	0	0
5	0.00	0	0	0
6	0.00	0	0	0
7	0.00	0	0	0
8	0.00	0	0	0
			TOTAL CYCLES:	2,157

EQUIVALENT NUMBER OF CYCLES, BASED ON δ = **2.025** INCHES

IS: $N_{eq} = SUM(\delta_i/\delta_{max})^5 * N_i =$ 2,157

FOR NOMINAL DIMENSIONS: $i = 245{,}000 * N_{eq}^{(-0.2)}/S =$ **1.614**

FOR Z(IN^3) = 3.215 i = **1.614**

COMMENTS:

Test Data

TEST #: **ELBOW - H** TEST TYPE: **COMBINED-45** **FATIGUE - LOAD DEFLECTION CURVE** 11/19/98

POSITIVE LOAD - LOADING CONDITION

F = Fo + m "m" TO BE BASED ON N DATA POINTS, N = 10
THE VALUE OF "m" = 1089 Fo (LBS) = 0

NOMINAL STRESS = M/Z KSI, M=F x L, L(IN) = 49.25 $Z(IN^3)$ = 3.215

DATA POINT #	MEASURED DEFLECTION (INCHES)	MEASURED LOAD F (LBS)	MODIFIED DEFLECTION (INCHES)	MODIFIED LOAD F (LBS)	SLOPE FOR START TO DATA POINT (LBS/INCH)	F BASED ON "m" (LBS)	NOMINAL STRESS (KSI)
1	0.00	0	0.000	0	N/A	0	
2	0.10	104	0.100	104	1,040	109	1.7
3	0.30	332	0.300	332	1,111	327	5.0
4	0.50	551	0.500	551	1,108	545	8.3
5	0.70	770	0.700	770	1,104	762	11.7
6	0.90	990	0.900	990	1,103	980	15.0
7	1.10	1210	1.100	1210	1,102	1198	18.3
8	1.30	1414	1.300	1414	1,094	1416	21.7
9	1.40	1527	1.400	1527	1,092	1525	23.4
10	1.50	1628	1.500	1628	1,089	1634	25.0
11	1.60	1724	1.600	1724	1,084	1742	26.7
12	1.70	1822	1.700	1822	1,079	1851	28.4
13	1.80	1921	1.800	1921	1,074	1960	30.0
14	1.90	2019	1.900	2019	1,069	2069	31.7
15	2.00	2095	2.000	2095	1,061	2178	33.4
16	2.10	2140	2.100	2140	1,047	2287	35.0
17	2.20	2220	2.200	2220	1,034	2396	36.7
18	2.30	2290	2.300	2290	1,020	2505	38.4
19	2.40	2330	2.400	2330	1,003	2614	40.0
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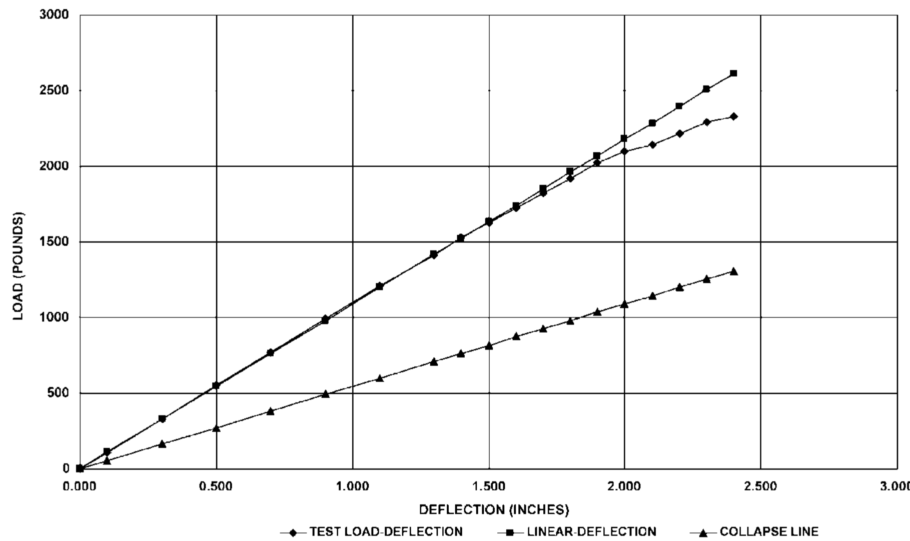

NOTES:
1. Positive oad is down.

TEST #: **ELBOW - H** TEST TYPE: **COMBINED-45**

FATIGUE - LOAD DEFLECTION CURVE 11/19/98

POSITIVE LOAD - UNLOADING CONDITION

F = Fo + m

"m" TO BE BASED ON N DATA POINTS, N – 11

THE VALUE OF "m" = 1184 Fo (LBS) = 200

NOMINAL STRESS = M/Z KSI, M=F x L, L(IN) = 49.25 $Z(IN^3)$ = 3.215

DATA POINT #	MEASURED DEFLECTION (INCHES)	LOAD F (LBS)	MODIFIED DEFLECTION (INCHES)	LOAD F (LBS)	SLOPE FOR START TO DATA POINT (LBS/INCH)	F BASED ON "m" (LBS)	NOMINAL STRESS (KSI)
1	2.40	2330	2.400	2330	N/A	2331	35.7
2	2.20	2030	2.200	2030	1,500	2094	32.1
3	2.00	1985	2.000	1985	862	1857	28.4
4	1.80	1550	1.800	1550	1,192	1621	24.8
5	1.60	1308	1.600	1308	1,262	1384	21.2
6	1.40	1066	1.400	1066	1,274	1147	17.6
7	1.20	839	1.200	839	1,264	910	13.9
8	1.00	619	1.000	619	1,246	674	10.3
9	0.80	400	0.800	400	1,227	437	6.7
10	0.60	203	0.600	203	1,205	200	3.1
11	0.40	0	0.400	0	1,184	-37	-0.6
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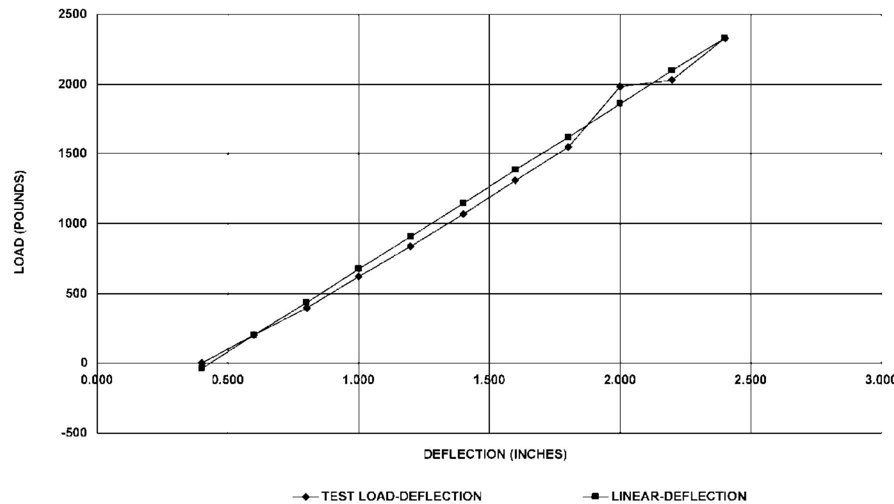
NOTES:



Test Data

TEST #: **ELBOW - H** TEST TYPE: **COMBINED-45**

F = Fo + m: : "m" TO BE BASED ON N DATA POINTS, N – 8

THE VALUE OF "m" = 915 Fo (LBS) = 0

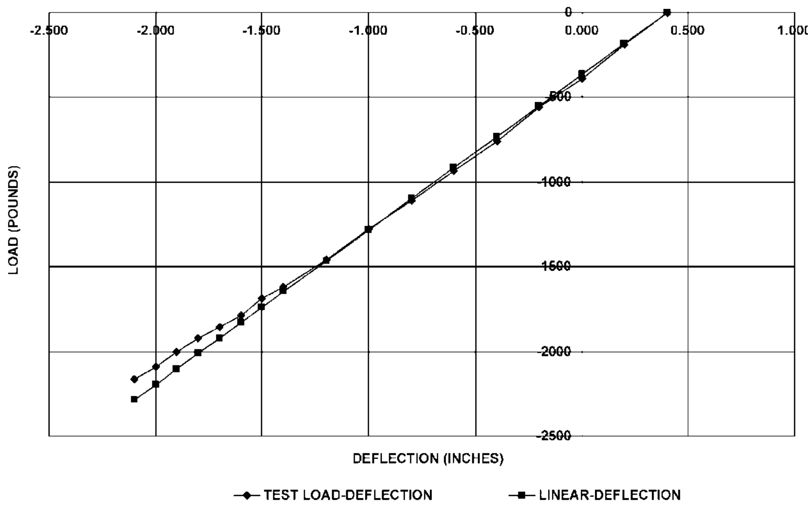
NOMINAL STRESS – M/Z KSI, M–F x L, L(IN) – 49.25 Z(IN³) = 3.215

DATA POINT #	MEASURED DEFLECTION (INCHES)	MEASURED LOAD F (LBS)	MODIFIED DEFLECTION (INCHES)	MODIFIED LOAD F (LBS)	SLOPE FOR START TO DATA POINT (LBS/INCH)	F BASED ON "m" (LBS)	NOMINAL STRESS (KSI)
1	0.40	0	0.40	0	N/A	0	0.0
2	0.20	-190	0.20	-190	950	-183	-2.8
3	0.00	-387	0.00	-387	968	-366	-5.6
4	-0.20	-561	-0.20	-561	940	-549	-8.4
5	-0.40	-757	-0.40	-757	943	-732	-11.2
6	-0 60	-931	-0.60	-931	933	-915	-14.0
7	-0 80	-1106	-0.80	-1106	923	-1098	-16.8
8	1 00	1280	1.00	1280	915	1281	19.6
9	-1 20	-1461	-1.20	-1461	910	-1464	-22.4
10	-1 40	-1620	-1.40	-1620	902	-1647	-25.2
11	-1 50	-1688	-1 50	-1688	892	-1738	-26.6
12	-1 60	-1787	-1.60	-1787	889	-1830	-28.0
13	-1.70	-1855	-1.70	-1855	883	-1921	-29.4
14	-1.80	-1923	-1.80	-1923	876	-2012	-30.8
15	-1.90	-2006	-1.90	-2006	871	-2104	-32.2
16	-2.00	-2089	-2.00	-2089	867	-2195	-33.6
17	-2.10	-2165	-2.10	-2165	862	-2287	-35.0
18							
19							
20							
21							
22							
23							
24							
25							

NOTES:

FATIGUE - LOAD DEFLECTION CURVE ######

NEGATIVE LOAD - LOADING CONDITION



TEST #: **ELBOW - H** TEST TYPE: **COMBINED-45**

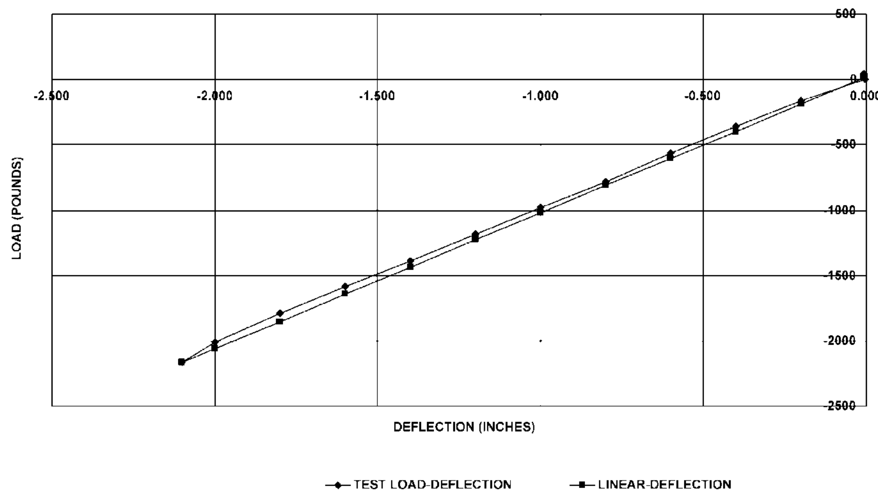
F = Fo + m "m" TO BE BASED ON N DATA POINTS, N = 10
THE VALUE OF "m" = 1041 Fo (LBS) = -2165

NOMINAL STRESS = M/Z KSI, M=F x L, L(IN) = 49.25 $Z(IN^3)$ = 3.215

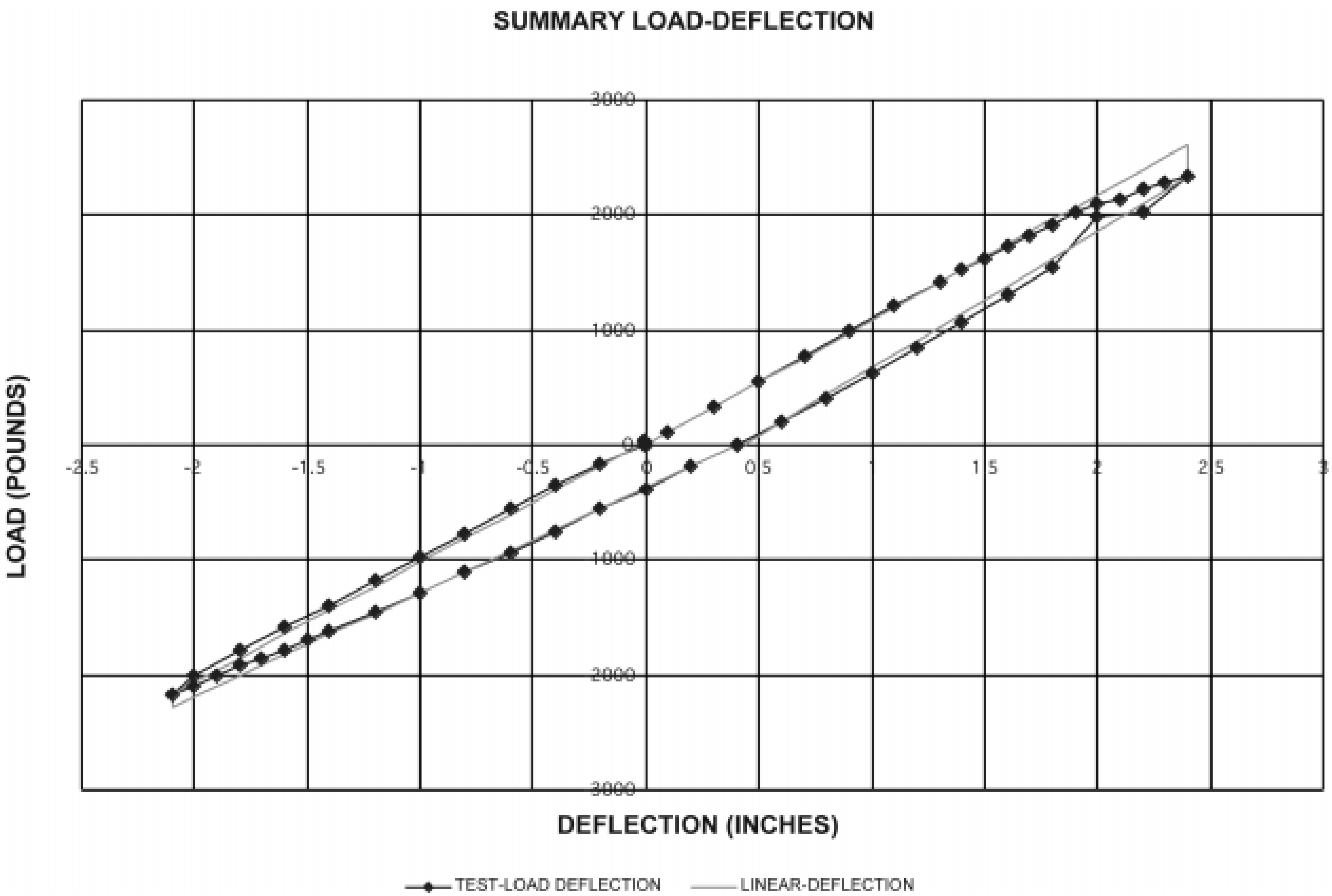
DATA POINT #	MEASURED DEFLECTION (INCHES)	MEASURED LOAD F (LBS)	MODIFIED DEFLECTION (INCHES)	MODIFIED LOAD F (LBS)	SLOPE FOR START TO DATA POINT (LBS/INCH)	F BASED ON "m" (LBS)	NOMINAL STRESS (KSI)
1	-2.10	-2165	-2.100	-2165	N/A	-2165	-33.2
2	-2.00	-2006	-2.000	-2006	1590	-2061	-31.6
3	-1.80	-1787	-1.800	-1787	1236	-1853	-28.4
4	-1.60	-1582	-1.600	-1582	1144	-1645	-25.2
5	-1.40	-1391	-1.400	-1391	1087	-1436	-22.0
6	-1.20	-1181	-1.200	-1181	1067	-1228	-18.8
7	-1.00	-977	-1.000	-977	1055	-1020	-15.6
8	-0.80	-780	-0.800	-780	1044	-812	-12.4
9	-0.60	-561	-0.600	-561	1043	-604	-9.2
10	-0.40	-356	-0.400	-356	1041	-395	-6.1
11	-0.20	-159	-0.200	-159	1037	-187	-2.9
12	-0.003	0	-0.003	0	1026	18	0.3
13	0.00	44	-0.006	44	1028	15	0.2
14							
15							
16							
17							
18							
19							
20							
21							
22							
23							
24							
25							

FATIGUE - LOAD DEFLECTION CURVE 11/19/98

NEGATIVE LOAD - UNLOADING CONDITION



NOTES:
1. At the beginning of the download, there was a problem with the software which required a shut down and restart. When restarted, the "offset" displacement was incorrect. The change in displacement and change in loads were correct.


SUMMARY LOAD-DEFLECTION
3000
2000
1000
0
-1000
-2000
-3000
-2.5
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
2.5
3
LOAD (POUNDS)
DEFLECTION (INCHES)
TEST-LOAD DEFLECTION
LINEAR-DEFLECTION

FATIGUE TEST DATA ANALYSIS 11/19/98

TEST #: **ELBOW - H** TYPE: **COMBINED-45**

AVERAGE STIFFNESS (lbs/in) = 1057
MOMENT ARM (in)= 49.25

D (in) = 4.5 t (in) = 0.237 Z (in^3) = $0.0982(D^4-(D-2t)^4)/D$= 3.215

TEST DISPLACEMENT/CYCLE DATA:

CONDITION #	DISPLACEMENT AMPLITUDE (+/-) (in.) d_i	EFFECTIVE APPLIED LOAD (lbs)	NOMINAL STRESS (+/-) (psi) S	NUMBER OF TEST CYCLES N_i
1	2.02	2135	32,708	2,230
2	2.08	2194	33,599	490
3	0.00	0	0	0
4	0.00	0	0	0
5	0.00	0	0	0
6	0.00	0	0	0
7	0.00	0	0	0
8	0.00	0	0	0
			TOTAL CYCLES:	2,720

EQUIVALENT NUMBER OF CYCLES, BASED ON δ = **2.075** INCHES

IS: $N_{eq} = SUM(\delta_i/\delta_{max})^5 * N_i$ = 2,440

FOR NOMINAL DIMENSIONS: $i = 245,000 * N_{eq}^{(-0.2)}/S$ = **1.532**

FOR Z(IN^3) = 3.215 i = **1.533**

COMMENTS: