Stress Intensification Factors and Flexibility Factors for Unreinforced Branch Connections

Technical Report

Stress Intensification Factors and Flexibility Factors for Unreinforced Branch Connections

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REPORT SUMMARY

This report provides equations, based on analyses and test data, for determining the stress intensification factors and flexibility factors for branch connections. The report contains results of an investigation into the flexibility and stress intensification factors of unreinforced fabricated tees (and other similar configurations). It provides flexibility equations for a more accurate evaluation of these configurations.

Background

Fatigue is a major concern in the design and engineering of piping systems. The ASME Section III Class 2&3, and B31 piping design codes use factors such as stress indices and stress intensification factors to account for fatigue effects produced by reversing loads.

Objectives

- To derive expressions for stress intensification factors for branch connections
- To derive expressions for flexibility factors for accurately modeling the behavior of branch connections in a piping analysis

Approach

A review of the present approach for evaluation of branch connections in accordance with the Code, provided an understanding of the current methodology in the determination of the various factors. Available data on studies, experiments, and testing were collected and reviewed. Tests and analyses were performed on representative models and the results were compared to existing data. Equations were developed to more accurately calculate stress intensification factors and flexibility factors for branch connections.

Results

This report summarizes the experimental data and the test program in Section 2, the combination of moments and stresses in Section 3, the investigation of flexibility in Section 4, the applicability of results in Section 5, and the results of the investigation on branch connections in Section 6.

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

TR-110996

Interest Categories

Piping, reactor vessel & internals

Keywords

ASME Code
Fatigue
Piping design and analysis
Stress intensity factors
Stress indices

ABSTRACT

This report was prepared under the auspices of the EPRI (Electric Power Research Institute) project on Stress Intensification Factor Optimization. Branch connections are a major consideration in the design and evaluation of piping systems. This report presents the results of an investigation into the flexibility and stress intensification factors of unreinforced fabricated tees (and other similar configurations). The report reviews existing test data and develops expressions for estimating the stress intensification factor, i, for each direction of moment loading. Also, flexibility factors for accurately modeling the behavior of a tee connection in a piping analysis are presented. The expressions presented in this report significantly improve evaluation of these connections.

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INTRODUCTION

Tee or branch connections are among the most complex of piping components to evaluate. They can be fabricated or forged, reinforced or unreinforced; and the three outlets of the tee connection may be of equal, or different, diameters and wall thickness. Stress concentration effects occur at or near the intersection of the branch and run pipe segments of a tee connection.

This study investigates stress intensification factors and flexibility factors for unreinforced fabricated tees and other types of branch connections. The unreinforced connections are termed “unreinforced” because the pipe walls are not locally thickened or otherwise reinforced to provide additional resistance to moment loads. These uniform wall thickness tee connections satisfy piping design code rules for pressure reinforcement. These connections are termed “fabricated” because they are made by joining run and branch pipe segments with a full penetration weld at the junction of the segment surfaces.

Typically, there is no fillet radius to reduce stress concentration effects at the intersection of the run and branch segments of the tee and the weld joint is left as-welded. The lengths of run and branch pipe segments that form the fabricated tee are sufficiently long to preclude interaction effects between the tee junction weld and the welds that join the fabricated tee to other piping segments. For this study, the ratios of the branch pipe mean radii to the run pipe mean radii, r/R, vary from slightly greater than one-tenth to a maximum value of one. The two run segment outlets of the tee connection are of equal diameter and wall thickness.

1.1 Nomenclature

Figure 1-1 shows the configuration and applied moments for evaluation of stress intensification factors for unreinforced tee connections. The nomenclature includes terminology used in the body of this report and the associated appendices.

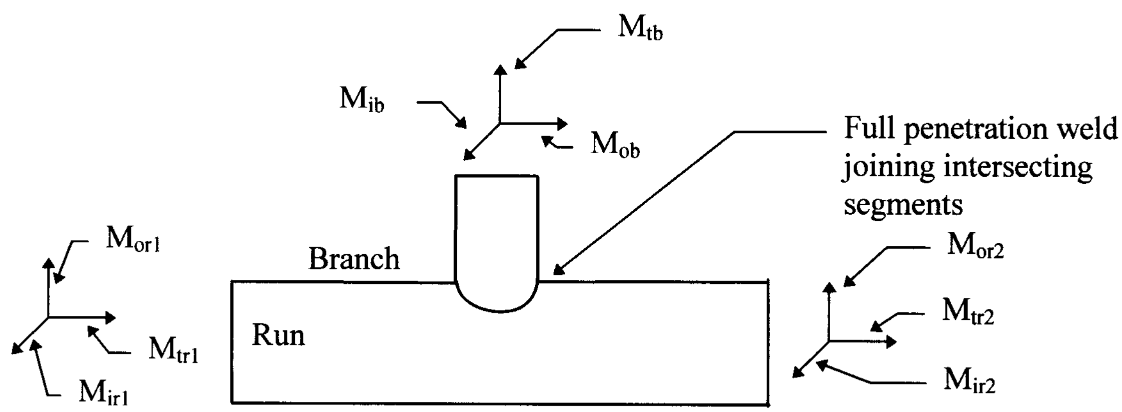


Figure 1-1
Unreinforced Fabricated Tee Connection

D_o = outside diameter of the run pipe, inches
d_o = outside diameter of the branch pipe, inches
D= mean diameter of the run pipe, inches
d = mean diameter of the branch pipe, inches
T = wall thickness of the run pipe, inches
t = wall thickness of the branch pipe, inches
R = mean radius of the run pipe, $R = (D_o - T)/2$, inches
r = mean radius of the branch pipe, $r = (d_o - t)/2$, inches
r^2= correlation factor squared
R/T = characteristic of the run pipe
r/t = characteristic of the branch pipe
r/R = characteristic of the connection
t/T = characteristic of the connection
Z = approximate section modulus of the run pipe, in^3, $=\pi R^2 T$
z = approximate section modulus of the branch pipe, in^3, $=\pi r^2 t$
r_2 = outside fillet radius, if any, at the intersection of the branch and run segments
r_p = outside radius of the branch pipe, $D_o/2$, inches
M_{ir1}, M_{ir2} = in-plane bending moments on the run, in-lb.
M_{or1}, M_{or2} = out-of-plane bending moments on the run, in-lb.
M_{tr1}, M_{tr2} = torsion moments on the run, in-lb.
M_{ib} = in-plane bending moment on the branch, in-lb.
M_{ob} = out-of-plane bending moment on the branch, in-lb.
M_{tb} = torsion moment on the branch, in-lb.
C_{xx} = stress intensity index at the juncture of the branch and run
C_{ib} = maximum stress intensity/(M_{ib}/z)
C_{ob} = maximum stress intensity/(M_{ob}/z)
C_{tb} = maximum stress intensity/(M_{tb}/z)
C_{ir} = maximum stress intensity/(M_{ir}/Z)
C_{or} = maximum stress intensity/(M_{or}/Z)

C_{tr} = maximum stress intensity / (M_{tr} / Z)
i_i = Stress Intensification Factor for in-plane bending moments on the branch or run pipe
i_o = Stress Intensification Factor for out-of-plane bending moments on the branch or run pipe
i_{ib} = Stress Intensification Factor for in-plane bending moments on the branch pipe
i_{ob} = Stress Intensification Factor for out-of-plane bending moments on the branch pipe
i_{tb} = Stress Intensification Factor for torsion moments on the branch pipe
i_{ir} = Stress Intensification Factor for through-run in-plane bending moments on the run pipe
i_{or} = Stress Intensification Factor for through-run, out-of-plane bending moments on the run pipe
i_{tr} = Stress Intensification Factor for through-run torsion moments on the run pipe
k_{ib} = Flexibility Factor for in-plane bending moments on the branch pipe
k_{ob} = Flexibility Factor for out-of-plane bending moments on the branch pipe
k_{tb} = Flexibility Factor for torsion moments on the branch pipe
k_{ir} = Flexibility Factor for through-run in-plane bending moments on the run pipe
k_{or} = Flexibility Factor for through-run, out-of-plane bending moments on the run pipe
k_{tr} = Flexibility Factor for through-run, torsion moments on the run pipe
ϕ_{i-j} = Rotation of point i with respect to point j, radians
M_i = In-plane moment on the branch or run end
M_o = Out-of-plane moment on the branch or run end
$S_{i,}$ = Stress resulting from in-plane moments
$S_{o,}$ = Stress resulting from out-of-plane moments
$S_{t,}$ = Stress resulting from torsion moments
M_a = Moment used in the FEA based on a nominal bending stress of 10 ksi. in the pipe (in. lb.)
M_b = Moment used in the FEA based on a nominal bending stress of 10 ksi. in the branch (in. lb.)
I_p = Moment of Inertia of the pipe (in.^{4})
I_b = Moment of Inertia of the branch (in.^{4})
A_0 = constant for SIF equations
B_0 = constant for Flexibility equations
n_1, n_2, n_3 = exponents for the SIF and Flexibility equations

1.2 Current Code Factors

Understanding the fatigue behavior of unreinforced fabricated tee connections begins with the work of A.R.C. Markl in 1952 [1]. Markl fatigue-tested four equal size outlet unreinforced fabricated tee configurations and proposed the following expression for the Stress Intensification Factor for equal size outlet unreinforced fabricated tees:

$$i = 0.9(R/T)^{2/3} \quad \geq 1.0;\ R/T > 50 \qquad \text{(eq. 1-1)}$$

This equation is for the stress intensification factor for in-plane bending, which Markl found to reasonably match the test results for equal size outlet unreinforced fabricated tees. Equation 1-1 is applied to the resultant moment on each of the three sides of the tee connection, although the data that validates the equation is primarily from tests of in-plane bending of the branch side of a tee. Markl noted that Equation 1-1 is conservative when applied to run moments, but might not be conservative when applied to out-of-plane branch moments on a tee [1]. Later, it was noted by Schneider and others that the Code might not be conservative in determining SIFs for branch connections [12].

In 1965, ANSI Code Case 53 [16] gave rules for evaluation of reduced branch outlet tee connections. These rules use $z=\pi r^2 t_s$, where t_s is the lesser of T or i*t, instead of $z=\pi r^2 t$ for evaluation of the branch side resultant moment. The Code Case is now incorporated in the sections of the Code on determination of moments and section modulus of tee connections. The effect of the Code Case is to change Equation 1-1 to the following two equations:

$$i_{run} = 0.9(R/T)^{2/3} \qquad \geq 1.0;\ R/T>50 \qquad \text{(eq. 1-2)}$$

$$i_{branch} = 0.9(R/T)^{2/3}(t/T) \qquad \geq 1.0;\ R/T>50 \qquad \text{(eq. 1-3)}$$

Equation 1-2 is used with $Z=\pi R^2 T$ to evaluate the resultant moments on the run sides of the tee connection, and Equation 1-3 is used with $z=\pi r^2 t$ to evaluate the resultant moment on the branch side of the tee connection.

Stress indices for evaluation of reduced branch outlet tee connections with $r/R \leq 0.5$ were developed by Rodabaugh in 1970 [2]. He derived the following expressions for C_2 factors to be used in ASME Section III [3] Class 1 analyses:

$$C_{2(branch)} = 3(R/T)^{2/3}(r/R)^{1/2}(t/T)(r/r_p) \quad \geq 1.5; \quad R/T>50 \quad r/R \leq 0.5 \qquad \text{(eq. 1-4)}$$

$$C_{2(run)} = 0.8(R/T)^{2/3}(r/R) \quad \geq 1.5; \quad R/T>50 \quad r/R \leq 0.5 \qquad \text{(eq. 1-5)}$$

Equation 1-4 is used with $z=\pi r^2 t$ to evaluate the resultant moment on the branch side of the tee connection, and Equation 1-5 is used with $Z=\pi R^2 T$ to evaluate the resultant moments on the run sides of the tee connection.

Equation 1-4 was derived by conservatively curve-fitting the experimental stress data shown in Table 1-1.

Table 1-1
Experimental Stress Data for the Determination of C2 branch, r/R <0.7

R/T	r/R	t/T	r/r_p	$\sigma/(M/z)$	C_2 branch	Difference	Type
12.25	0.35	0.474	0.73	3.99	3.28	-18%	Weldolet
21.5	0.19	0.67	0.93	6.2	6.30	2%	Uniform wall
13.5	0.19	0.42	0.93	3.8	2.90	-24%	Uniform wall
38	0.18	0.76	0.95	10	10.39	4%	Uniform wall
38	0.53	0.8	0.98	12	19.35	61%	Uniform wall
46.5	0.12	0.42	0.96	3.5	5.42	55%	Uniform wall
46.5	0.18	0.75	0.96	10.5	11.85	13%	Uniform wall
39	0.13	0.45	0.96	4.4	5.37	22%	Uniform wall
9.5	0.32	0.43	0.93	2.19	3.04	39%	Uniform wall
9.5	0.63	0.69	0.95	4.36	7.00	61%	Uniform wall
9.5	0.65	0.38	0.97	2.33	4.00	72%	Uniform wall
9.5	0.63	0.69	0.95	8.55	7.00	-18%	Uniform wall
38	0.18	0.76	0.44	4	4.81	20%	Saddle
38	0.35	0.8	0.48	7	7.70	10%	Saddle
38	0.53	0.8	0.53	7	10.47	50%	Saddle
38	0.18	0.76	0.55	5	6.01	20%	Pad
38	0.35	0.8	0.53	6	8.51	42%	Pad
38	0.53	0.8	0.51	8	10.07	26%	Pad
39	0.13	0.45	0.6	4.3	3.36	-22%	Pad
9.5	0.32	0.43	0.5	1.49	1.64	10%	Reinforced
9.5	0.32	0.43	0.54	1.14	1.77	55%	Reinforced
9.5	0.32	0.43	0.73	1.18	2.39	102%	Reinforced
					Average =	**26%**	

The data shown in Table 1-1 was obtained by various researchers with strain gauges applied to various tee configurations. The data is for out-of-plane bending moments on the branch, unlike Equation 1-1, which is primarily based on in-plane bending moment tests on the branch. The equation applies to tees with an outside radius at the juncture of the branch and run segments, and bounds strain gauge data for a variety of reinforcement designs. It is seen from Table 1-1 that the expression for $C_{2(branch)}$ is conservative by amounts that vary between two and one-hundred percent.

Equation 1-5 is based on one test point. This expression has since been changed in the ASME Section III Class 1 Code to:

$$C_{2(run)} = 1.15(r/t)^{1/4} \quad \geq 1.5; \qquad R/T > 50 \qquad r/R \leq 0.5 \qquad \text{(eq. 1-6)}$$

based on later work by Rodabaugh and Moore [15] in which the $C_{2(run)}$ factor was correlated to finite element analysis results for twenty-five tee configurations.

The i-factors in the piping design codes [3,4] for reduced branch outlet tees with $r/R \leq 0.5$ (also referred to as branch connections) are one-half the Equation 1-4 and 1-5 C_2 factors. The run i-factor has not been updated to reflect Equation 1-6. Because Equations 1-4 and 1-5 are derived for tees with an outside radius of a minimum dimension at the junction of the branch and run segments, the Code requires that the i-factor values be doubled when such a radius is not provided. This requirement is contained in Note (6) item (h) in ASME Section III Figure NC-3673.2(b), for example. Thus, for unreinforced fabricated tees with $r/R \leq 0.5$:

$$i_{(branch)} = 3(R/T)^{2/3}(r/R)^{1/2}(t/T)(r/r_p) \quad \geq 2.1; \quad R/T > 50 \quad r/R \leq 0.5 \qquad \text{(eq. 1-7)}$$

$$i_{(run)} = 0.8(R/T)^{2/3}(r/R) \quad \geq 2.1; \quad R/T > 50 \quad r/R \leq 0.5 \qquad \text{(eq. 1-8)}$$

In summary, the current Code i-factors for branch connections are given by Equations 1-2, 1-3, 1-7, and 1-8.

2

EXPERIMENTAL AND FINITE ELEMENT ANALYSIS

2.1 Introduction

The experimental data and the results of the finite element analysis form the basis of this investigation. This section discusses the available test data and describes the finite element analysis performed as part of the project.

2.2 Experimental Data

Table 2-1 lists unreinforced fabricated tee connection tests performed by various investigators to determine stress intensification factors (i-factors). The data in the table is sorted by increasing r/R and, within r/R, by increasing R/T (except for the tests identified as "W/EPRI", which were performed as a part of this study). The tested tee connections have the following characteristics:

$$8.0 < R/T < 50$$

$$0.5 < r/t < 50$$

$$0.125 < r/R \leq 1.0$$

$$0.211 < t/T < 9$$

$$0.5 \leq r/r_p < 1.0$$

Note that Table 2-1, as for most of the tables in this report, is from an Excel spread sheet. Consequently, the number of significant figures used in the calculations is greater than indicated in the tables. The presentation in the tables of a certain number of significant figures is arbitrary.

Table 2-1
Test/Experimental Results—Unreinforced Fabricated Tees

Test	D_o	T	d_o	t	R	r	R/T	r/t	r/R	t/T	r/rp	Test i_{ib}	Test i_{ob}	Test i_{tb}	Test i_{ir}	Test i_{or}
ORNL-3	10.00	0.200	1.290	0.168	4.900	0.561	24.50	3.34	0.11	0.84	0.87					
ECR/EAW	4.142	0.058	1.000	0.500	2.042	0.250	35.33	0.50	0.12	8.65	0.50				0.93	
ORNL-4	10.00	0.200	1.290	0.064	4.900	0.613	24.50	9.58	0.13	0.32	0.95					
Roarty	4.50	0.237	1.000	0.250	2.132	0.375	8.99	1.50	0.18	1.05	0.75				1.13	
Roarty	4.50	0.237	1.000	0.250	2.132	0.375	8.99	1.50	0.18	1.05	0.75				0.97	
Decock	20.00	0.239	4.130	0.239	9.881	1.946	41.34	8.14	0.20	1.00	0.94	2.67				
Roarty	4.50	0.237	1.000	0.100	2.132	0.450	8.99	4.50	0.21	0.42	0.90				1.25	
Roarty	4.50	0.237	1.000	0.100	2.132	0.450	8.99	4.50	0.21	0.42	0.90				1.23	
ECR/EAW	4.146	0.060	1.000	0.100	2.043	0.450	34.11	4.50	0.22	1.67	0.90				1.05	
ECR/EAW	4.138	0.056	1.000	0.050	2.041	0.475	36.45	9.50	0.23	0.89	0.95				1.51	
Decock	20.00	0.398	8.625	0.199	9.801	4.213	24.60	21.15	0.43	0.50	0.98	2.75				
ORNL-1	10.00	0.100	5.000	0.050	4.950	2.475	49.50	49.50	0.50	0.50	0.99					
Pickett	20.00	1.000	12.750	0.687	9.500	6.032	9.50	8.78	0.63	0.69	0.95		3.90			
Decock	20.00	0.398	14.000	0.239	9.801	6.880	24.60	28.78	0.70	0.60	0.98	3.47				
Khan	8.625	0.322	6.625	0.280	4.152	3.173	12.89	11.33	0.76	0.87	0.96	1.85	5.84			
Khan	12.75	0.375	10.750	0.365	6.188	5.193	16.50	14.23	0.84	0.97	0.97		8.93			
Khan	12.75	0.375	10.750	0.365	6.188	5.193	16.50	14.23	0.84	0.97	0.97		7.75			
Moffat 4	10.70	0.851	10.7	0.851	4.925	4.925	5.79	5.79	1.00	1.00	0.92		---			
Moffat 3	10.70	0.661	10.7	0.661	5.020	5.020	7.59	7.59	1.00	1.00	0.94					
Markl	4.50	0.237	4.500	0.237	2.132	2.132	8.99	8.99	1.00	1.00	0.95	2.40	2.69	2.69	1.74	1.06
Markl	4.50	0.237	4.500	0.237	2.132	2.132	8.99	8.99	1.00	1.00	0.95	2.28	2.73	2.73	1.82	1.34
Markl	4.50	0.237	4.500	0.237	2.132	2.132	8.99	8.99	1.00	1.00	0.95	2.15				
Markl	4.50	0.237	4.500	0.237	2.132	2.132	8.99	8.99	1.00	1.00	0.95	2.03				
Markl	4.50	0.237	4.500	0.237	2.132	2.132	8.99	8.99	1.00	1.00	0.95	2.04				
Markl	4.50	0.237	4.500	0.237	2.132	2.132	8.99	8.99	1.00	1.00	0.95	2.49				
Markl	4.50	0.237	4.500	0.237	2.132	2.132	8.99	8.99	1.00	1.00	0.95	2.43				
Markl	4.50	0.237	4.500	0.237	2.132	2.132	8.99	8.99	1.00	1.00	0.95	2.40				
Markl	4.50	0.237	4.500	0.237	2.132	2.132	8.99	8.99	1.00	1.00	0.95	2.32				
Markl	4.50	0.237	4.500	0.237	2.132	2.132	8.99	8.99	1.00	1.00	0.95	2.53				
Markl	4.50	0.237	4.500	0.237	2.132	2.132	8.99	8.99	1.00	1.00	0.95	2.57				
Markl	4.50	0.237	4.500	0.237	2.132	2.132	8.99	8.99	1.00	1.00	0.95	2.34				
Markl	4.50	0.237	4.500	0.237	2.132	2.132	8.99	8.99	1.00	1.00	0.95	2.30				
Markl	4.50	0.203	4.500	0.203	2.149	2.149	10.58	10.58	1.00	1.00	0.95	2.87				
Markl	4.50	0.203	4.500	0.203	2.149	2.149	10.58	10.58	1.00	1.00	0.95	3.05				
Blair	6.63	0.265	6.625	0.265	3.180	3.180	12.00	12.00	1.00	1.00	0.96	3.62				
Moffat 2	10.70	0.416	10.7	0.416	5.142	5.142	12.36	12.36	1.00	1.00	0.96					
Moffat 1	10.70	0.252	10.7	0.252	5.224	5.224	20.73	20.73	1.00	1.00	0.98					
Markl	4.50	0.100	4.500	0.100	2.200	2.200	22.00	22.00	1.00	1.00	0.98	4.70				
Markl	4.50	0.100	4.500	0.100	2.200	2.200	22.00	22.00	1.00	1.00	0.98	8.38				
Decock	20.00	0.239	20.000	0.239	9.881	9.881	41.40	41.40	1.00	1.00	0.99	6.90				
Markl	4.50	0.053	4.500	0.053	2.223	2.223	41.79	41.79	1.00	1.00	0.99	8.64				
Markl	4.50	0.053	4.500	0.053	2.223	2.223	41.79	41.79	1.00	1.00	0.99	14.03				
ORNL-2	10.00	0.100	10.000	0.100	4.950	4.950	49.50	49.50	1.00	1.00	0.99					
W/EPRI-A	8.625	0.188	2.5	0.07	4.219	1.218	22.44	18.73	0.29	0.35	0.97		3.15			
W/EPRI-B	8.625	0.188	2.5	0.07	4.219	1.218	22.44	18.73	0.29	0.35	0.97		3.45			
W/EPRI-C	8.625	0.188	2.5	0.07	4.219	1.218	22.44	18.73	0.29	0.35	0.97		3.88			
W/EPRI-D	8.625	0.188	2.5	0.07	4.219	1.218	22.44	18.73	0.29	0.35	0.97		3.84			

If several tests were conducted on a specific configuration, the individual test results are listed. There are forty-nine entries in Table 2-1 for twenty-seven different unreinforced fabricated tee configurations. The tests identified as ORNL-1, ORNL-2, ORNL-3 and ORNL-4 [17] indicate special test specimens, forged and machined to achieve, as closely as possible, the ninety degree intersection of two cylinders. These specimens did not have a weld at the intersection of the run and branch side segments. The specimens were instrumented with strain gages and are useful for validating analytical models. The tests identified as Moffat 1, Moffat 2, Moffat 3 and Moffat 4 are equal size outlet unreinforced fabricated tees that were tested to determine their flexibility factors. The test labeled Moffat 2 was instrumented with strain gages and analyzed with Finite Element Analysis (FEA) by others. References [22 - 25] contain additional studies that were not included in the forty-nine entries but were reviewed in the preparation of this report.

The tests labeled W/EPRI are tests performed specifically for this project. They will be discussed in more detail later in this section.

As can be seen from the table, Markl performed many of the tests. Figure 2-1 illustrates the end conditions and applied load directions used by Markl to experimentally determine i-factors.

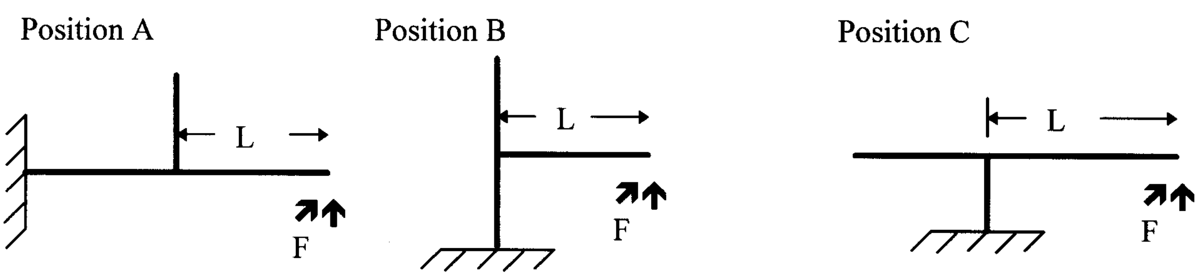


Figure 2-1
Markl Fatigue Test Configurations

In Position A, one end of the run is fixed. An in-plane force, F, on the free run end applies an in-plane bending, through-run nominal moment stress at the juncture equal to FL/Z. An out-of-plane force, F, on the free run end applies an out-of-plane bending, through-run nominal moment stress at the juncture equal to FL/Z.

In Position B, one end of the run is fixed. An in-plane force, F, on the branch applies an in-plane bending, branch nominal moment stress at the juncture equal to FL/z. An out-of-plane force, F, on the branch applies an out-of-plane bending, branch nominal moment stress at the juncture equal to FL/z.

In Position C, the branch end is fixed. An in-plane force, F, on a run end applies an in-plane bending, branch nominal moment stress equal to FL/z at the juncture. An out-of-plane force, F, on a run end applies a torsional branch nominal moment stress equal to FL/z.

In Positions B and C, the load path is through the branch. These positions are used to determine branch side i-factors. For an equal size outlet tee (Z=z), positions B and C are equivalent. In Position A the load path is solely through the run. This position is used to determine i-factors for through-run moments. These test configurations do not provide for the determination of i-factors for through-run torsional moments.

2.3 Project Test Program

As part of this project, out-of-plane (Position B) fatigue tests were performed on four specimens made of carbon steel. The purpose of this test program was to obtain some specific data for out-of-plane bending for values of d / D, d / t, etc., which were not available in the literature. These tests corresponded to the test methodology followed by Markl. The tests are identified as W / EPRI-A, B, C, and D in Table 2-6, which appears later in this section. The test methodology is described in detail in reference [26]. A summary is provided below.

2.4 Design of Test Specimens

Four specimens were manufactured by Wilson Welding Service, Inc., of Decatur, GA. The test specimens consisted of a run pipe of 8.625 inches outside diameter (OD) (T = 0.188 inches), with a branch pipe OD of 2.5 inches (t = 0.065 inch). The welds at the interface of the branch and pipe were normal full penetration in an as-welded condition. The test specimens were labeled A, B, C, and D. The length of run pipe was 32 inches. The branch was located at the center of the run pipe and had a length of 30 inches.

2.5 Testing Performance

The testing was performed at the Ohio State University. See reference [26] for a description of the test equipment and methodology.

The test distance from the load point to the surface of the pipe (~46 inches) varies slightly for each test specimen. The measured distance that is dependent on the installation is included in the test data.

The test data, results, and other information are provided in Appendix C. The tests were displacement controlled cantilever bending tests. The tests followed the standard approach corresponding to Markl type tests [13] [21]. 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 throughwall cracks formed and water leaked through the cracks. Figure 2-2 shows the basic test configuration. Table 2-2 provides a summary of the test data.

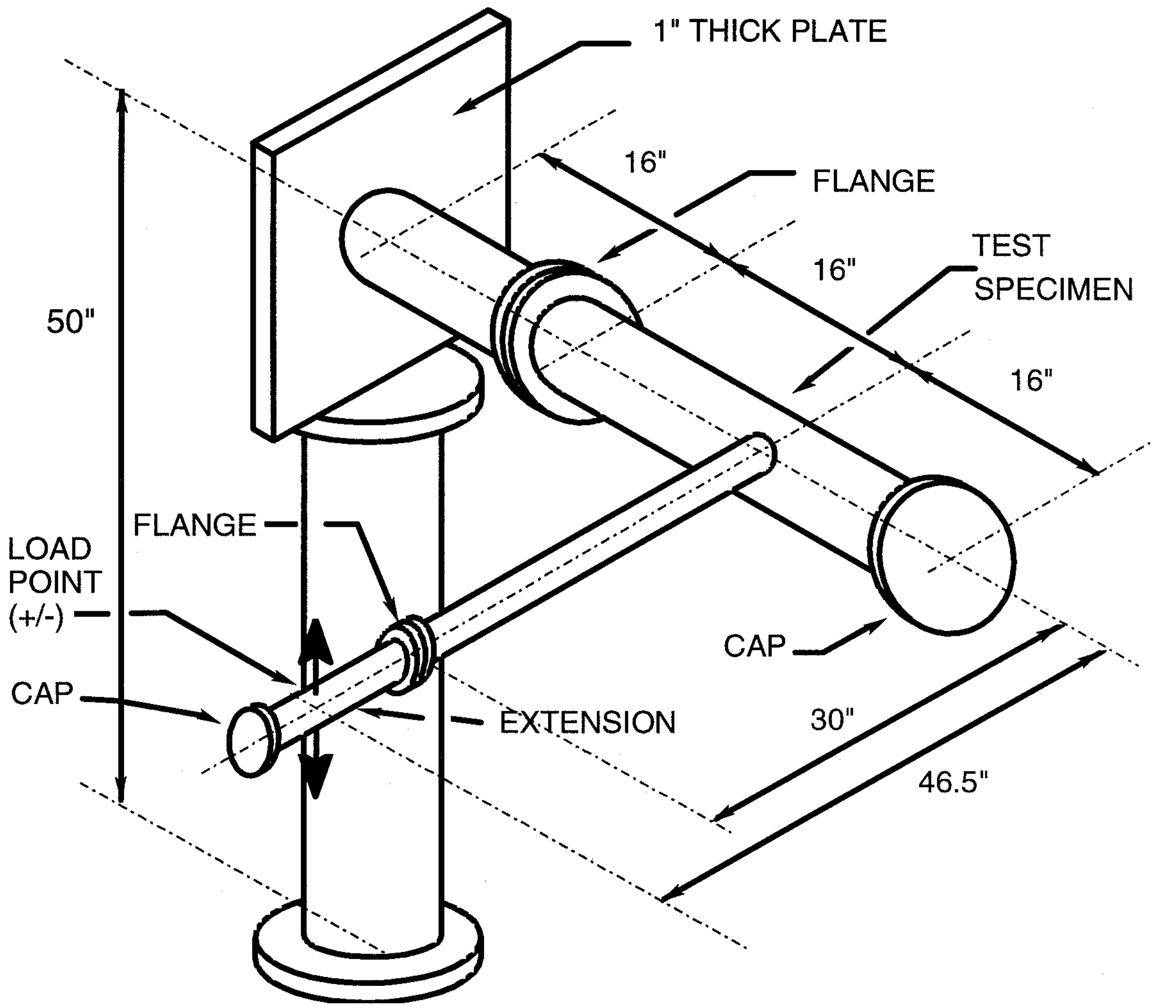


Figure 2-2
Test Configuration

Table 2-2
Summary of Test Results

Test	L	N	Nominal Stress, S	i
	(inches)	(cycles to failure)	(+/- ksi.)	(note 1)
A	46.5	459	22.8	3.15
B	45.875	754	18.9	3.45
C	46.5	923	16.1	3.88
D	46.5	1816	14.2	3.84

(note 1) The value of i is calculated from $i = 245{,}000\ N^{-0.2} / S$, where N = cycles to failure, and S = M / z. z is based on nominal dimensions of the branch.

2.6 Finite Element Analysis

A finite element investigation of tee intersections was performed for the purposes of investigating the:

- differences in stress intensities for each direction of loading
- relationship between stress intensity and the various geometric parameters
- relationship between experimentally determined i-factors and stress intensities

Finite element analyses were performed for the thirty-six tee configurations listed in Table 2-3. The tee connections selected for analysis include the configurations of Table 2-1 with the following characteristics:

$$8.0 < R/T < 50$$

$$8.0 < r/t < 75$$

$$0.1 < r/R \leq 1.0$$

$$0.2 < t/T \leq 2.0$$

$$0.94 \leq r/r_p < 1.0$$

Table 2-3
FEA Models

	Model	D_o	T	d_o	t	d_o/D_o	t/T	D_o/T	d_o/t	D	d	D/T	d/D	d/t
		(in.)	(in.)	(in.)	(in.)					(in.)	(in.)			
1	ORNL-4	10.0	0.200	1.29	0.064	0.129	0.320	50.0	20.2	9.800	1.226	49.00	0.125	19.16
2	Decock	10.0	0.120	2.07	0.120	0.207	1.000	83.3	17.2	9.880	1.945	82.33	0.197	16.21
3	Wais(Roarty	10.0	0.527	2.22	0.111	0.222	0.211	19.0	20.0	9.473	2.111	17.98	0.223	19.02
4	ECR/EAW	10.0	0.135	2.42	0.121	0.242	0.896	74.1	20.0	9.865	2.295	73.07	0.233	18.97
5	Wais	10.0	0.100	2.50	0.050	0.250	0.500	100.0	50.0	9.900	2.450	99.00	0.247	49.00
6	Wais	10.0	0.100	2.50	0.025	0.250	0.250	100.0	100.0	9.900	2.475	99.00	0.250	99.00
7	OSU1	10.0	0.294	3.53	0.186	0.353	0.633	34.0	19.0	9.706	3.344	33.01	0.345	17.98
8	Decock	10.0	0.199	4.31	0.100	0.431	0.503	50.3	43.1	9.801	4.213	49.25	0.430	42.13
9	Wais	10.0	0.100	5.00	0.200	0.500	2.000	100.0	25.0	9.900	4.800	99.00	0.485	24.00
10	Wais	10.0	0.100	5.00	0.140	0.500	1.400	100.0	35.7	9.900	4.860	99.00	0.491	34.71
11	Wais	10.0	0.100	5.00	0.075	0.500	0.750	100.0	66.7	9.900	4.925	99.00	0.497	65.67
12	ORNL-1	10.0	0.100	5.00	0.050	0.500	0.500	100.0	100.0	9.900	4.950	99.00	0.500	99.00
13	OSU2	10.0	0.290	5.22	0.275	0.522	0.948	34.5	19.0	9.710	4.942	33.48	0.509	17.97
14	Wais	10.0	0.101	6.00	0.069	0.600	0.683	99.0	87.0	9.899	5.931	98.01	0.599	85.96
15	Pickett	10.0	0.500	6.38	0.344	0.638	0.688	20.0	18.5	9.500	6.031	19.00	0.635	17.53
16	Decock	10.0	0.199	7.00	0.120	0.700	0.603	50.3	58.3	9.801	6.880	49.25	0.702	57.33
17	Wais	10.0	0.100	7.50	0.080	0.750	0.800	100.0	93.8	9.900	7.420	99.00	0.749	92.75
18	Wais	10.0	0.100	7.50	0.075	0.750	0.750	100.0	100.0	9.900	7.425	99.00	0.750	99.00
19	Wais	10.0	0.100	7.50	0.050	0.750	0.500	100.0	150.0	9.900	7.450	99.00	0.753	149.00
20	Khan	10.0	0.373	7.68	0.325	0.768	0.871	26.8	23.6	9.627	7.356	25.81	0.764	22.63
21	Khan	10.0	0.294	8.43	0.286	0.843	0.973	34.0	29.5	9.706	8.145	33.01	0.839	28.48
22	Wais	10.0	0.100	9.00	0.090	0.900	0.900	100.0	100.0	9.900	8.910	99.00	0.900	99.00
23	Markl	10.0	0.527	10.00	0.527	1.000	1.000	19.0	19.0	9.473	9.473	17.98	1.000	17.98
24	Markl	10.0	0.451	10.00	0.451	1.000	1.000	22.2	22.2	9.549	9.549	21.17	1.000	21.17
25	Blair	10.0	0.400	10.00	0.400	1.000	1.000	25.0	25.0	9.600	9.600	24.00	1.000	24.00
26	Wais	10.0	0.294	10.00	0.294	1.000	1.000	34.0	34.0	9.706	9.706	33.01	1.000	33.01
27	Markl	10.0	0.222	10.00	0.222	1.000	1.000	45.0	45.0	9.778	9.778	44.05	1.000	44.05
28	Wais	10.0	0.178	10.00	0.178	1.000	1.000	56.2	56.2	9.822	9.822	55.18	1.000	55.18
29	Wais	10.0	0.135	10.00	0.135	1.000	1.000	74.1	74.1	9.865	9.865	73.07	1.000	73.07
30	Decock	10.0	0.119	10.00	0.119	1.000	1.000	84.0	84.0	9.881	9.881	83.03	1.000	83.03
31	Markl	10.0	0.118	10.00	0.118	1.000	1.000	84.7	84.7	9.882	9.882	83.75	1.000	83.75
32	ORNL-2	10.0	0.100	10.00	0.100	1.000	1.000	100.0	100.0	9.900	9.900	99.00	1.000	99.00
33	W/EPRI	10.0	0.218	2.90	0.075	0.290	0.346	45.9	38.5	9.782	2.823	44.88	0.289	37.46
34	Wais34	10.0	0.100	3.75	0.038	0.375	0.375	100.0	100.0	9.900	3.713	99.00	0.375	99.00
35	Wais35	10.0	0.100	6.25	0.063	0.625	0.625	100.0	100.0	9.900	6.188	99.00	0.625	99.00
36	Wais36	10.0	0.100	8.75	0.088	0.875	0.875	100.0	100.0	9.900	8.663	99.00	0.875	99.00

Configurations from Table 2-1 with $r/t < 8$ were not selected for finite element analysis because of r/t limitations of shell models. The configurations labeled Moffat 1 and Moffat 2 were not analyzed because of their geometric similarity to cases titled Blair and Markl. The configurations selected from Table 2-1 were supplemented with additional configurations titled OSU1, OSU2, Wais or W/EPRI. Configurations OSU1 and OSU2 were tested for reinforcement and elbow effects under other research efforts for this EPRI program. Configurations titled Wais were included to enhance the scatter of the data. The configuration labeled W/EPRI corresponds to the test specimen used in the tests associated with this investigation. For simplicity, the FEA models were standardized on an OD of ten inches. The dimensions were selected to yield the same values of D/T, d/t, d/D, etc. as the test specimens. The other parameters were calculated based on the ratios of Table 2-1.

Finite element analyses were conducted with COSMOS version 1.75 [10]. Figure 2-3 shows a representative finite element mesh.

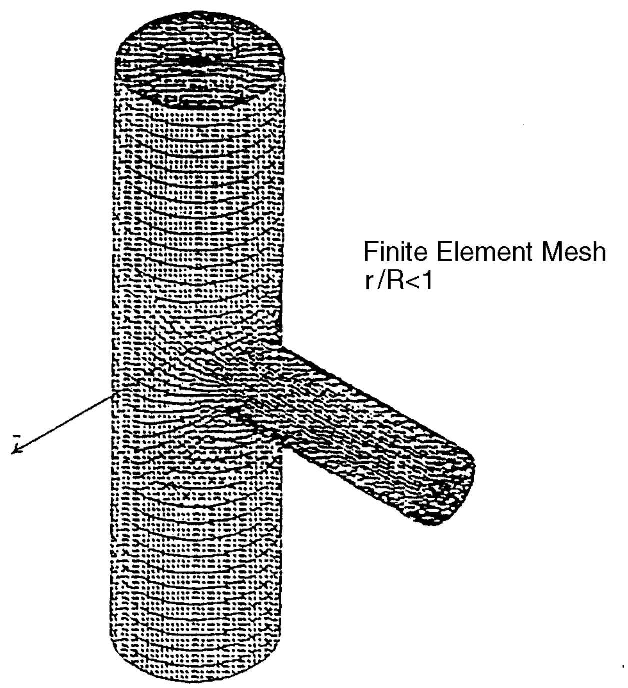


Figure 2-3
Finite Element Mesh

The total run segment length was set at 39 inches, or about four times OD. The branch segment length was set at 19.5 inches from the centerline of the run to the end of the branch, or about two times OD. This was done to match the ORNL-1, 2, 3 and 4 experimental models. The finite element models used four node, quadrilateral shell elements composed of four triangular elements to achieve good symmetry of results. The models typically consist of over 5,000 elements and the element aspect ratios are all less than four. In the vicinity of the juncture, most of the element aspect ratios are close to two and all are less than three.

The models were fixed at one run end, and moments in the three orthogonal directions were applied at the branch or other run end (Figure 2-4). For branch moments this represents the upper bound for the stresses resulting in the connection.

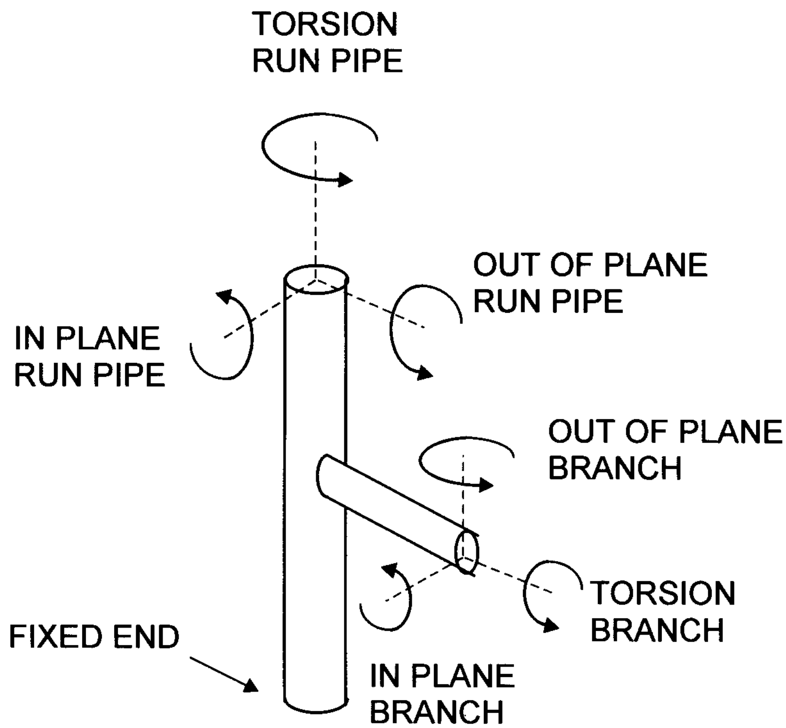


Figure 2-4
Loading Conditions

When modeling branch connections using shell elements, special care must be made when specifying the elements at the branch-pipe intersections. Since shell elements are used, the nodes represent the midsection of the branch or the pipe. The stresses at the node at the intersection of the branch and pipe are unreliable according to studies performed by G. E. O. Widera at Marquette University for the Pressure Vessel Research Council (PVRC) on nozzle/vessel intersections. The methodology accepted by the PVRC is to size the elements in the run (pipe) near the intersection with a length of 1/2 the thickness of the branch. Similarly the elements in the branch near the intersection are sized such that they have a length 1/2 the thickness of the run (pipe). This is shown in Figure 2-5. The element length in the run pipe is equal to one half the thickness of the branch, t/2. The element length in the branch is equal to one half the thickness of the run pipe, T/2. The nodal stresses used are either at the outside nodes on the element in the branch and the run at points B_o and R_o or are on the inside of the element in the branch and the run at points B_i or R_i. The stresses at other points, such as A in Figure 2-5, are neglected.

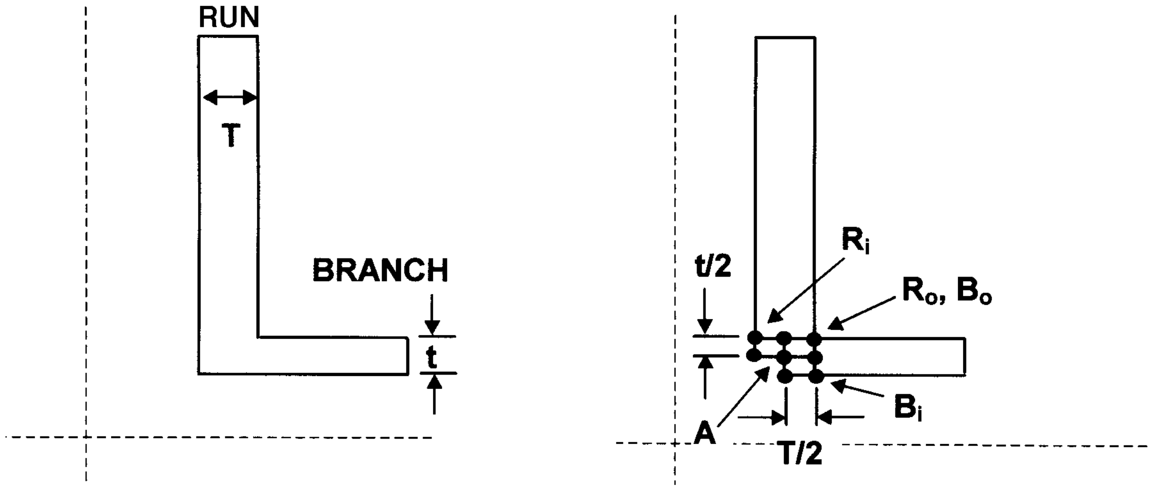


Figure 2-5
FEA Element Configuration

2.7 FEA Results Validation

The cases titled ORNL-1, ORNL-2 and ORNL-4 are configurations carefully manufactured to replicate the ninety degree intersection of two cylinders. These configurations were experimentally tested with strain gauges and FEA analyzed by others [11]. Table 2-4 compares the stress intensity results of this study to the results obtained by others for these configurations.

Table 2-4
Comparison of Stress Intensity Results to Studies by Others

	This Study	ORNL Study	
	FEA	**Strain Gauge**	**FEA**
ORNL-1			
(R/T=49.5,r/R=0.5,t/T=0.5,r/r_p=0.99)			
in-plane branch	11.1	10.0	10.9
out-of-plane branch	37.2	35.3	37.2
branch torsion	2.5	6.2	2.6
in-plane run	5.4	3.8	5.7
out-of-plane run	1.5	2.3	2.7
run torsion	7.8	5.0	6.5
ORNL-2	**FEA**	**Strain Gauge**	**FEA**
(R/T=49.5,r/R=1,t/T=1,r/r_p=0.99)			
in-plane branch	12.8	11.0	15.2
out-of-plane branch	16.5	15.8	17.8
branch torsion	15.6	15.6	18.8
in-plane run	8.1	14.9	10.1
out-of-plane run	3.7	4.5	5.9
run torsion	12.9	12.1	18.8
ORNL-4	**FEA**	**Strain Gauge**	**FEA**
(R/T=49.5,r/R=0.13,t/T=0.32,r/r_p=0.95)			
in-plane branch	3.8	6.1	7.2
out-of-plane branch	4.8	8.5	7.6
branch torsion	1.1	0.8	0.5
in-plane run	2.7	4.0	3.1
out-of-plane run	1.1	1.3	1.0
run torsion	1.6	2.5	2.5

2.8 Curve Fit Expressions

Table 2-5 lists the FEA stress intensities and the results from equations developed from regression analysis for the six loading conditions. It should be noted that the equations from the regression analysis all have a lower limit of 1.0. Also included in this table is the percentage difference between the regression analysis and the FEA analysis. The results are summarized following the table.

Table 2-5
Finite Element Analysis Results

							Load Case 1			Load Case 2			Load Case 3			Load Case 4			Load Case 5			Load Case 6		
							In-Plane Moment			Out-of Plane Moment			Torsion			In-Plane Moment			Out-of Plane				Torsion	
							on Branch			on Branch			on Branch			on Run Pipe			on Run Pipe			on Run Pipe		
Case	Configuration	R/T	r/t	r/R	t/T	r/r_p	C-fea	C-Regr	% DIF	C-fea	C-Regr	% DIF	C-fea	C-Regr	% DIF	C-fea	C-Regr	% DIF	C-fea	C-Regr	% DIF	C-fea	C-Regr	% DIF
1	ORNL-4	24.5	9.58	0.13	0.32	0.95	3.83	4.47	17	4.80	4.52	-6	1.12	1.00	-11	2.68	2.29	-15	1.14	1.10	-3	1.60	1.43	-11
2	Decock	41.3	8.14	0.20	1.00	0.94	8.71	10.30	18	16.76	19.48	16	1.42	1.00	-29	2.56	2.20	-14	1.08	1.10	1	2.07	1.68	-19
3	Wais ('Roarty	9.0	9.51	0.22	0.21	0.95	1.75	2.08	19	2.05	2.47	20	1.15	1.00	-13	2.82	3.01	7	1.04	1.10	6	2.33	2.12	-9
4	ECR/EAW	36.4	9.50	0.23	0.89	0.95	7.88	9.22	17	16.84	18.85	12	1.35	1.00	-26	2.76	2.51	-9	1.02	1.10	8	2.17	2.04	-6
5	Wais	49.5	24.50	0.25	0.50	0.98	11.11	9.09	-18	26.04	18.61	-29	1.25	1.00	-20	4.42	3.85	-13	1.01	1.10	9	3.81	3.49	-8
6	Wais	49.5	49.50	0.25	0.25	0.99	7.91	6.97	-12	17.29	12.75	-26	1.09	1.00	-8	5.32	5.42	2	1.01	1.10	9	4.32	5.14	19
7	OSU1	16.5	8.99	0.34	0.63	0.95	5.32	4.97	-7	10.96	10.81	-1	1.28	1.00	-22	2.95	2.99	1	1.03	1.10	6	2.37	2.61	10
8	Decock	24.6	21.15	0.43	0.50	0.98	6.95	6.05	-13	18.15	15.56	-14	1.35	1.54	14	4.59	4.51	-2	1.03	1.10	7	3.93	4.66	18
9	Wais	49.5	12.00	0.48	2.00	0.96	20.36	16.66	-18	73.29	65.76	-10	5.53	5.31	-4	2.97	3.21	8	1.02	1.10	8	3.51	3.56	2
10	Wais	49.5	17.36	0.49	1.40	0.97	14.89	14.53	-2	51.32	54.26	6	4.03	4.53	13	3.82	3.85	1	1.02	1.10	8	3.69	4.39	19
11	Wais	49.5	32.83	0.50	0.75	0.99	10.91	11.44	5	36.43	38.57	6	2.84	3.39	19	5.51	5.25	-5	1.15	1.13	-2	5.81	6.25	8
12	ORNL-1	49.5	49.50	0.50	0.50	0.99	11.13	9.78	-12	37.24	30.85	-17	2.51	2.79	11	5.42	6.40	18	1.51	1.41	-7	7.83	7.84	0
13	OSU2	16.7	8.99	0.51	0.95	0.95	5.12	6.11	19	13.19	17.69	34	1.90	2.30	21	3.28	3.28	0	1.02	1.10	8	2.81	3.30	18
14	Wais	49.0	42.98	0.60	0.68	0.99	10.97	11.17	2	37.75	39.12	4	3.74	4.33	16	6.79	6.26	-8	1.68	1.69	1	7.75	8.11	5
15	Pickett	9.5	8.77	0.63	0.69	0.95	3.92	3.79	-3	8.80	9.83	12	1.85	2.10	14	3.70	3.69	0	1.18	1.17	-1	3.86	3.83	-1
16	Decock	24.6	28.78	0.70	0.60	0.98	6.82	6.84	0	20.62	20.31	-1	2.93	3.71	27	6.24	5.89	-6	1.84	2.02	10	6.42	7.42	16
17	Wais	49.5	46.38	0.75	0.80	0.99	10.68	12.24	15	34.90	42.03	20	5.98	6.74	13	7.45	6.84	-8	2.29	2.42	6	9.07	9.68	7
18	Wais	49.5	49.50	0.75	0.75	0.99	10.82	11.94	10	35.36	40.52	15	5.92	6.54	10	7.83	7.06	-10	2.39	2.50	5	9.60	10.04	5
19	Wais	49.5	74.50	0.75	0.50	0.99	10.55	10.21	-3	34.50	32.25	-7	5.20	5.37	3	10.25	8.61	-16	3.15	3.12	-1	12.97	12.56	-3
20	Khan	12.9	11.32	0.76	0.87	0.96	4.46	5.19	16	11.35	13.86	22	3.73	3.71	-1	4.77	4.19	-12	1.59	1.62	2	5.37	4.85	-10
21	Khan	16.5	14.24	0.84	0.97	0.97	5.55	6.44	16	13.03	16.26	25	5.93	5.15	-13	5.38	4.63	-14	2.01	1.97	-2	7.03	5.75	-18
22	Wais	49.5	49.50	0.90	0.90	0.99	11.13	13.05	17	27.59	33.62	22	9.95	9.59	-4	8.79	7.38	-16	3.34	3.24	-3	11.89	11.22	-6
23	Markl	9.0	8.99	1.00	1.00	0.95	5.49	4.43	-19	7.05	4.64	-34	6.52	5.10	-22	4.04	4.20	4	2.24	2.29	2	5.40	5.13	-5
24	Markl	10.6	10.58	1.00	1.00	0.95	6.10	4.93	-19	7.97	5.33	-33	7.33	5.53	-25	4.41	4.45	1	2.38	2.40	1	6.16	5.57	-10
25	Blair	12.0	12.00	1.00	1.00	0.96	6.55	5.36	-18	8.68	5.93	-32	7.99	5.89	-26	4.68	4.64	-1	2.49	2.49	0	6.77	5.92	-13
26	Wais	16.5	16.51	1.00	1.00	0.97	7.67	6.63	-14	10.35	7.78	-25	9.62	6.91	-28	5.50	5.18	-6	2.77	2.74	-1	8.32	6.94	-17
27	Markl	22.0	22.00	1.00	1.00	0.98	8.51	8.02	-6	11.59	9.94	-14	10.99	7.97	-27	6.28	5.72	-9	3.01	2.97	-1	9.52	8.00	-16
28	Wais	27.6	27.59	1.00	1.00	0.98	9.54	9.32	-2	12.64	12.05	-5	12.00	8.93	-26	6.83	6.19	-9	3.17	3.18	0	10.98	8.95	-18
29	Wais	36.5	36.54	1.00	1.00	0.99	11.13	11.23	1	14.62	15.30	5	13.88	10.28	-26	7.37	6.82	-7	3.44	3.45	0	12.68	10.29	-19
30	Decock	41.4	41.41	1.00	1.00	0.99	11.85	12.21	3	15.41	17.02	10	14.73	10.94	-26	7.61	7.12	-6	3.54	3.58	1	13.35	10.95	-18
31	Markl	41.8	41.80	1.00	1.00	0.99	11.90	12.28	3	15.59	17.16	10	14.66	10.99	-25	7.63	7.14	-6	3.55	3.59	1	13.39	11.00	-18
32	ORNL-2	49.5	49.50	1.00	1.00	0.99	12.79	13.74	7	16.52	19.81	20	15.59	11.96	-23	8.06	7.57	-6	3.67	3.77	2	12.87	11.96	-7
33	W/EPRI	22.4	18.73	0.29	0.35	0.97	5.51	4.74	-14	10.56	8.74	-17	1.17	1.00	-14	3.65	3.91	7	1.00	1.10	10	2.93	3.43	17
34	WAIS	49.5	49.50	0.38	0.38	0.99	10.32	8.50	-18	30.50	21.87	-28	1.50	1.52	1	6.69	5.97	-11	1.08	1.10	2	6.45	6.58	2
35	WAIS	49.5	49.50	0.63	0.63	0.99	11.08	10.92	-2	38.27	37.86	-1	3.96	4.46	13	7.52	6.76	-10	1.93	1.93	0	8.81	8.98	2
36	WAIS	49.5	49.50	0.88	0.88	0.99	10.89	12.87	18	29.32	35.78	22	8.64	9.04	5	8.49	7.33	-14	3.13	3.12	0	10.54	11.03	5
								Maximum =	19		Maximum =	34		Maximum =	27		Maximum =	18		Maximum =	10		Maximum =	19
								Minimum =	-19		Minimum =	-34		Minimum =	-29		Minimum =	-16		Minimum =	-7		Minimum =	-19
								Average =	0		Average =	-1		Average =	-7		Average =	-5		Average =	3		Average =	-2
								Std Dev.=	13		Std Dev.=	19		Std Dev.=	18		Std Dev.=	8		Std Dev.=	4		Std Dev.=	12
								r^2 =	0.889		r^2 =	0.931		r^2 =	0.867		r^2 =	0.910		r^2 =	0.995		r^2 =	0.928

Notes:

1. Std Dev = Standard Deviation
2. r^2 = "goodness of fit"

2.8.1 In-plane bending of the branch

$$C_{ib} = 1.03\,(R/T)^{1.05}\,(r/t)^{-0.387}\,(r/R)^{0.49} \qquad \geq 1.0 \qquad \text{(eq. 2-1)}$$

Average difference between the FEA and Equation 2-1: 0%

Maximum difference between the FEA and Equation 2-1: 19%

Standard deviation of difference between the FEA and Equation 2-1: 13%

Goodness of fit: r^2 : 0.889

2.8.2 Out-of-plane bending of the branch

$$C_{ob} = 2.56\,(1.28\,(r/R)-(r/R)^{4})\,(R/T)^{1.409}\,(r/t)^{-0.558}\,(r/R)^{0.4057} \geq 1.0 \qquad \text{(eq. 2-2)}$$

Average difference between the FEA and Equation 2-2: -1%

Maximum difference between the FEA and Equation 2-2: 34%

Standard deviation of difference between the FEA and Equation 2-2: 19%

Goodness of fit: r^2 : 0.931

2.8.3 Torsion of the branch

$$C_{tb} = 1.70\,(R/T)\,(r/t)^{-0.5}\,(r/R)^{2.1} \qquad \geq 1.0 \qquad \text{(eq. 2-3)}$$

Average difference between the FEA and Equation 2-3: -7%

Maximum difference between the FEA and Equation 2-3: 29%

Standard deviation of difference between the FEA and Equation 2-3: 18%

Goodness of fit: r^2 : 0.867

2.8.4 In-plane bending of the run

$$C_{ir} = 1.97\,(R/T)^{-0.137}\,(r/t)^{0.482}\,(r/R)^{.241} \quad \geq 1.0 \qquad \text{(eq. 2-4)}$$

Average difference between the FEA and Equation 2-4: -5%

Maximum difference between the FEA and Equation 2-4: 18%

Standard deviation of difference between the FEA and Equation 2-4: 8%

Goodness of fit: r^2 : 0.910

2.8.5 Out-of-plane bending of the run

$$C_{or} = 1.21\,(R/T)^{-0.237}\,(r/t)^{0.528}\,(r/R)^{1.42} \qquad \geq 1.0 \qquad \text{(eq. 2-5)}$$

Average difference between the FEA and Equation 2-5: 3%

Maximum difference between the FEA and Equation 2-5: 10%

Standard deviation of difference between the FEA and Equation 2-5: 4%

Goodness of fit: r^2 : 0.995

2.8.6 Torsion of the run

$$C_{tr} = 1.73\,(R/T)^{-0.0473}\,(r/t)^{0.5433}\,(r/R)^{0.6093} \qquad \geq 1.0 \qquad \text{(eq. 2-6)}$$

Average difference between the FEA and Equation 2-6: -2%

Maximum difference between the FEA and Equation 2-6: 19%

Standard deviation of difference between the FEA and Equation 2-6: 12%

Goodness of fit: r^2 : 1.000

The form of the regression equation for out-of-plane bending of the branch, Equation 2-2, differs from the other equations. This equation includes the terms: $(1.28\,(r/R)-(r/R)^4)$. The reason for this is that, while all of the other stress intensities monotonically increase as r/R increases, for out-of-plane bending, the stress intensity increases, peaks at a value of about 0.6, and then decreases. These terms were developed by examining the data for those cases where the parameters are held constant ($R/T = r/t = 49.5$). The expression $(1.28\,(r/R)-(r/R)^4)$ was developed by curve-fitting these data. The percentage difference between the data points and the curve fit was 2.8% on the average with a maximum difference of 10.6%, and a standard deviation of 2.8%.

2.9 Comparison of Test Data to FEA Results

Tables 2-6 and 2-7 list the experimental, FEA, and regression equation results for the various tests listed in Table 2-1. (Note that "torsion of the run" is not included because there is no test data available.) The ratios of i/FEA results and i/regression equation results are also provided. Table 2-8 summarizes the results that were obtained.

Table 2-6
Test/FEA Results - Unreinforced Fabricated Tees

							In-plane Bending of the Branch			Out of Plane Bending of the Branch			Torsion of the Branch			In-plane Bending of the Run			Out of Plane Bending of the Run		
Ref.	Test	R/T	r/t	r/R	t/T	r/rp	Test i_{ib}	FEA C_{ib}	$Test_{ib}/C_{ib}$	Test i_{ob}	FEA C_{ob}	$Test_{ob}/C_{ob}$	Test i_{tb}	FEA C_{tb}	$Test_{tb}/C_{tb}$	Test i_{ir}	FEA C_{ir}	$Test_{ir}/C_{ir}$	Test i_{or}	FEA C_{or}	$Test_{or}/C_{or}$
11	ORNL-3	24.50	3.34	0.11	0.84	0.87															
18	ECR/EAW	35.33	0.50	0.12	8.65	0.50										0.93					
11	ORNL-4	24.50	9.58	0.13	0.32	0.95															
19	Roarty	8.99	1.50	0.18	1.05	0.75										1.13					
19	Roarty	8.99	1.50	0.18	1.05	0.75										0.97					
7	Decock	41.34	8.14	0.20	1.00	0.94	2.67	8.71	0.31												
19	Roarty	8.99	4.50	0.21	0.42	0.90										1.25					
19	Roarty	8.99	4.50	0.21	0.42	0.90										1.23					
18	ECR/EAW	34.11	4.50	0.22	1.67	0.90										1.05					
19	Roarty	8.99	9.50	0.22	0.21	0.95										1.68					
19	Roarty	8.99	9.50	0.22	0.21	0.95										1.54					
18	ECR/EAW	36.45	9.50	0.23	0.89	0.95										1.51	2.76	0.55			
7	Decock	24.60	21.15	0.43	0.50	0.98	2.75	6.95	0.40												
11	ORNL-1	49.50	49.50	0.50	0.50	0.99															
6	Pickett	9.50	8.78	0.63	0.69	0.95				3.90	20.62	0.19									
7	Decock	24.60	28.78	0.70	0.60	0.98	3.47	6.82	0.51												
8	Khan	12.89	11.33	0.76	0.87	0.96	1.85	4.45	0.42	5.84	11.35	0.51									
8	Khan	16.50	14.23	0.84	0.97	0.97				8.93	13.03	0.69									
8	Khan	16.50	14.23	0.84	0.97	0.97				7.75	13.03	0.59									
21	Moffat 4	5.79	5.79	1.00	1.00	0.92															
21	Moffat 3	7.59	7.59	1.00	1.00	0.94															
1	Markl	8.99	8.99	1.00	1.00	0.95	2.40	5.49	0.44	2.69	7.05	0.38	2.69	6.52	0.41	1.74	4.04	0.43	1.06	2.24	0.47
1	Markl	8.99	8.99	1.00	1.00	0.95	2.28	5.49	0.42	2.73	7.05	0.39	2.73	6.52	0.42	1.82	4.04	0.45	1.34	2.24	0.60
1	Markl	8.99	8.99	1.00	1.00	0.95	2.15	5.49	0.39												
1	Markl	8.99	8.99	1.00	1.00	0.95	2.03	5.49	0.37												
1	Markl	8.99	8.99	1.00	1.00	0.95	2.04	5.49	0.37												
1	Markl	8.99	8.99	1.00	1.00	0.95	2.49	5.49	0.45												
1	Markl	8.99	8.99	1.00	1.00	0.95	2.43	5.49	0.44												
1	Markl	8.99	8.99	1.00	1.00	0.95	2.40	5.49	0.44												
1	Markl	8.99	8.99	1.00	1.00	0.95	2.32	5.49	0.42												
1	Markl	8.99	8.99	1.00	1.00	0.95	2.53	5.49	0.46												
1	Markl	8.99	8.99	1.00	1.00	0.95	2.57	5.49	0.47												
1	Markl	8.99	8.99	1.00	1.00	0.95	2.34	5.49	0.43												
1	Markl	8.99	8.99	1.00	1.00	0.95	2.30	5.49	0.42												
1	Markl	10.58	10.58	1.00	1.00	0.95	2.87	6.10	0.47												
1	Markl	10.58	10.58	1.00	1.00	0.95	3.05	6.10	0.50												
5	Blair	12.00	12.00	1.00	1.00	0.96	3.62	6.55	0.55												
21	Moffat 2	12.36	12.36	1.00	1.00	0.96															
21	Moffat 1	20.73	20.73	1.00	1.00	0.98															
1	Markl	22.00	22.00	1.00	1.00	0.98	4.70	8.51	0.55												
1	Markl	22.00	22.00	1.00	1.00	0.98	8.38	8.51	0.98												
7	Decock	41.40	41.40	1.00	1.00	0.99	6.90	11.85	0.58												
1	Markl	41.79	41.79	1.00	1.00	0.99	8.64	11.90	0.73												
1	Markl	41.79	41.79	1.00	1.00	0.99	14.03	11.90	1.18												
11	ORNL-2	49.50	49.50	1.00	1.00	0.99															
Note 1	W/EPRI-A	22.44	18.73	0.29	0.35	0.97				3.15	10.56	0.30									
Note 1	W/EPRI-B	22.44	18.73	0.29	0.35	0.97				3.45	10.56	0.33									
Note 1	W/EPRI-C	22.44	18.73	0.29	0.35	0.97				3.88	10.56	0.37									
Note 1	W/EPRI-D	22.44	18.73	0.29	0.35	0.97				3.84	10.56	0.36									
								Average =	0.51		Average =	0.41		Average =	0.42		Average =	0.48		Average =	0.54
Note 1: W/EPRI-A,B,C, and D correspond to the test configurations used for this report.																					
Note 2. Average values are only from data with r/t>8.0.																					
Note 3. Corresponding references can be found in Section 7.																					

Table 2-7
Test/Regression Analysis Results—Unreinforced Fabricated Tees

							In-plane Bending of the Branch			Out of plane Bending of the Branch			Torsion of the Branch			In-plane Bending of the Run			Out of plane Bending of the Run		
Ref.	**Test**	**R/T**	**r/t**	**r/R**	**t/T**	**r/rp**	**Test i_{ib}**	**C_{ib}**	**$Test_{ib}/C_{ib}$**	**Test i_{ob}**	**C_{ob}**	**$Test_{ob}/C_{ob}$**	**Test i_{tb}**	**C_{tb}**	**$Test_{tb}/C_{tb}$**	**Test i_{ir}**	**C_{ir}**	**$Test_{ir}/C_{ir}$**	**Test i_{or}**	**C_{or}**	**$Test_{or}/C_{or}$**
11	**ORNL-3**	24.50	3.34	0.11	0.84	0.87															
18	**ECR/EAW**	35.33	0.50	0.12	8.65	0.50										0.93	0.52	1.78			
11	**ORNL-4**	24.50	9.58	0.13	0.32	0.95															
19	**Roarty**	8.99	1.50	0.18	1.05	0.75										1.13	1.17	0.97			
19	**Roarty**	8.99	1.50	0.18	1.05	0.75										0.97	1.17	0.83			
7	**Decock**	41.34	8.14	0.20	1.00	0.94	2.67	10.28	0.26												
19	**Roarty**	8.99	4.50	0.21	0.42	0.90										1.25	2.07	0.60			
19	**Roarty**	8.99	4.50	0.21	0.42	0.90										1.23	2.07	0.59			
18	**ECR/EAW**	34.11	4.50	0.22	1.67	0.90										1.05	1.74	0.60			
18	**ECR/EAW**	36.45	9.50	0.23	0.89	0.95										1.51	2.51	0.60			
7	**Decock**	24.60	21.15	0.43	0.50	0.98	2.75	6.04	0.46												
11	**ORNL-1**	49.50	49.50	0.50	0.50	0.99															
6	**Pickett**	9.50	8.78	0.63	0.69	0.95				3.90	9.82	0.40									
7	**Decock**	24.60	28.78	0.70	0.60	0.98	3.47	6.81	0.51												
8	**Khan**	12.89	11.33	0.76	0.87	0.96	1.85	5.17	0.36	5.84	13.84	0.42									
8	**Khan**	16.50	14.23	0.84	0.97	0.97				8.93	16.27	0.55									
8	**Khan**	16.50	14.23	0.84	0.97	0.97				7.75	16.27	0.48									
21	**Moffat 4**	5.79	5.79	1.00	1.00	0.92				---											
21	**Moffat 3**	7.59	7.59	1.00	1.00	0.94															
1	**Markl**	8.99	8.99	1.00	1.00	0.95	2.40	4.42	0.54	2.69	4.65	0.58	2.69	5.10	0.528	1.74	4.20	0.41	1.06	2.29	0.46
1	**Markl**	8.99	8.99	1.00	1.00	0.95	2.28	4.42	0.52	2.73	4.65	0.59	2.73	5.10	0.535	1.82	4.20	0.43	1.34	2.29	0.58
1	**Markl**	8.99	8.99	1.00	1.00	0.95	2.15	4.42	0.49												
1	**Markl**	8.99	8.99	1.00	1.00	0.95	2.03	4.42	0.46												
1	**Markl**	8.99	8.99	1.00	1.00	0.95	2.04	4.42	0.46												
1	**Markl**	8.99	8.99	1.00	1.00	0.95	2.49	4.42	0.56												
1	**Markl**	8.99	8.99	1.00	1.00	0.95	2.43	4.42	0.55												
1	**Markl**	8.99	8.99	1.00	1.00	0.95	2.40	4.42	0.54												
1	**Markl**	8.99	8.99	1.00	1.00	0.95	2.32	4.42	0.53												
1	**Markl**	8.99	8.99	1.00	1.00	0.95	2.53	4.42	0.57												
1	**Markl**	8.99	8.99	1.00	1.00	0.95	2.57	4.42	0.58												
1	**Markl**	8.99	8.99	1.00	1.00	0.95	2.34	4.42	0.53												
1	**Markl**	8.99	8.99	1.00	1.00	0.95	2.30	4.42	0.52												
1	**Markl**	10.58	10.58	1.00	1.00	0.95	2.87	4.92	0.58												
1	**Markl**	10.58	10.58	1.00	1.00	0.95	3.05	4.92	0.62												
5	**Blair**	12.00	12.00	1.00	1.00	0.96	3.62	5.35	0.68												
21	**Moffat 2**	12.36	12.36	1.00	1.00	0.96															
21	**Moffat 1**	20.73	20.73	1.00	1.00	0.98															
1	**Markl**	22.00	22.00	1.00	1.00	0.98	4.70	8.00	0.59												
1	**Markl**	22.00	22.00	1.00	1.00	0.98	8.38	8.00	1.05												
7	**Decock**	41.40	41.40	1.00	1.00	0.99	6.90	12.16	0.57												
1	**Markl**	41.79	41.79	1.00	1.00	0.99	8.64	12.24	0.71												
1	**Markl**	41.79	41.79	1.00	1.00	0.99	14.03	12.24	1.15												
11	**ORNL-2**	49.50	49.50	1.00	1.00	0.99															
Note 1	**W/EPRI-A**	22.44	18.73	0.29	0.35	0.97				3.15	8.75	0.36									
Note 1	**W/EPRI-B**	22.44	18.73	0.29	0.35	0.97				3.45	8.75	0.39									
Note 1	**W/EPRI-C**	22.44	18.73	0.29	0.35	0.97				3.88	8.75	0.44									
Note 1	**W/EPRI-D**	22.44	18.73	0.29	0.35	0.97				3.84	8.75	0.44									
								Average	0.57		Average	0.46		Average	0.532		Average	0.48		Average	0.52

Average values are only from data with r/t> 8.0.

Note 1: W/EPRI-A,B,C, and D correspond to the test configurations used in this report.

Note 2. Corresponding references can be found in Section 7.

Table 2-8
Comparison of Stresses to Experimental Data

Test Condition	Average i_{test}/C(FEA)	Average i/C(Regression)
In-plane bending of the branch:	0.508	0.575
Out-of-plane bending of the branch:	0.411	0.465
Torsion of the branch:	0.416	0.432
In-plane bending of the run:	0.476 (Note 1)	0.483 (Note 1)
Out-of-plane bending of the run:	0.535	0.523

(Note 1) The average values are calculated only for the test data where $r/t > 8.0$ since the FEA covers only those configurations.

The regression equations, 2-1 to 2-6, correspond to equations for secondary stress indices. ASME Section III uses the expression $i = C_2 K_2/2$ as a method for determining stress intensification factors where C_2 and K_2 are respectively the secondary stress indice and the local stress indice. The product $C_2 K_2$ corresponds to the maximum stress. Consequently, assuming that $K_2 \cong 1.0$, Table 2-8 supports the expression $i = C_2 K_2/2$. In addition, there is a lower limit to the stress intensification factor of 1.0. This then leads to the following expressions for the stress intensification factors:

2.9.1 In-plane bending of the branch

$$i_{ib} = 0.515\,(R/T)^{1.05}(r/t)^{-0.387}(r/R)^{0.49} \quad \text{where} \quad i_{ib} \geq 1.0 \qquad \text{(eq. 2-7)}$$

2.9.2 Out-of-plane bending of the branch

$$i_{ob} = 1.28(1.28(r/R)-(r/R)^{4})\,(R/T)^{1.4}(r/t)^{-0.558}(r/R)^{0.4057} \quad \text{where} \quad i_{ob} \geq 1.0 \qquad \text{(eq. 2-8)}$$

2.9.3 Torsion of the branch

$$i_{tb} = 0.85\,(R/T)(r/t)^{-0.5}(r/R)^{2.1} \quad \text{where} \quad i_{tb} \geq 1.0 \qquad \text{(eq. 2-9)}$$

2.9.4 In-plane bending of the run

$$i_{ir} = 0.985\,(R/T)^{-0.137}(r/t)^{0.482}(r/R)^{0.241} \quad \text{where} \quad i_{ir} \geq 1.0 \qquad \text{(eq. 2-10)}$$

2.9.5 Out-of-plane bending of the run

$$i_{or} = 0.605\,(R/T)^{-0.237}(r/t)^{0.528}(r/R)^{1.42} \quad \text{where} \quad i_{or} \geq 1.0 \qquad \text{(eq. 2-11)}$$

2.9.6 Torsion of the run

$$i_{tr} = 0.864\,(R/T)^{-0.0473}(r/t)^{0.543}(r/R)^{0.6093} \quad \text{where} \quad i_{tr} \geq 1.0 \qquad \text{(eq. 2-12)}$$

The applicability of these expressions will be discussed in more detail in Section 5, Applicability of Results.

3

COMBINATION OF MOMENTS AND STRESSES

3.1 Discussion

ASME Section III [3] (for Class 2 or Class 3 piping) and ANSI B31.1 [4] prescribe methodologies for checking branch ends and run ends. This methodology results in the calculation of a stress by the use of the following general expression:

$$S = \frac{i(M_i^2 + M_o^2 + M_t^2)^{1/2}}{Z_i} \quad \text{(eq. 3-1)}$$

Where M_i, M_o, and M_t are respectively the in-plane, out-of-plane, and torsional moment acting on the branch or run end. The branch and each of the run ends are evaluated separately. The value of Z_i used is the one corresponding to the branch or run, depending upon which is being evaluated. The expression for Z_i for the branch connection is:

$$z = \pi r^2 t \quad \text{(eq. 3-2)}$$

The expression for the run pipe is:

$$Z = \pi R^2 T \quad \text{(eq. 3-3)}$$

(In Section 5, modifications for the values of z (branch) will be discussed for configurations with local reinforcement).

The value of i as presently specified by Section III and B31.1 is the maximum of i_o, i_i, or i_t where these are the corresponding SIFs to the in-plane, out-of-plane, and torsional moment loading at the point of interest (branch or run point).

WRC Bulletin 329 [9] suggests that the “combined fatigue-effective stress” could be represented by:

$$S = \frac{i_i M_i + i_o M_o + i_t M_t}{Z_i} \qquad \text{(eq. 3-4)}$$

or by:

$$S = \frac{\left[(i_i M_i)^2 + (i_o M_o)^2 + (i_t M_t)^2\right]^{1/2}}{Z_i} \qquad \text{(eq. 3-5)}$$

As discussed in [9] Equation 3-4 represents an upper bound since it assumes that the stress contribution of each moment acts in the same direction and occurs at the same point in the component. Hence the stresses are added algebraically.

Equation 3-5, as applied to branch connections, “represents a judgmental evaluation of the effect of the three combined moments” [9]. Equation 3-1 is more conservative than Equation 3-5 because the value of i in Equation 3-1 is the maximum.

The Section III Class 1 approach of combining moments represents an additional approach. Reference [14] discusses this approach in great detail.

It should also be noted that there are inconsistencies among the various B31 Codes. B31.3 combines stress using:

$$S = (S_b^2 + 4 S_t^2)^{1/2} \qquad \text{(eq. 3-6)}$$

where

$$S_b = \frac{\left[(i_i M_i)^2 + (i_o M_o)^2\right]^{1/2}}{Z_i} \qquad \text{(eq. 3-7)}$$

and

$$S_t = 1/2\ M / Z_i \qquad \text{(eq. 3-8)}$$

While there are different i factors for the in-plane and out-of-plane bending, no intensification is applied to the torsional stress.

Because of the inconsistencies between the various B31 codes regarding this matter, there was a joint meeting in October 1996 on the subject where it was agreed to consider using the same equations for stress calculations. One methodology under consideration uses the following expression for calculating stresses:

$$S = \left[\{i_f F/A + [(i_i M_i/Z_i)^2 + (i_o M_o/Z_i)^2]^{1/2}\}^2 + (i_t M_t/Z_i)^2\right]^{1/2} \qquad \text{(eq. 3-9)}$$

where F is the axial force, A is the pipe cross-sectional area, and i_f is a stress intensification factor associated with the axial force.

In general, i_f would equal unity. The force term is included as a "warning to the designer" that the design layout might have a potential problem such as a long riser with a resulting high axial load due to dead weight or thermal expansion. This would be of particular concern for configurations with large values of R/T.

Clearly there are conditions where the Section III approach (for Class 2 or 3 piping), Equation 3-1, would be very conservative. As an example, if the moment loading was only in one plane, corresponding to the plane with a small SIF, using the maximum loading would be very conservative. It appears that the approach suggested by Equation 3-5 is more reasonable.

It should be noted that the B31.1 Foreword states that:

"The Code *never intentionally puts a ceiling limit on conservatism.* A designer is free to specify more rigid requirements as he feels they may be justified. *Conversely, a designer who is capable* of a more rigorous analysis than is specified in the Code may justify a less conservative design, and still satisfy the basic intent of the Code."

If B31.1 is the applicable Code of record, then the Foreward might serve as a mechanism for using one of the approaches suggested above. Until the applicable Code committees implement the expected changes, it is suggested that Equation 3-3 be utilized if the individual SIFs are to be used.

However, if Section III is the applicable Code of record, this option is not available at this time.

It is anticipated that there will be modifications to the present methodology in the future. However, until these changes are made, Equation 3-1 is still required to satisfy the Code (Section III)-specific requirements.

4

INVESTIGATION OF FLEXIBILITY OF BRANCH CONNECTIONS

4.1 Introduction

The flexibility of branch connections is directly related to the size and thickness of the run pipe and the branch connection. This is important because branch connections affect the stresses and flexibility of all piping systems.

This flexibility study is based on the results from FEA. Thirty six FEA analyses were performed including a wide range of run / branch configurations.

4.2 General Discussion

In piping analysis the various components are modeled as one dimensional beam elements. In order to accurately represent the load displacement (flexibility) action of the components, flexibility factors are used.

For bending of a straight pipe of length L, the rotation of one end, ϕ, with respect to the other is:

$$\phi = 1 / EI \int_o^L M \, dx \qquad \text{(eq. 4-1)}$$

where M is the bending moment.

For a torsional moment, the rotation is given by:

$$\phi = (1 / GJ) \int_o^L M \, dx = 1.3 / EI \int_o^L M \, dx \qquad \text{(eq. 4-2)}$$

where M is the torsional moment. This is based on the relationship between J and I in addition to $G = E / (2(1+\mu))$.

There are several possible ways to model the run / branch connection. Figure 4-1 indicates one possible model that is provided in the Code (Figure NB-3686-1). A rigid link is used to connect point 2 to 3. At point 3, a point spring is used to represent the local flexibility of the connection.

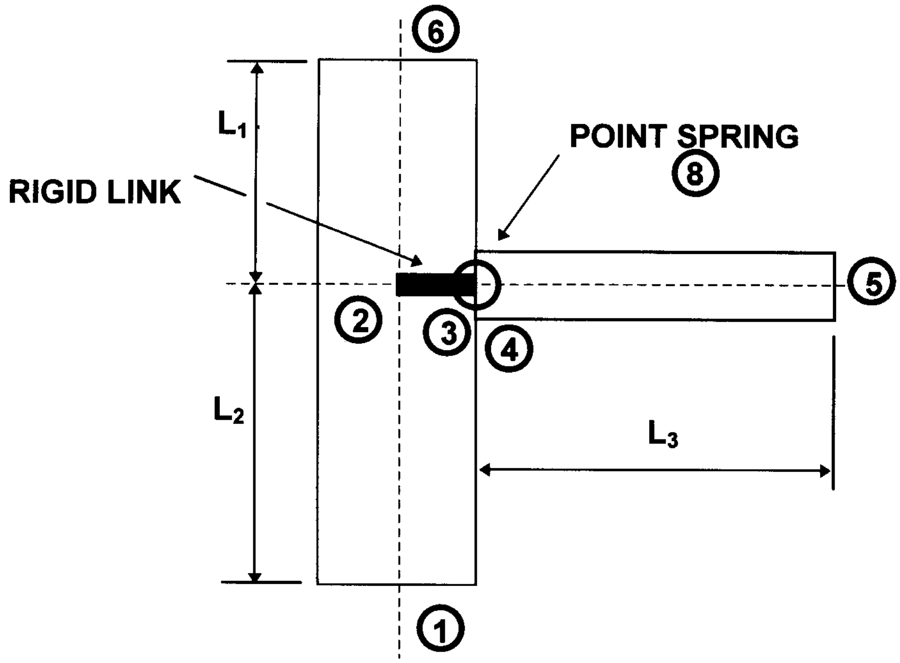


Figure 4-1
Beam Model for Branch Loading

It is convenient to define the flexibility of the spring by:

$$\phi = k\ M\ d_o / EI_b \qquad \text{(eq. 4-3)}$$

where I_b is the moment of inertia of the branch. Then k is equivalent to the number of branch pipe diameters that would be added to represent the local flexibility.

The flexibility factor for the spring will be calculated by:

$$k = (\phi_{fea} - \phi_b) / (Md_o / I_b) \qquad \text{(eq. 4-4)}$$

where ϕ_{fea} is the rotation from the FEA and ϕ_b is the rotation from the beam model.

4.3 Finite Element Analysis

The same models that were discussed earlier were used in the flexibility analysis. COSMOS version 1.75 from Structural Research and Analysis Corporation [10] was used in the analyses. The material properties used in the analyses are E = 30E6 psi., G = 12E6 psi., and μ = 0.28. The beam equations (Equations 4-2, etc.) assumed a value of μ = 0.3. This difference is considered insignificant. The flexibility equations are valid for other values of E.

The local rotation at the juncture of the run pipe and the branch is somewhat dependent on the boundary conditions at the ends of the run pipe (points A and C, Figure 4-2).

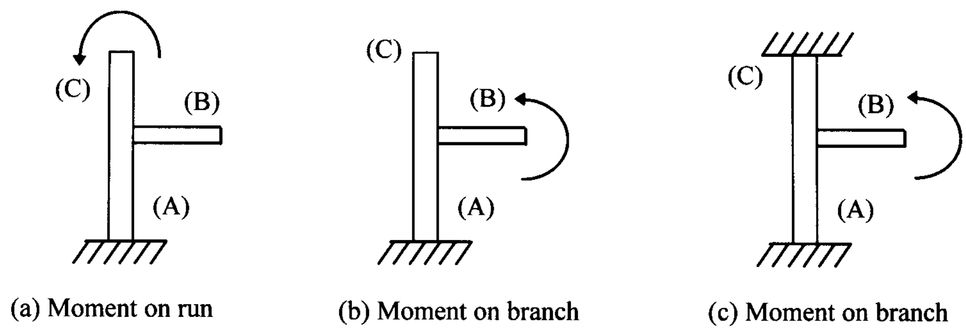


Figure 4-2
Boundary Conditions

It is important to recognize that, in evaluating flexibility factors, there is no "conservative" value that would be applicable for all piping layouts. As an example, a high value might mean that the loads are lower in some components in a piping system than the "true" values.

Consequently the "best" value to use is the one that is most representative of the actual value. This is complicated because the flexibility is a function of the end conditions at the ends of the attached run pipe. This will, of course, be a function of the layout.

As a result of this, two sets of boundary conditions were used in the evaluation. The first was where the lower end of the model (point A, Figure 4-2) was fixed and the upper end (point C) was free. The loads were applied at the end of the branch (point B), as is depicted in Figure 4-2. In the second case, both ends were fixed and the loads were applied at the end of the branch. The flexibility factors are based on the average of the results.

For evaluation of the flexibility of the run pipe, one end of the model (the lower end), point A (Figure 4-2), was fixed and moments were applied to the upper end, point C. The branch end (point B) was free.

The 36 models are listed in Table 4-1 along with the dimensions. Other pertinent data is also included. Table 4-1 includes the moments used in the FEA, which are based on a nominal bending stress of 10 ksi. in the pipe or branch.

Analysis was performed for the same load cases that were discussed earlier (see Figure 4-2 for definition of loads):

Load Case 1 - In-plane moment on the branch (point B), point A fixed, point C free.

Load Case 2 - Out-of-plane moment on the branch (point B), point A fixed, point C free.

Load Case 3 - Torsion on the branch (point B), point A fixed, point C free.

Load Case 4 - In-plane moment on the run (point C), point A fixed, point C free.

Load Case 5 - Out-of-plane moment on the run (point C), point A fixed, point C free.

Load Case 6 - Torsion on the run (point C), point A fixed, point C free.

Load Case 7 - In-plane moment on the branch (point B), points A and C fixed.

Load Case 8 - Out-of-plane moment on the branch (point B), points A and C fixed.

Load Case 9 - Torsion on the branch (point B), points A and C fixed.

Table 4-1
FEA Models

	Model	D_o	T	d_o	t	d_o/D_o	t/T	D_o/T	d_o/t	D	d	D/T	d/D	d/t	Ma	Mb	Ip	Ib
		(in.)	(in.)	(in.)	(in.)					(in.)	(in.)				(in. lbs.)	(in. lbs.)	(in^4)	(in^4)
1	ORNL-4	10.0	0.200	1.29	0.064	0.129	0.320	50.0	20.2	9.80	1.23	49.0	0.125	19.2	150859	756	74.0	0.046
2	Decock	10.0	0.120	2.07	0.120	0.207	1.00	83.3	17.2	9.88	1.95	82.3	0.197	16.2	91999	3565	45.5	0.348
3	Roarty	10.0	0.527	2.22	0.111	0.222	0.211	19.0	20.0	9.47	2.11	18.0	0.223	19.0	371428	3885	177	0.411
4	ECR/EAW	10.0	0.135	2.42	0.121	0.242	0.896	74.1	20.0	9.87	2.30	73.1	0.233	19.0	103185	5005	50.9	0.576
5	Wais	10.0	0.100	2.50	0.050	0.250	0.500	100	50.0	9.90	2.45	99.0	0.247	49.0	76977	2357	38.1	0.289
6	Wais	10.0	0.100	2.50	0.025	0.250	0.250	100	100	9.90	2.48	99.0	0.250	99.0	76977	1203	38.1	0.149
7	OSU1	10.0	0.294	3.53	0.186	0.353	0.633	34.0	19.0	9.71	3.34	33.0	0.345	18.0	217529	16336	106	2.74
8	Decock	10.0	0.199	4.31	0.100	0.431	0.503	50.3	43.1	9.80	4.21	49.3	0.430	42.1	150135	13940	73.6	2.94
9	Wais	10.0	0.100	5.00	0.200	0.500	2.00	100	25.0	9.90	4.80	99.0	0.485	24.0	76977	36191	38.1	8.70
10	Wais	10.0	0.100	5.00	0.140	0.500	1.40	100	35.7	9.90	4.86	99.0	0.491	34.7	76977	25971	38.1	6.32
11	Wais	10.0	0.100	5.00	0.075	0.500	0.750	100	66.7	9.90	4.93	99.0	0.497	65.7	76977	14288	38.1	3.52
12	ORNL-1	10.0	0.100	5.00	0.050	0.500	0.500	100	100	9.90	4.95	99.0	0.500	99.0	76977	9622	38.1	2.38
13	OSU2	10.0	0.290	5.22	0.275	0.522	0.948	34.5	19.0	9.71	4.94	33.5	0.509	18.0	214746	52751	104	13.1
14	Wais	10.0	0.101	6.00	0.069	0.600	0.683	99.0	87.0	9.90	5.93	98.0	0.599	86.0	77731	19063	38.5	5.66
15	Pickett	10.0	0.500	6.38	0.344	0.638	0.688	20.0	18.5	9.50	6.03	19.0	0.635	17.5	354411	98271	169	29.7
16	Decock	10.0	0.199	7.00	0.120	0.700	0.603	50.3	58.3	9.80	6.88	49.3	0.702	57.3	150135	44612	73.6	15.4
17	Wais	10.0	0.100	7.50	0.080	0.750	0.800	100	93.8	9.90	7.42	99.0	0.749	92.8	76977	34593	38.1	12.8
18	Wais	10.0	0.100	7.50	0.075	0.750	0.750	100	100	9.90	7.43	99.0	0.750	99.0	76977	32475	38.1	12.1
19	Wais	10.0	0.100	7.50	0.050	0.750	0.500	100	150	9.90	7.45	99.0	0.753	149	76977	21796	38.1	8.12
20	Khan	10.0	0.373	7.68	0.325	0.768	0.871	26.8	23.6	9.63	7.36	25.8	0.764	22.6	271507	138120	131	50.9
21	Khan	10.0	0.294	8.43	0.286	0.843	0.973	34.0	29.5	9.71	8.15	33.0	0.839	28.5	217529	149018	106	60.8
22	Wais	10.0	0.100	9.00	0.090	0.900	0.900	100	100	9.90	8.91	99.0	0.900	99.0	76977	56116	38.1	25.0
23	Markl	10.0	0.527	10.0	0.527	1.00	1.00	19.0	19.0	9.47	9.47	18.0	1.00	18.0	371428	371429	177	177
24	Markl	10.0	0.451	10.0	0.451	1.00	1.00	22.2	22.2	9.55	9.55	21.2	1.00	21.2	322985	322985	155	155
25	Blair	10.0	0.400	10.0	0.400	1.00	1.00	25.0	25.0	9.60	9.60	24.0	1.00	24.0	289529	289529	139	139
26	Wais	10.0	0.294	10.0	0.294	1.00	1.00	34.0	34.0	9.71	9.71	33.0	1.00	33.0	217529	217529	106	106
27	Markl	10.0	0.222	10.0	0.222	1.00	1.00	45.0	45.0	9.78	9.78	44.0	1.00	44.0	166703	166703	81.6	81.6
28	Wais	10.0	0.178	10.0	0.178	1.00	1.00	56.2	56.2	9.82	9.82	55.2	1.00	55.2	134868	134868	66.3	66.3
29	Wais	10.0	0.135	10.0	0.135	1.00	1.00	74.1	74.1	9.87	9.87	73.1	1.00	73.1	103185	103185	50.9	50.9
30	Decock	10.0	0.119	10.0	0.119	1.00	1.00	84.0	84.0	9.88	9.88	83.0	1.00	83.0	91251	91251	45.1	45.1
31	Markl	10.0	0.118	10.0	0.118	1.00	1.00	84.7	84.7	9.88	9.88	83.7	1.00	83.7	90503	90503	44.7	44.7
32	ORNL-2	10.0	0.100	10.0	0.100	1.00	1.00	100	100	9.90	9.90	99.0	1.00	99.0	76977	76977	38.1	38.1
33	W/EPRI	10.0	0.218	2.90	0.0750	0.290	0.346	45.9	38.5	9.78	2.82	44.9	0.289	37.5	163811	4717	80.2	0.667
34	Wais34	10.0	0.100	3.75	0.0380	0.375	0.375	100	100	9.90	3.71	99.0	0.375	99.0	76977	4059	38.1	0.754
35	Wais35	10.0	0.100	6.25	0.0630	0.625	0.625	100	100	9.90	6.19	99.0	0.625	99.0	76977	18793	38.1	5.82
36	Wais36	10.0	0.100	8.75	0.0880	0.875	0.875	100	100	9.90	8.66	99.0	0.875	99.0	76977	51568	38.1	22.3

Note 1. This table is produced on a spreadsheet using EXCEL. The number of significant figures is greater than indicated.

4.4 FEA Results—Flexibility of Branch Pipe

Table 4-2 lists the rotations at the specified points for the various load cases as well as other data. These rotations were taken directly from the FEA output. The results are discussed in the following sections. The rotations that are listed in this table corresponds to the loadings as indicated in Figure 4-3. The flexibilities, k, correspond to the same loading direction.

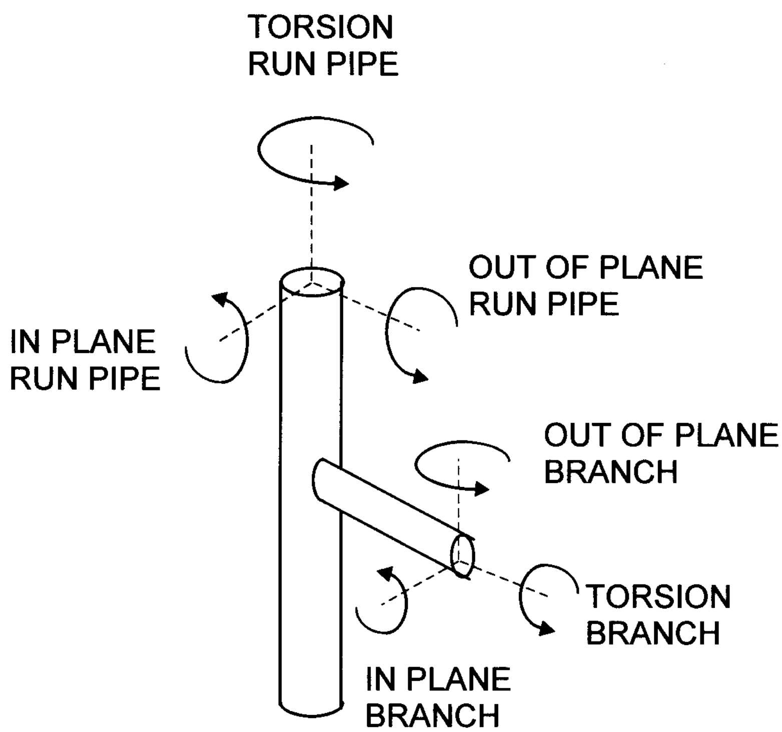


Figure 4-3
Loading Conditions

Table 4-2
Flexibility Factors

		Load Case - 1				Load Case - 7				Comparison LC1 to LC7				
		In-Plane Moment				In-Plane Moment								
		on Branch				on Branch								
	Model	$\phi_{5\text{-}4}$	$\phi_{2\text{-}1}$	ϕ_{fea}	**k**	$\phi_{5\text{-}4}$	$\phi_{2\text{-}1}$	ϕ_{fea}	**k**	ϕ_{fea}	**k**	**k ave**	**k -Regr**	**%Dif**
										%dif	**%dif**		**Eq. (4-11)**	**%**
1	**ORNL-4**	7.86E-03	6.64E-06	1.09E-02	4.35	7.86E-03	8.30E-07	1.09E-02	4.36	0.000	-0.190	4.35	5.31	-22.0
2	**Decock**	4.95E-03	5.10E-05	1.48E-02	13.9	4.95E-03	6.37E-06	1.48E-02	13.9	0.270	-0.050	13.9	13.6	2.10
3	**Roarty**	4.57E-03	1.43E-05	5.63E-03	1.50	4.57E-03	1.79E-06	5.62E-03	1.50	0.230	0.050	1.50	1.85	-23.3
4	**ECR/EAW**	4.20E-03	6.39E-05	1.24E-02	11.7	4.20E-03	7.99E-06	1.24E-02	11.7	0.480	0.050	11.7	11.4	2.70
5	**Wais**	3.94E-03	4.02E-05	1.23E-02	12.2	3.94E-03	5.02E-06	1.23E-02	12.2	0.330	0.060	12.2	9.69	20.8
6	**Wais**	3.90E-03	2.05E-05	9.98E-03	8.99	3.90E-03	2.56E-06	9.96E-03	8.99	0.210	0.050	8.99	6.37	29.2
7	**OSU1**	2.88E-03	1.00E-04	6.30E-03	4.73	2.88E-03	1.26E-05	6.20E-03	4.72	1.51	0.210	4.72	4.95	-4.80
8	**Decock**	2.29E-03	1.23E-04	6.34E-03	5.76	2.29E-03	1.54E-05	6.22E-03	5.74	1.95	0.420	5.75	5.39	6.20
9	**Wais**	2.01E-03	6.17E-04	1.64E-02	19.9	2.01E-03	7.71E-05	1.58E-02	19.8	3.78	0.580	19.8	19.4	2.40
10	**Wais**	1.99E-03	4.43E-04	1.28E-02	15.2	1.99E-03	5.54E-05	1.24E-02	15.0	3.59	0.700	15.1	15.6	-3.20
11	**Wais**	1.96E-03	2.44E-04	9.31E-03	10.5	1.96E-03	3.05E-05	9.05E-03	10.4	2.83	0.700	10.5	10.7	-2.00
12	**ORNL-1**	1.95E-03	1.64E-04	8.13E-03	8.94	1.95E-03	2.05E-05	7.95E-03	8.87	2.28	0.690	8.90	8.35	6.20
13	**OSU2**	1.95E-03	3.28E-04	5.91E-03	5.18	1.95E-03	4.11E-05	5.58E-03	5.12	5.57	1.14	5.15	5.87	-14.0
14	**Wais**	1.63E-03	3.22E-04	7.88E-03	8.80	1.63E-03	4.02E-05	7.49E-03	8.64	4.92	1.79	8.72	9.64	-10.5
15	**Pickett**	1.60E-03	3.78E-04	3.96E-03	2.83	1.60E-03	4.73E-05	3.56E-03	2.72	10.2	3.68	2.77	3.15	-13.5
16	**Decock**	1.40E-03	3.94E-04	5.11E-03	4.89	1.40E-03	4.92E-05	4.61E-03	4.65	9.82	4.75	4.77	5.43	-13.7
17	**Wais**	1.30E-03	5.90E-04	7.33E-03	8.08	1.30E-03	7.37E-05	6.48E-03	7.57	11.7	6.28	7.82	10.2	-30.1
18	**Wais**	1.30E-03	5.54E-04	7.14E-03	7.85	1.30E-03	6.92E-05	6.32E-03	7.36	11.4	6.26	7.60	9.79	-28.7
19	**Wais**	1.30E-03	3.72E-04	6.13E-03	6.66	1.30E-03	4.65E-05	5.54E-03	6.25	9.70	6.04	6.45	7.66	-18.7
20	**Khan**	1.31E-03	6.86E-04	4.67E-03	3.85	1.31E-03	8.57E-05	3.83E-03	3.51	17.9	8.87	3.68	4.29	-16.8
21	**Khan**	1.19E-03	9.16E-04	5.48E-03	4.90	1.19E-03	1.15E-04	4.19E-03	4.20	23.4	14.2	4.55	5.31	-16.8
22	**Wais**	1.08E-03	9.57E-04	7.92E-03	8.74	1.08E-03	1.20E-04	5.91E-03	6.99	25.4	20.0	7.87	10.5	-33.6
23	**Markl**	1.02E-03	1.37E-03	5.62E-03	4.61	1.02E-03	1.71E-04	3.44E-03	3.22	38.7	30.2	3.91	3.45	11.8
24	**Markl**	1.01E-03	1.36E-03	6.04E-03	5.28	1.01E-03	1.70E-04	3.71E-03	3.63	38.6	31.2	4.45	3.86	13.4
25	**Blair**	1.00E-03	1.35E-03	6.40E-03	5.83	1.00E-03	1.69E-04	3.93E-03	3.97	38.6	31.9	4.90	4.20	14.3
26	**Wais**	9.95E-04	1.34E-03	7.42E-03	7.41	9.95E-04	1.67E-04	4.54E-03	4.92	38.8	33.6	6.17	5.21	15.6
27	**Markl**	9.88E-04	1.33E-03	8.51E-03	9.09	9.88E-04	1.66E-04	5.17E-03	5.90	39.2	35.2	7.50	6.33	15.6
28	**Wais**	9.84E-04	1.32E-03	9.50E-03	10.6	9.84E-04	1.65E-04	5.73E-03	6.75	39.7	36.3	8.67	7.37	15.0
29	**Wais**	9.79E-04	1.32E-03	1.09E-02	12.7	9.79E-04	1.65E-04	6.50E-03	7.92	40.4	37.7	10.3	8.92	13.6
30	**Decock**	9.78E-04	1.32E-03	1.16E-02	13.8	9.78E-04	1.64E-04	6.87E-03	8.50	40.7	38.4	11.1	9.72	12.8
31	**Markl**	9.78E-04	1.31E-03	1.17E-02	13.9	9.78E-04	1.64E-04	6.90E-03	8.54	40.8	38.5	11.2	9.78	12.7
32	**ORNL-2**	9.76E-04	1.31E-03	1.26E-02	15.4	9.76E-04	1.64E-04	7.42E-03	9.33	41.3	39.3	12.3	11.0	11.3
33	**W/EPRI**	3.42E-03	3.82E-05	6.95E-03	5.11	3.42E-03	4.78E-06	6.92E-03	5.11	0.460	-0.040	5.11	4.40	13.9
34	**Wais34**	2.60E-03	6.92E-05	9.02E-03	9.43	2.60E-03	8.65E-06	8.95E-03	9.41	0.810	0.200	9.42	7.46	20.8
35	**Wais35**	1.56E-03	3.20E-04	7.46E-03	8.29	1.56E-03	4.01E-05	7.06E-03	8.10	5.42	2.22	8.19	9.11	-11.2
36	**Wais36**	1.12E-03	8.79E-04	7.59E-03	8.31	1.12E-03	1.10E-04	5.89E-03	6.94	22.4	16.6	7.62	10.4	-36.3
													MAX=	29.2
													MIN=	-36.3
													AVER=	-1.60
													STD=	17.5

Note 1. This table is produced on a spreadsheet using EXCEL. The number of significant figures is greater than indicated.

Table 4-2 (cont.)
Flexibility Factors

		Load Case - 2				Load Case - 8				Comparison LC2 to LC8						
		Out-of-Plane Moment				Out-of-Plane Moment										
		on Branch				on Branch									W/factor	
	Model	ϕ_{5-4}	ϕ_{2-1}	ϕ_{fea}	k	ϕ_{5-4}	ϕ_{2-1}	ϕ_{fea}	k	ϕ_{fea}	k	k ave	k -Regr	%Dif	k -Regr	%Dif
										%dif	%dif		Eq. (4-17)	%	Eq. (4-18)	%
1	ORNL-4	7.86E-03	8.63E-06	1.31E-02	7.44	7.86E-03	4.32E-06	1.31E-02	7.43	0.080	0.109	7.43	20.2	-172	8.96	-20.6
2	Decock	4.95E-03	6.63E-05	3.66E-02	44.8	4.95E-03	3.31E-05	3.66E-02	44.8	0.110	0.0218	44.8	62.0	-38.4	44.1	1.50
3	Roarty	4.57E-03	1.86E-05	6.25E-03	2.39	4.57E-03	9.30E-06	6.24E-03	2.39	0.160	0.0420	2.39	3.63	-52.0	3.33	-39.6
4	ECR/EAW	4.20E-03	8.31E-05	3.18E-02	39.3	4.20E-03	4.15E-05	3.17E-02	39.3	0.160	0.0308	39.3	46.3	-17.8	39.1	0.40
5	Wais	3.94E-03	5.23E-05	3.59E-02	46.9	3.94E-03	2.61E-05	3.58E-02	46.9	0.080	0.0121	46.9	43.5	7.20	35.9	23.5
6	Wais	3.90E-03	2.67E-05	2.64E-02	33.4	3.90E-03	1.33E-05	2.64E-02	33.4	0.040	-0.0148	33.4	27.5	17.6	21.9	34.4
7	OSU1	2.88E-03	1.31E-04	1.24E-02	13.4	2.88E-03	6.53E-05	1.24E-02	13.4	0.560	0.0499	13.4	12.1	9.70	15.7	-16.9
8	Decock	2.29E-03	1.60E-04	1.72E-02	21.7	2.29E-03	8.00E-05	1.71E-02	21.6	0.520	0.0677	21.6	14.8	31.6	20.4	6.00
9	Wais	2.01E-03	8.02E-04	8.87E-02	124	2.01E-03	4.01E-04	8.83E-02	124	0.500	0.0452	124	77.2	37.7	109	11.8
10	Wais	1.99E-03	5.76E-04	6.49E-02	90.9	1.99E-03	2.88E-04	6.45E-02	90.9	0.490	0.0516	90.9	60.8	33.2	84.5	7.00
11	Wais	1.96E-03	3.17E-04	4.22E-02	59.0	1.96E-03	1.58E-04	4.20E-02	58.9	0.430	0.0542	59.0	40.1	31.9	53.9	8.60
12	ORNL-1	1.95E-03	2.13E-04	3.48E-02	48.5	1.95E-03	1.07E-04	3.47E-02	48.5	0.370	0.0715	48.5	30.7	36.7	40.2	17.1
13	OSU2	1.95E-03	4.27E-04	1.48E-02	17.8	1.95E-03	2.14E-04	1.46E-02	17.7	1.62	0.213	17.7	13.2	25.5	21.4	-20.6
14	Wais	1.63E-03	4.19E-04	3.40E-02	47.4	1.63E-03	2.09E-04	3.37E-02	47.3	0.790	0.190	47.4	34.0	28.1	46.5	1.80
15	Pickett	1.60E-03	4.92E-04	7.17E-03	7.24	1.60E-03	2.46E-04	6.88E-03	7.17	4.13	0.986	7.20	4.99	30.8	8.67	-20.4
16	Decock	1.40E-03	5.12E-04	1.39E-02	17.7	1.40E-03	2.56E-04	1.36E-02	17.6	2.65	0.948	17.7	13.1	25.9	18.7	-5.90
17	Wais	1.30E-03	7.67E-04	2.65E-02	36.2	1.30E-03	3.83E-04	2.58E-02	35.8	2.46	1.09	36.0	34.2	5.10	42.4	-17.7
18	Wais	1.30E-03	7.20E-04	2.55E-02	34.9	1.30E-03	3.60E-04	2.49E-02	34.5	2.39	1.07	34.7	32.7	5.60	40.4	-16.6
19	Wais	1.30E-03	4.83E-04	2.07E-02	28.2	1.30E-03	2.42E-04	2.03E-02	27.9	2.22	1.15	28.1	25.1	10.6	30.1	-7.20
20	Khan	1.31E-03	8.91E-04	9.25E-03	10.1	1.31E-03	4.46E-04	8.61E-03	9.86	6.93	2.77	10.0	7.56	24.4	11.4	-13.6
21	Khan	1.19E-03	1.19E-03	1.09E-02	12.3	1.19E-03	5.96E-04	9.81E-03	11.6	9.63	5.30	12.0	10.3	13.8	13.1	-9.80
22	Wais	1.08E-03	1.24E-03	1.84E-02	23.9	1.08E-03	6.22E-04	1.64E-02	21.9	10.7	8.39	22.9	33.7	-47.4	30.8	-35.0
23	Markl	1.02E-03	1.78E-03	6.64E-03	5.48	1.02E-03	8.89E-04	5.04E-03	4.47	24.1	18.5	4.98	4.77	4.20	3.75	24.6
24	Markl	1.01E-03	1.77E-03	7.33E-03	6.55	1.01E-03	8.83E-04	5.57E-03	5.29	24.0	19.3	5.92	5.76	2.60	4.42	25.2
25	Blair	1.00E-03	1.76E-03	7.92E-03	7.45	1.00E-03	8.78E-04	6.02E-03	5.97	24.0	19.9	6.71	6.66	0.700	5.02	25.2
26	Wais	9.95E-04	1.74E-03	9.62E-03	10.0	9.95E-04	8.70E-04	7.26E-03	7.87	24.5	21.6	8.95	9.63	-7.60	6.91	22.8
27	Markl	9.88E-04	1.73E-03	1.13E-02	12.6	9.88E-04	8.64E-04	8.46E-03	9.70	25.3	23.3	11.2	13.4	-20.3	9.22	17.5
28	Wais	9.84E-04	1.72E-03	1.28E-02	14.8	9.84E-04	8.60E-04	9.41E-03	11.2	26.3	24.8	13.0	17.4	-34.2	11.6	11.0
29	Wais	9.79E-04	1.71E-03	1.46E-02	17.6	9.79E-04	8.56E-04	1.06E-02	13.0	27.5	26.5	15.3	24.1	-57.6	15.3	-0.100
30	Decock	9.78E-04	1.71E-03	1.55E-02	19.0	9.78E-04	8.55E-04	1.11E-02	13.8	28.0	27.2	16.4	28.0	-70.7	17.4	-6.30
31	Markl	9.78E-04	1.71E-03	1.55E-02	19.1	9.78E-04	8.55E-04	1.12E-02	13.9	28.1	27.3	16.5	28.2	-71.6	17.6	-6.70
32	ORNL-2	9.76E-04	1.71E-03	1.67E-02	20.8	9.76E-04	8.53E-04	1.19E-02	15.0	28.7	28.1	17.9	34.3	-91.3	20.8	-16.0
33	W/EPRI	3.42E-03	4.97E-05	1.34E-02	14.5	3.42E-03	2.49E-05	1.34E-02	14.5	0.150	-0.0490	14.5	12.7	12.5	13.2	9.20
34	Wais	2.60E-03	9.00E-05	3.39E-02	46.3	2.60E-03	4.50E-05	3.38E-02	46.3	0.150	0.0161	46.3	29.3	36.6	32.9	28.9
35	Wais	1.56E-03	4.17E-04	3.13E-02	43.6	1.56E-03	2.08E-04	3.10E-02	43.5	0.890	0.244	43.5	31.8	26.9	42.9	1.50
36	Wais	1.12E-03	1.14E-03	1.94E-02	25.4	1.12E-03	5.72E-04	1.78E-02	23.9	8.11	5.84	24.6	33.5	-36.1	32.9	-33.6
													MAX=	37.7	MAX=	34.4
													MIN=	-172	MIN=	-39.6
													AVER=	-7.20	AVER=	-0.200
													STD=	45.3	STD=	19.2

Note 1. This table is produced on a spreadsheet using EXCEL. The number of significant figures is greater than indicated.

Table 4-2 (cont.)
Flexibility Factors

		Load Case - 3				Load Case - 9				Comparison LC3 to LC9				
		Torsion				Torsion								
		on Branch				on Branch								
	Model	ϕ_{5-4}	ϕ_{2-1}	ϕ_{fea}	k	ϕ_{5-4}	ϕ_{2-1}	ϕ_{fea}	k	ϕ_{fea}	k	k ave	k -Regr	% Dif
										% dif	% dif		Eq. (4-25)	%
1	ORNL-4	1.02E-02	6.64E-06	1.04E-02	0.306	1.02E-02	8.30E-07	1.04E-02	0.300	0.100	2.00	0.303	0.110	-63.7
2	Decock	6.43E-03	5.10E-05	6.93E-03	0.634	6.43E-03	6.37E-06	6.88E-03	0.627	0.700	1.00	0.631	0.463	-26.5
3	Roarty	5.94E-03	1.43E-05	6.17E-03	0.313	5.94E-03	1.79E-06	6.15E-03	0.311	0.200	0.700	0.312	0.176	-43.6
4	ECR/EAW	5.46E-03	6.39E-05	5.96E-03	0.622	5.46E-03	7.99E-06	5.90E-03	0.612	1.10	1.60	0.617	0.552	-10.5
5	Wais	5.13E-03	4.02E-05	5.49E-03	0.463	5.13E-03	5.02E-06	5.45E-03	0.452	0.800	2.40	0.458	0.468	2.20
6	Wais	5.08E-03	2.05E-05	5.32E-03	0.314	5.08E-03	2.56E-06	5.29E-03	0.306	0.500	2.80	0.310	0.324	4.50
7	OSU1	3.75E-03	1.00E-04	4.25E-03	0.571	3.75E-03	1.26E-05	4.14E-03	0.543	2.50	4.80	0.557	0.717	28.8
8	Decock	2.98E-03	1.23E-04	3.58E-03	0.686	2.98E-03	1.54E-05	3.42E-03	0.607	4.50	11.5	0.646	0.965	49.4
9	Wais	2.61E-03	6.17E-04	4.78E-03	2.22	2.61E-03	7.71E-05	4.03E-03	1.92	15.7	13.6	2.07	2.87	38.9
10	Wais	2.58E-03	4.43E-04	4.28E-03	1.79	2.58E-03	5.54E-05	3.69E-03	1.50	13.8	16.0	1.64	2.40	46.0
11	Wais	2.55E-03	2.44E-04	3.67E-03	1.26	2.55E-03	3.05E-05	3.29E-03	1.01	10.4	19.2	1.14	1.74	53.0
12	ORNL-1	2.54E-03	1.64E-04	3.41E-03	1.01	2.54E-03	2.05E-05	3.12E-03	0.800	8.60	21.0	0.906	1.40	54.3
13	OSU2	2.53E-03	3.28E-04	3.67E-03	1.15	2.53E-03	4.11E-05	3.25E-03	0.967	11.4	16.1	1.06	1.65	55.9
14	Wais	2.12E-03	3.22E-04	3.63E-03	1.70	2.12E-03	4.02E-05	2.95E-03	1.14	18.6	33.1	1.42	2.20	55.3
15	Pickett	2.08E-03	3.78E-04	3.33E-03	1.25	2.08E-03	4.73E-05	2.75E-03	0.901	17.3	28.2	1.08	1.75	61.9
16	Decock	1.83E-03	3.94E-04	3.67E-03	2.07	1.83E-03	4.92E-05	2.66E-03	1.12	27.5	45.8	1.60	2.29	43.6
17	Wais	1.69E-03	5.90E-04	4.83E-03	3.64	1.69E-03	7.37E-05	2.87E-03	1.58	40.6	56.7	2.61	3.41	30.7
18	Wais	1.69E-03	5.54E-04	4.71E-03	3.53	1.69E-03	6.92E-05	2.82E-03	1.51	40.2	57.2	2.52	3.29	30.6
19	Wais	1.69E-03	3.72E-04	4.08E-03	2.89	1.69E-03	4.65E-05	2.55E-03	1.17	37.4	59.4	2.03	2.64	30.2
20	Khan	1.70E-03	6.86E-04	4.29E-03	2.72	1.70E-03	8.57E-05	2.77E-03	1.40	35.5	48.5	2.06	2.82	36.8
21	Khan	1.54E-03	9.16E-04	5.75E-03	4.71	1.54E-03	1.15E-04	2.91E-03	1.79	49.5	62.1	3.25	3.64	12.0
22	Wais	1.41E-03	9.57E-04	9.85E-03	10.7	1.41E-03	1.20E-04	2.99E-03	2.09	69.6	80.5	6.40	4.83	-24.5
23	Markl	1.32E-03	1.37E-03	6.52E-03	5.47	1.32E-03	1.71E-04	2.74E-03	1.79	57.9	67.3	3.63	4.31	18.6
24	Markl	1.31E-03	1.36E-03	7.23E-03	6.52	1.31E-03	1.70E-04	2.81E-03	1.89	61.2	71.0	4.21	4.45	5.70
25	Blair	1.31E-03	1.35E-03	7.85E-03	7.43	1.31E-03	1.69E-04	2.85E-03	1.97	63.7	73.5	4.70	4.56	-3.00
26	Wais	1.29E-03	1.34E-03	9.72E-03	10.1	1.29E-03	1.67E-04	2.95E-03	2.14	69.6	78.9	6.14	4.86	-20.9
27	Markl	1.28E-03	1.33E-03	1.18E-02	13.1	1.28E-03	1.66E-04	3.03E-03	2.25	74.2	82.8	7.66	5.14	-32.9
28	Wais	1.28E-03	1.32E-03	1.35E-02	15.6	1.28E-03	1.65E-04	3.07E-03	2.33	77.3	85.1	8.98	5.38	-40.1
29	Wais	1.27E-03	1.32E-03	1.59E-02	19.0	1.27E-03	1.65E-04	3.12E-03	2.40	80.4	87.4	10.7	5.68	-47.0
30	Decock	1.27E-03	1.32E-03	1.70E-02	20.6	1.27E-03	1.64E-04	3.14E-03	2.43	81.6	88.2	11.5	5.83	-49.5
31	Markl	1.27E-03	1.31E-03	1.71E-02	20.7	1.27E-03	1.64E-04	3.14E-03	2.43	81.7	88.3	11.6	5.84	-49.6
32	ORNL-2	1.27E-03	1.31E-03	1.86E-02	22.8	1.27E-03	1.64E-04	3.16E-03	2.46	83.0	89.2	12.6	6.04	-52.3
33	W/EPRI	4.45E-03	3.82E-05	4.74E-03	0.364	4.45E-03	4.78E-06	4.70E-03	0.352	0.900	3.40	0.358	0.414	15.7
34	Wais34	3.38E-03	6.92E-05	3.86E-03	0.582	3.38E-03	8.65E-06	3.76E-03	0.528	2.50	9.20	0.555	0.762	37.2
35	Wais35	2.03E-03	3.20E-04	3.61E-03	1.80	2.03E-03	4.01E-05	2.86E-03	1.12	20.8	37.5	1.46	2.24	53.4
36	Wais36	1.45E-03	8.79E-04	8.33E-03	8.58	1.45E-03	1.10E-04	2.95E-03	1.98	64.6	76.9	5.28	4.55	-13.8
													MAX=	61.9
													MIN=	-63.7
													AVER=	8.00
Note 1. This table is produced on a spreadsheet using EXCEL. The number of significant figures is greater than indicated.													STD=	38.5

Table 4-2 (cont.)
Flexibility Factors

					Load Case - 4				
					In-Plane Moment				
						on Run		d/D>.5	
	Model	ϕ_{6-1}	ϕ_{fea}	**%**	**k**	**k -Regr**	**% Dif**	**k -Regr**	**% Dif**
				DIF		**Eq. (4-31)**	**%**	**Eq. (4-41)**	**%**
1	**ORNL-4**	2.65E-03	2.67E-03	-0.706	0.028	0.014	-48.2		
2	**Decock**	2.63E-03	2.67E-03	-1.43	0.056	0.045	-18.4		
3	**Roarty**	2.74E-03	2.79E-03	-1.99	0.078	0.064	-17.1		
4	**ECR/EAW**	2.63E-03	2.69E-03	-2.03	0.079	0.073	-8.05		
5	**Wais**	2.63E-03	2.70E-03	-2.88	0.112	0.108	-4.20		
6	**Wais**	2.63E-03	2.71E-03	-3.26	0.127	0.131	2.64		
7	**OSU1**	2.68E-03	2.80E-03	-4.57	0.178	0.201	12.7		
8	**Decock**	2.65E-03	2.89E-03	-9.17	0.357	0.442	23.5		
9	**Wais**	2.63E-03	2.88E-03	-9.78	0.381	0.533	39.9		
10	**Wais**	2.63E-03	2.94E-03	-11.9	0.465	0.601	29.5		
11	**Wais**	2.63E-03	3.01E-03	-14.5	0.567	0.724	27.7		
12	**ORNL-1**	2.63E-03	3.04E-03	-15.9	0.619	0.809	30.7	0.511	-17.5
13	**OSU2**	2.67E-03	2.96E-03	-10.8	0.422	0.561	32.9	0.402	-4.60
14	**Wais**	2.63E-03	3.28E-03	-24.8	0.969	1.26	29.9	1.04	7.40
15	**Pickett**	2.73E-03	3.25E-03	-19.2	0.750	0.993	32.5	0.637	-15.0
16	**Decock**	2.65E-03	3.60E-03	-35.9	1.40	1.73	23.3	1.32	-5.80
17	**Wais**	2.63E-03	3.92E-03	-49.1	1.92	2.31	20.5	2.40	25.1
18	**Wais**	2.63E-03	3.93E-03	-49.8	1.94	2.35	20.8	2.36	21.6
19	**Wais**	2.63E-03	4.05E-03	-54.3	2.12	2.61	23.3	2.16	2.10
20	**Khan**	2.70E-03	3.66E-03	-35.7	1.39	1.72	23.6	1.48	6.30
21	**Khan**	2.68E-03	4.11E-03	-53.6	2.09	2.33	11.5	2.35	12.6
22	**Wais**	2.63E-03	5.35E-03	-104	4.05	3.80	-6.35	4.71	16.2
23	**Markl**	2.74E-03	4.77E-03	-74.4	2.90	3.30	13.7	3.40	17.1
24	**Markl**	2.72E-03	5.04E-03	-85.5	3.33	3.43	3.01	3.64	9.30
25	**Blair**	2.70E-03	5.25E-03	-94.4	3.68	3.54	-3.83	3.84	4.30
26	**Wais**	2.68E-03	5.85E-03	-119	4.63	3.83	-17.4	4.40	-5.00
27	**Markl**	2.66E-03	6.44E-03	-142	5.55	4.11	-26.0	4.97	-10.4
28	**Wais**	2.65E-03	6.91E-03	-161	6.28	4.34	-30.9	5.47	-12.9
29	**Wais**	2.63E-03	7.49E-03	-184	7.19	4.65	-35.4	6.17	-14.3
30	**Decock**	2.63E-03	7.76E-03	-195	7.60	4.80	-36.9	6.51	-14.3
31	**Markl**	2.63E-03	7.77E-03	-196	7.63	4.81	-37.0	6.53	-14.3
32	**ORNL-2**	2.63E-03	8.11E-03	-209	8.14	5.01	-38.5	7.01	-13.8
33	**W/EPRI**	2.66E-03	2.75E-03	-3.69	0.144	0.150	4.50		
34	**Wais34**	2.63E-03	2.83E-03	-7.91	0.309	0.380	23.0		
35	**Wais35**	2.63E-03	3.38E-03	-28.7	1.12	1.45	30.1	1.19	6.10
36	**Wais36**	2.63E-03	5.00E-03	-90.5	3.53	3.52	0.112	4.23	20.0
						MAX=	39.9	MAX=	25.1
						MIN=	-48.2	MIN=	-17.5
						AVER=	3.60	AVER=	0.90
						STD=	25.2	STD=	13.7
Note 1. This table is produced on a spreadsheet using EXCEL.									
The number of significant figures is greater than indicated.									

Table 4-2 (cont.)
Flexibility Factors

					Load Case - 5				
					Out-of-Plane Moment				
						on Run		d/D>=.5	
	Model	ϕ_{6-1}	ϕ_{fea}	%	k	k -Regr	% Dif	k -Regr	% Dif
				DIF		Eq. (4-35)	%	Eq. (4-45)	%
1	ORNL-4	2.65E-03	2.67E-03	-0.700	0.086	0.001	-98.9		
2	Decock	2.63E-03	2.64E-03	-0.400	0.016	0.007	-54.7		
3	Roarty	2.74E-03	2.74E-03	-0.300	0.058	0.052	-10.6		
4	ECR/EAW	2.63E-03	2.64E-03	-0.400	0.016	0.012	-25.7		
5	Wais	2.63E-03	2.64E-03	-0.600	0.050	0.031	-37.0		
6	Wais	2.63E-03	2.65E-03	-0.800	0.129	0.079	-38.7		
7	OSU1	2.68E-03	2.68E-03	-0.200	0.015	0.040	170		
8	Decock	2.65E-03	2.66E-03	-0.500	0.038	0.099	161		
9	Wais	2.63E-03	2.64E-03	-0.500	0.010	0.025	150		
10	Wais	2.63E-03	2.64E-03	-0.700	0.019	0.042	122		
11	Wais	2.63E-03	2.65E-03	-0.900	0.045	0.097	116		
12	ORNL-1	2.63E-03	2.65E-03	-1.00	0.076	0.167	119	0.047	-38.2
13	OSU2	2.67E-03	2.69E-03	-0.400	0.018	0.059	238	0.019	9.40
14	Wais	2.63E-03	2.66E-03	-1.50	0.084	0.170	104	0.090	8.00
15	Pickett	2.73E-03	2.76E-03	-1.00	0.057	0.135	137	0.051	-10.2
16	Decock	2.65E-03	2.71E-03	-2.10	0.139	0.251	80.7	0.147	5.60
17	Wais	2.63E-03	2.71E-03	-3.40	0.165	0.237	43.8	0.237	44.0
18	Wais	2.63E-03	2.72E-03	-3.50	0.180	0.258	43.7	0.248	38.3
19	Wais	2.63E-03	2.73E-03	-3.90	0.302	0.442	46.2	0.331	9.60
20	Khan	2.70E-03	2.76E-03	-2.20	0.100	0.165	65.6	0.123	24.0
21	Khan	2.68E-03	2.78E-03	-3.90	0.158	0.189	19.4	0.203	28.8
22	Wais	2.63E-03	2.87E-03	-9.40	0.407	0.314	-22.9	0.524	28.7
23	Markl	2.74E-03	2.96E-03	-8.30	0.323	0.242	-25.2	0.337	4.50
24	Markl	2.72E-03	2.98E-03	-9.50	0.372	0.251	-32.6	0.367	-1.30
25	Blair	2.70E-03	2.99E-03	-10.5	0.411	0.258	-37.4	0.391	-4.90
26	Wais	2.68E-03	3.04E-03	-13.4	0.524	0.276	-47.3	0.460	-12.1
27	Markl	2.66E-03	3.09E-03	-16.3	0.634	0.294	-53.6	0.533	-15.9
28	Wais	2.65E-03	3.14E-03	-18.6	0.726	0.309	-57.4	0.599	-17.5
29	Wais	2.63E-03	3.20E-03	-21.6	0.843	0.329	-61.0	0.691	-18.1
30	Decock	2.63E-03	3.24E-03	-23.0	0.897	0.338	-62.3	0.738	-17.7
31	Markl	2.63E-03	3.24E-03	-23.1	0.900	0.339	-62.3	0.741	-17.7
32	ORNL-2	2.63E-03	3.28E-03	-24.8	0.968	0.352	-63.7	0.807	-16.7
33	W/EPRI	2.66E-03	2.67E-03	-0.300	0.039	0.061	59.0		
34	Wais34	2.63E-03	2.64E-03	-0.700	0.074	0.122	65.3		
35	Wais35	2.63E-03	2.67E-03	-1.70	0.109	0.212	95.3	0.118	8.40
36	Wais36	2.63E-03	2.83E-03	-7.80	0.349	0.305	-12.8	0.467	33.7
						MAX=	238	MAX=	44.0
						MIN=	-98.9	MIN=	-38.2
						AVER=	28.6	AVER=	3.20
Note 1. This table is produced on a spreadsheet using EXCEL.						STD=	84.8	STD=	21.8
	The number of significant figures is greater than indicated.								

Table 4-2 (cont.)
Flexibility Factors

			Load Case - 6						
			Torsion on Run						
								d/D>.5	
	Model	ϕ_{6-1}	ϕ_{fea}	%	k	k -Regr	% Dif	k -Regr	% Dif
				DIF		Eq. (4-40)	%	Eq. (4-46)	%
1	ORNL-4	3.45E-03	3.50E-03	-1.40	0.071	0.024	-66.0		
2	Decock	3.42E-03	3.48E-03	-1.90	0.095	0.072	-24.3		
3	Roarty	3.56E-03	3.63E-03	-2.20	0.110	0.097	-11.9		
4	ECR/EAW	3.42E-03	3.50E-03	-2.30	0.117	0.113	-3.40		
5	Wais	3.41E-03	3.52E-03	-3.10	0.158	0.174	10.1		
6	Wais	3.41E-03	3.54E-03	-3.60	0.184	0.216	17.2		
7	OSU1	3.48E-03	3.63E-03	-4.40	0.221	0.286	29.1		
8	Decock	3.45E-03	3.75E-03	-8.90	0.451	0.634	40.4		
9	Wais	3.41E-03	3.72E-03	-8.90	0.452	0.750	66.1		
10	Wais	3.41E-03	3.79E-03	-11.1	0.563	0.857	52.2		
11	Wais	3.41E-03	3.91E-03	-14.6	0.738	1.06	43.0		
12	ORNL-1	3.41E-03	3.99E-03	-16.9	0.857	1.20	39.7	0.742	-13.4
13	OSU2	3.48E-03	3.84E-03	-10.4	0.528	0.749	41.8	0.501	-5.00
14	Wais	3.41E-03	4.37E-03	-28.1	1.42	1.80	26.4	1.69	18.6
15	Pickett	3.55E-03	4.26E-03	-20.0	1.01	1.26	23.9	0.755	-25.5
16	Decock	3.45E-03	5.02E-03	-45.5	2.31	2.32	0.300	1.96	-14.9
17	Wais	3.41E-03	5.73E-03	-68.0	3.45	3.20	-7.30	4.38	27.0
18	Wais	3.41E-03	5.80E-03	-70.0	3.55	3.26	-8.20	4.29	20.9
19	Wais	3.41E-03	6.24E-03	-82.8	4.20	3.68	-12.4	3.78	-10.1
20	Khan	3.50E-03	5.04E-03	-43.9	2.22	2.16	-3.10	2.08	-6.50
21	Khan	3.48E-03	6.09E-03	-75.1	3.81	2.92	-23.3	3.67	-3.80
22	Wais	3.41E-03	1.04E-02	-204	10.4	5.11	-50.7	9.45	-8.90
23	Markl	3.56E-03	6.35E-03	-78.6	3.99	3.88	-2.70	5.06	27.0
24	Markl	3.53E-03	6.95E-03	-96.9	4.91	4.08	-16.9	5.61	14.3
25	Blair	3.51E-03	7.48E-03	-113	5.72	4.25	-25.7	6.08	6.30
26	Wais	3.48E-03	9.08E-03	-161	8.16	4.69	-42.5	7.44	-8.90
27	Markl	3.45E-03	1.08E-02	-214	10.8	5.14	-52.6	8.93	-17.7
28	Wais	3.44E-03	1.24E-02	-260	13.2	5.52	-58.2	10.3	-22.0
29	Wais	3.42E-03	1.45E-02	-323	16.4	6.03	-63.2	12.3	-24.9
30	Decock	3.42E-03	1.55E-02	-352	17.9	6.28	-64.8	13.3	-25.3
31	Markl	3.42E-03	1.55E-02	-354	18.0	6.29	-65.0	13.4	-25.3
32	ORNL-2	3.41E-03	1.68E-02	-393	19.9	6.63	-66.7	14.9	-25.1
33	W/EPRI	3.45E-03	3.58E-03	-3.70	0.187	0.228	22.2		
34	Wais34	3.41E-03	3.69E-03	-8.00	0.407	0.588	44.5		
35	Wais35	3.41E-03	4.58E-03	-34.0	1.73	2.08	20.4	1.95	12.9
36	Wais36	3.41E-03	9.08E-03	-166	8.41	4.77	-43.3	8.36	-0.600
						MAX=	66.1	MAX=	27.0
						MIN=	-66.7	MIN=	-25.5
						AVER=	-6.50	AVER=	-4.80
						STD=	39.2	STD=	17.6
Notes:	1. This table is produced on a spreadsheet using EXCEL.								
	The number of significant figures is greater than indicated.								

Figure 4-1 shows the model for branch connections. A rigid link is included in the model from the center line of the run pipe to its surface. At that juncture, a point spring is used to represent the local flexibility of the connection.

The model depicted in Figure 4-1 will be used as the basis for evaluating the FEA results and determining the flexibility of the branch connection. The rotation at the end of the branch (point 5) with respect to the fixed end (point 1) is given by:

$$\phi = \phi_{5-4} + \phi_{4-3} + \phi_{3-2} + \phi_{2-1} \quad \text{(eq. 4-5)}$$

where ϕ_{i-j} is the rotation of point "i" with respect to point "j"

4.4.1 In-Plane Bending of the Branch

For in-plane bending (where M_{ib} is the in-plane bending moment on the branch):

$$\phi_{5-4} = M_{ib}L_3 / EI_b \quad \text{(eq. 4-6)}$$

$$\phi_{4-3} = k_{ib}\, M_{ib}\, d_o / EI_b \text{ point spring, from Equation 4-3} \quad \text{(eq. 4-7)}$$

$$\phi_{3-2} = 0\text{, since this is the rotation over a rigid link}$$

and assuming only one end of the run pipe is fixed:

$$\phi_{2-1} = M_{ib}\, L_2 / EI_p \quad \text{(eq. 4-8)}$$

As discussed earlier, the FEA was performed with two sets of boundary conditions, fixed at the run pipe bottom end and fixed at both ends. When fixed at both of the run pipe ends, for in-plane moments, Equation 4-8 is modified (considering that $L_2 = L_1$):

$$\phi_{2-1} = 1/8\, M_{ib}\, L_2 / (EI_p) \quad \text{(eq. 4-9)}$$

Replacing ϕ with ϕ_{fea}, substituting and rearranging Equation 4-5 yields:

$$k_{ib} = 1/(M_{ib}d_o / EI_b)\, [\phi_{fea} - \phi_{5-4} - \phi_{2-1}] \quad \text{(eq. 4-10)}$$

Table 4-2 lists the data for in-plane bending of the branch, Load Cases 1 and 7. Calculated values of ϕ_{5-4} and ϕ_{2-1} as well as the results from the FEA, are provided. The values of k_{ib} are listed and a comparison of Load Cases 1 and 7 is also provided. The average values (column labeled “k ave” in Table 4-2) are used as the basis. A comparison to the results from an equation developed from regression analysis (“k-Regr” in Table 4-2) is also provided. The equation is:

$$k_{ib} = .488\,(D/T)^{1.279}\,(d/D)^{0.391}\,(d/t)^{-0.602} \qquad \text{(eq. 4-11)}$$

For the 36 cases, the average % difference between the regression analysis and the FEA data is 1.6%. The maximum difference is 36% and the standard deviation is 17.5%.

In Table 4-2, in the columns labeled “Comparison LC1-LC7”, the data in the column labeled “ϕ_{fea} % dif” is the percentage difference between the value of the rotation for the two FEA load cases. The data in the column labeled “k % dif” is the percentage difference between the values of k for the two FEA load cases. The column labeled “k ave” indicates the average of the two values of k, and the column labeled “% dif” indicates the percentage difference between the average value of k from the FEA analysis and the value calculated using the regression equation. The value “MAX” is the maximum percentage difference between “k-Regr” and “k ave”, “MIN” is the minimum % difference, “AVER” is the average % difference and “STD” is the standard deviation of the distribution of the percentage differences.

4.4.2 Out-of-Plane Bending of the Branch

For out-of-plane bending where M_{ob} is the out-of-plane bending moment:

$$\phi_{5\text{-}4} = M_{ob} L_3 / EI_b \qquad \text{(eq. 4-12)}$$

The value of $\phi_{4\text{-}3}$ is given by

$$\phi_{4\text{-}3} = k_{ob}\, M_{ob}\, d_o / EI_b \qquad \text{(eq. 4-13)}$$

Again $\phi_{3\text{-}2} = 0$, since this is the rotation over a rigid link

Since the segment of the beam model from point 1 to point 2 is in torsion for out-of-plane bending of the branch, for the case where only one end of the run pipe is fixed, Equation 4-8 is replaced by:

$$\phi_{2\text{-}1} = 1.3\, M_{ob}\, L_2 / EI_p \qquad \text{(eq. 4-14)}$$

For out-of-plane moments on the branch with both ends of the run pipe fixed, Equation 4-9 is replaced by:

$$\phi_{2\text{-}1} = (1/2) * 1.3\ M_{ob}\ L_2 / EI_b \qquad \text{(eq. 4-15)}$$

As before, replacing ϕ with ϕ_{fea}, substituting and rearranging Equation 4-5 yields:

$$k_{ob} = 1/(M_{ob}\ d_o / EI_b)\ [\phi_{fea} - \phi_{5\text{-}4} - \phi_{2\text{-}1}] \qquad \text{(eq. 4-16)}$$

Table 4-2 also lists the FEA and other data for out-of-plane bending of the branch, Load Cases 2 and 8. A comparison to the results from an equation developed from regression analysis (k-Regr) is also provided. The equation is:

$$k_{ob} = 0.169\ (D/T)^{1.81}\ (d/D)^{0.158}\ (d/t)^{-0.654} \qquad \text{(eq. 4-17)}$$

For the 36 cases, the average percentage difference between the regression analysis and the FEA data is -7.2%. The maximum difference is 172% and the standard deviation is 45%. The model where the maximum difference was 172% was ORNL-4. The next highest maximum difference was 91%.

Because of the differences and the recognition that the flexibility was not always monotonically increasing as a function of d / D, the dependence on d / D was further investigated. Eight models with R / T = r / t = 49.5, and with d / D = t / T varying from 0.25 to 1.00 were investigated. It was determined that the flexibility of these cases varied as a function of a constant times $f = 3(d/D) - 3.75(d/D)^2 + (d/D)^3$. This correlation provided results that were within about 10% of the data. The k ave data was normalized to this factor (f) and an equation was developed from regression analysis. The factored equation is:

$$k_{ob} = 0.828\ (3(d/D) - 3.75(d/D)^2 + (d/D)^3)\ (D/T)^{1.72}\ (d/D)^{0.5057}\ (d/t)^{-0.717} \qquad \text{(eq. 4-18)}$$

For the 36 cases, the average percentage difference between Equation 4-18 and the FEA data is -.2%. The maximum difference is 39.6% and the standard deviation is 19.2%. This information is listed in Table 4-2 in the columns indicated as “W / factor” where the factor is “$3(d/D) - 3.75(d/D)^2 + (d/D)^3$”. Equation 4-18 is an improvement over Equation 4-17.

4.4.3 Torsion of the Branch

For torsion of the branch, where M_{tb} is the torsional moment, we have:

$$\phi_{5\text{-}4} = 1.3\ M_{tb}\ L_3 / EI_b \qquad \text{(eq. 4-19)}$$

$$\phi_{4\text{-}3} = k_{tb}\ M_{tb}\ d_o / EI_b \qquad \text{(eq. 4-20)}$$

$$\phi_{3\text{-}2} = 0 \qquad \text{(eq. 4-21)}$$

For one end of the run pipe fixed:

$$\phi_{2\text{-}1} = M_{tb}\ L_2 / EI_p \qquad \text{(eq. 4-22)}$$

For both ends fixed:

$$\phi_{2\text{-}1} = 1/8\ M_{tb}\ L_2 / EI_p \qquad \text{(eq. 4-23)}$$

and:

Replacing ϕ with ϕ_{fea}, substituting and rearranging Equation 4-5 yields:

$$k_{tb} = 1/(M_{tb}\ d_o / EI_b)\ [\phi_{fea} - \phi_{5\text{-}4} - \phi_{2\text{-}1}] \qquad \text{(eq. 4-24)}$$

Table 4-2 lists similar data for torsion of the branch, Load Cases 3 and 9. A comparison to the results from an equation developed from regression analysis (k-Regr) is also provided. The equation is:

$$k_{tb} = 2.43\ (D/T)^{0.751}(d/D)^{2.11}\ (d/t)^{-0.553} \qquad \text{(eq. 4-25)}$$

For the 36 cases, the average percentage difference between Equation 4-25 and the FEA data is 8.0%. The maximum difference is 63.7% and the standard deviation is 38.5%.

4.5 FEA Results—Flexibility of Run Pipe

As part of this study, the effects of the branch connection on the flexibility of the run pipe was investigated. The results for the load cases where the run pipe is loaded are also presented in Table 4-2. The beam model for loading of the run pipe is similar to that of the loading of the branch (see Figure 4-4). At the intersection of the centerlines of the run pipe and the branch, a point spring is assumed, point 8.

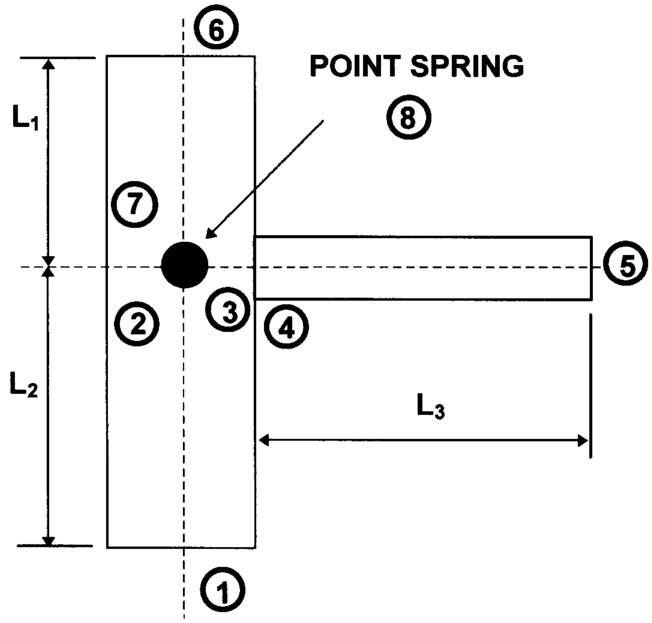


Figure 4-4
Beam Model for Run Pipe Loads

All moments are applied at point 6. The rotation at point 6, ϕ, is:

$$\phi = \phi_{6\text{-}7} + \phi_{7\text{-}2} + \phi_{2\text{-}1} \quad \text{(eq. 4-26)}$$

Three loading conditions were considered and the results are given below:

4.5.1 In-Plane Bending of the Run Pipe

For in-plane bending (where M_{ir} is the in-plane bending moment on the run pipe):

$$\phi_{6\text{-}7} = M_{ir} L_1 / EI_p \quad \text{(eq. 4-27)}$$

$$\phi_{7\text{-}2} = k_{ir}\, M_{ir}\, D_o / EI_p \text{ point spring,} \quad \text{(eq. 4-28)}$$

and:

$$\phi_{2\text{-}1} = M_{ir}\, L_2 / EI_p \quad \text{(eq. 4-29)}$$

Replacing ϕ with ϕ_{fea}, substituting and rearranging Equation 4-26 yields:

$$k_{ir} = 1 / (M_{ir} D_o / EI_p) [\phi_{fea} - \phi_{6-7} - \phi_{2-1}] \quad \text{(eq. 4-30)}$$

For in-plane bending of the run pipe (LC-4), the regression equation is:

$$k_{ir} = 1.627 (D / T)^{0.008} (d / D)^{2.63} (d / t)^{0.2366} \quad \text{(eq. 4-31)}$$

Average percentage difference between the regression analysis and the FEA data: 3.6%

Maximum difference: 48%

Standard deviation: 25%

4.5.2 Out-of-Plane Bending of the Run Pipe

For out-of-plane bending (where M_{or} is the out-of-plane bending moment on the run pipe):

$$\phi_{6-7} = M_{or} L_1 / EI_p \quad \text{(eq. 4-32)}$$

$$\phi_{7-2} = k_{or} M_{or} D_o / EI_p \text{ point spring,} \quad \text{(eq. 4-33)}$$

and:

$$\phi_{2-1} = M_{or} L_2 / EI_p \quad \text{(eq. 4-33a)}$$

and:

$$k_{or} = 1 / (M_{or} D_o / EI_p) [\phi_{fea} - \phi_{6-7} - \phi_{2-1}] \quad \text{(eq. 4-34)}$$

For out-of-plane bending of the run pipe (LC-5), the regression equation is:

$$k_{or} = 0.128 (D / T)^{-1.085} (d / D)^{1.077} (d / t)^{1.305} \quad \text{(eq. 4-35)}$$

Average percentage difference between the regression analysis and the FEA data: 28.9%

Maximum difference: 238%

Standard deviation: 85%

4.5.3 Torsion of the Run Pipe

For torsion of the run pipe, where M_{tr} is the torsional moment, we have:

$$\phi_{6-7} = 1.3\ M_{tb}\ L_1 / EI_p \qquad \text{(eq. 4-36)}$$

$$\phi_{7-2} = k_{tr}\ M_{tr} D_o / EI_p \qquad \text{(eq. 4-37)}$$

$$\phi_{2-1} = 1.3\ M_{tr}\ L_2 / EI_p \qquad \text{(eq. 4-38)}$$

$$k_{tr} = 1 / (M_{tr}\ D_o / EI_p)\ [\phi_{fea} - \phi_{6-7} - \phi_{2-1}] \qquad \text{(eq. 4-39)}$$

For torsion of the run pipe (LC-6), the regression equation is:

$$k_{tr} = 1.56\ (D/T)^{0.039}\ (d/D)^{2.47}\ (d/t)^{0.276} \qquad \text{(eq. 4-40)}$$

Average percentage difference between the regression analysis and the FEA data: 6.5%

Maximum difference: 66.7%

Standard deviation: 39.2%

4.6 Review of the Run Pipe Flexibilities

A review of the FEA data for all load cases for the run pipe loadings indicates that the value of k is on the order of or less than 1.0 for $d/D < 0.5$. Considering the accuracy of the overall design process, flexibility of this order can be neglected. In order to improve on the accuracy of the equations, regression analyses were performed to determine representative equations for these load cases when $d/D \geq 0.5$. The results are given below:

For in-plane bending of the run pipe (LC-4), the regression equation is:

$$k_{ir} = 0.995\ (D/T)^{0.675}\ (d/D)^{3.78}\ (d/t)^{-0.25} \qquad \text{where } d/D \geq 0.5 \qquad \text{(eq. 4-41)}$$

Average percentage difference between the regression analysis and the FEA data: 0.9%

Maximum difference: 25%

Standard deviation: 13.7%

For out-of-plane bending of the run pipe (LC-5), the regression equation is:

$$k_{or} = 0.0771\,(D/T)^{-0.159}\,(d/D)^{4.096}\,(d/t)^{0.67} \quad \text{where } d/D \geq 0.5 \qquad \text{(eq. 4-45)}$$

Average percentage difference between the regression analysis and the FEA data: 3.2%

Maximum difference: 44.0%

Standard deviation: 21.8%

For torsion of the run pipe (LC-6), the regression equation is:

$$k_{tr} = 0.813\,(D/T)^{0.982}\,(d/D)^{4.328}\,(d/t)^{-0.349} \quad \text{where } d/D \geq 0.5 \qquad \text{(eq. 4-46)}$$

Average percentage difference between the regression analysis and the FEA data: 4.8%

Maximum difference: 27%

Standard deviation: 17.6%

These equations represent an improvement over the other regression equations.

4.7 Sensitivity of Results to Accuracy of FEA

A brief study of the effects of the accuracy of the FEA on the determination of the flexibility factors was performed for loads on the branch connection. A ± 10% variation was assumed in the FEA rotations and then flexibility factors were determined in the same manner as discussed earlier for all the models.

For in-plane bending of the branch (Load Cases 1 and 7), the average variation in the calculated values of k was about 16%. The maximum variation was 53.5% for model number 3 “Roarty” which had an original flexibility of 0.7. In general, the larger variations were associated with small values of k. Both the +10% and -10% results were very similar.

The results were similar for out-of-plane bending of the branch (Load Cases 2 and 8) with an average variation of 13%. The maximum variation was 37.5%, as it was also for model number 3, where the original value of k was 1.49. Again, the larger variations were associated with the small values of k. Likewise, the ± 10% results were very similar.

For torsion of the branch (Load Cases 3 and 9), the results were somewhat different. The average variation was about 75% with a maximum of 503% for an assumed change of ±10% in the FEA. The large variations were for models 1 to 7 and 33, which had very small original values of k, less then 0.63.

When the FEA results were reduced by 10%, the calculated values of k were negative for the models where the original values were less than about 0.63 (models 1 to 7 and 33). The average magnitude of the negative values was less than 0.5. When the FEA results were increased by +10%, the new values were positive. The variations were the same.

As for the other load cases, the greatest variation occurred when the values of k were small. In this case, for torsion of the branch, for those models with original values of k greater than 1.0, the average variation was about 21%.

In summary, for those cases where the flexibility is significant, for example, k > 1.0, minor variations in the FEA results will yield only minor variations in the calculation of the values of k. Considering the variations in the values of k for the two sets of boundary conditions and the conservatism of the overall process, it is deemed that minor inaccuracies in the FEA will not significantly affect the results.

4.8 Comparison to Test Data

The tests discussed previously were not specifically for determining flexibility factors, however, they can be used to evaluate one of the equations derived above. Loads and deflections at the loading point for in-plane bending were recorded and are included in Appendix C. The average deflection of the four tests at a load of 100 pounds was 0.79 inches. Using an average branch length of 46.5 inches, the dimensions of the test specimens and Equation 4-45 for out-of-plane bending, the calculated deflection was 0.93. Considering that the calculation estimates the flexibility of the testing assembly, and that Equation 4-45 was developed using average k data, this is considered to be a confirmation of the methodology.

5

APPLICABILITY OF RESULTS

5.1 Introduction

Section 2 discussed the results of the FEA and comparison to the available test data. It was determined that the relationship: $i = Cxy/2$ is reasonable for the configurations considered, (Cxy is the secondary stress indice, where x corresponds to in-plane, out-of-plane, or torsional moment and y corresponds to the location, for example, branch or run pipe end). This chapter discusses these results in more detail and also discusses the applicability limitations. In addition, the applicability of the flexibility factors is also discussed.

The applicability of the results covers two main areas: (1) configurations or geometries covered by the results and (2) limitations of the parameters of the equations. These areas are discussed below:

5.2 Branch Connection Configurations

Section III of the Code identifies several configurations for branch connections for Class 2 components in Figure NC-3673.2(b)-2 (in this report as Figure 5-1). The B31.1 Code and Section III Class 1 requirements have similar figures. The applicable notes regarding this figure are given in Figure NC-3673.2(b)-1 and are included in this report as Figure 5-2. Note 6 of NC-3673.2(b)-1 establishes the specific requirements for the applicability of the SIF equations in the Code for the configurations of Figure NC-3673.2(b)-2.

It should be noted that Figure NC-3673.2(b)-1 states that the flexibility factor is “1” for branch connections. As noted in WRC Bulletin 329, this is misleading at best. While not clear, it might be that the original intent was to assume a rigid connection at the juncture of the run and the branch. This report provides a more accurate approach.

Figure NC-3673.2(b)-2 includes sketches showing four configurations that are applicable to various designs. The tests and FEA models used in the evaluation of stresses and flexibility in this report (Sections 2 and 4) are directly applicable to the configuration of sketch (d) of this figure.

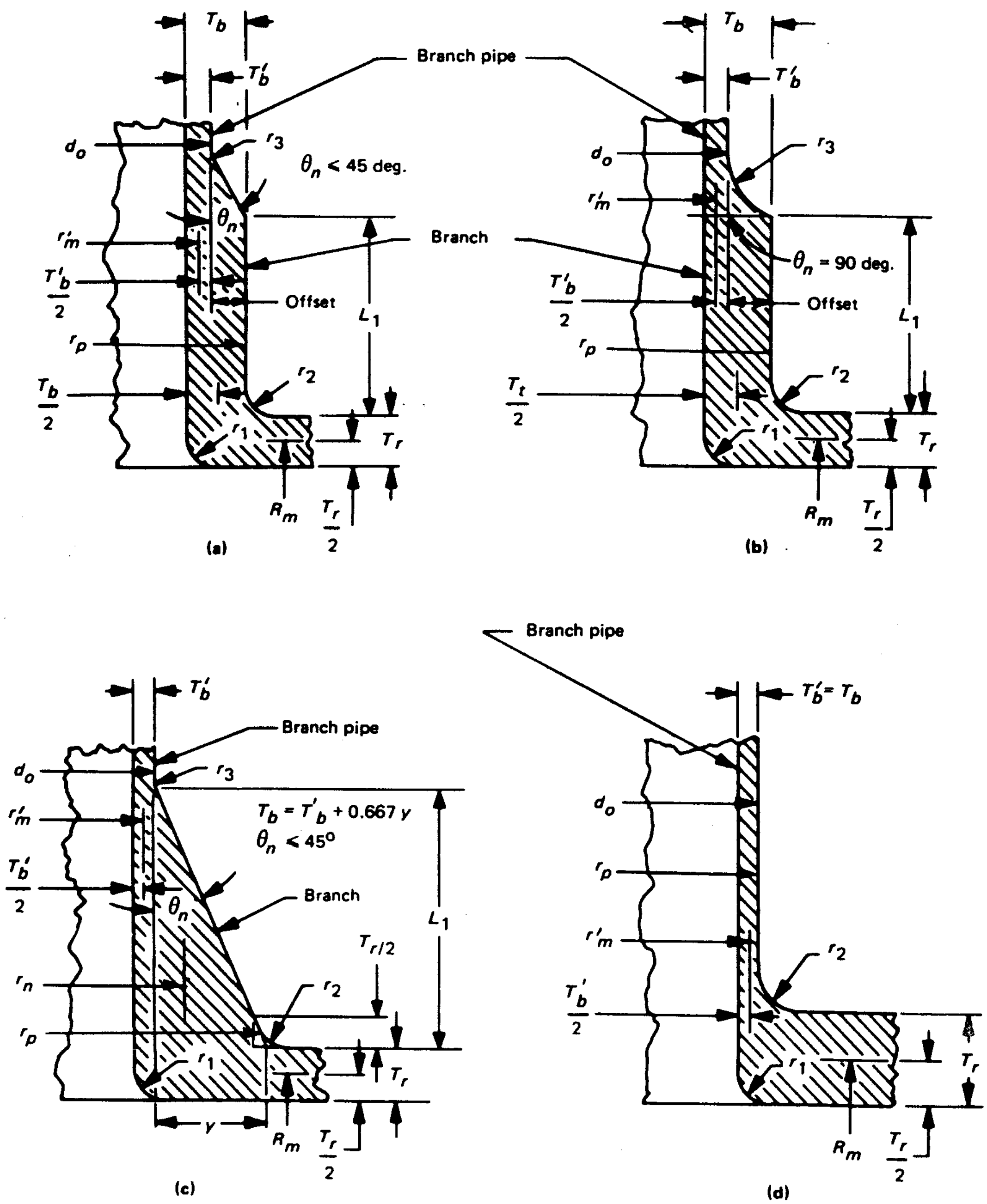
The results of this study can be extended to the configurations of sketches (a) and (b). However, the results of this study cannot be readily extended to the configuration of sketch (c). This configuration is not in the scope of this study.

For the configurations of sketches (a) and (b), the thickness of the branch can be represented by T_b (Figure NC-3673.2(b)-2) if the value of L_1 is sufficiently long so that the branch will perform as a branch of thickness T_b.

The note in Figure NC-3673.2(b)-2 indicates that, if L_1 equals or exceeds $0.5\,(r'_m T_b)^{0.5}$ (see Figure 5-1 for the definition of the terms), the mean radius of the branch can be based on the thickness of the reinforced section, T_b. This is the value of thickness to be used in the determination of the section modulus of the branch.

Based on a review of the of the results of the ORNL studies [11] and other studies, it is reasonable to assume that, if $L_1 \geq 0.5\,(r'_m T_b)^{0.5}$ and the requirements of θ_n of Figure NC-3673.2(b)-2 are satisfied, then T_b can be substituted for the branch thickness t subject to the requirements discussed below.

It must be noted that this approach might be used to qualify the area of the branch connection near the intersection of the branch and the run. Under certain circumstances, the location where the branch pipe joins the reinforced section could be critical. (This location is indicated in Figure NC-3673.2(b)-2 just below the points indicated by the arrows labeled “Branch pipe”.) It might be, depending upon the configuration, that this area should be treated as a tapered transition joint.



d_o = outside diameter of branch pipe, in.
r_m = mean radius of branch pipe in.
T'_b = nominal thickness of branch pipes, in.
R_m = mean radius of run pipe, in.
T_r = nominal thickness of run pipe, in.

GENERAL NOTES:

(1) T_b, θ, r_1, r_2, r_3, r_p, and y are defined in this figure.

(2) If L_1 equals or exceeds $0.5\sqrt{r_i T_b}$ then r'_m can be taken as the radius to the center of T_b.

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Figure 5-1
Branch Dimensions - Figure NC-3673.2(b)-2

NOTES:

(1) The following nomenclature applies:
r = mean radius of pipe, in. (matching pipe for tees and elbows)
t_n = nominal wall thickness of pipe, in. [matching pipe for tees and elbows, see Note (9)]
R = bend radius of elbow or pipe bend, in.
θ = one-half angle between adjacent miter axes, deg.
s = miter spacing at center line, in.
t_e = reinforced thickness, in.
D_o = outside diameter, in.

(2) The flexibility factors k and stress intensification factors i apply to bending in any plane for fittings and shall in no case be taken less than unity. Both factors apply over the effective arc length (shown by heavy center lines in the sketches) for curved and miter elbows, and to the intersection point for tees.

(3) Where flanges are attached to one or both ends, the values of k and i shall be corrected by the factor c given below.
(a) One end flanged, $c = h^{1/6}$
(b) Both ends flanged, $c = h^{1/3}$

(4) Also includes single miter joints.

(5) When $t_e > 1.5t_n$, $h = 4.05t_n/r$

(6) The equation applies only if the following conditions are met.
(a) The reinforcement area requirements of NC-3643 are met.
(b) The axis of the branch pipe is normal to the surface of run pipe wall.
(c) For branch connections in a pipe, the arc distance measured between the centers of adjacent branches along the surface of the run pipe is not less than three times the sum of their inside radii in the longitudinal direction or not less than two times the sum of their inside radii along the circumference of the run pipe.
(d) The inside corner radius r_1 [Fig. NC-3673.2(b)-2] for nominal branch pipe size greater than 4 in. shall be between 10% and 50% T_r. The radius r_1 is not required for nominal branch pipe size smaller than 4 in.
(e) The outer radius r_2 is not less than the larger of $T_b/2$, $(T_{b'} + Y)/2$ [Fig. NC-3673-2(b)-2 sketch (c)] or $T_r/2$.
(f) The outer radius r_3 is not less than the larger of
(1) $0.002\theta\ d_o$
(2) 2 $(\sin\theta)^3$ times the offset for the configurations shown in Fig. NC-3673.2(b)-2 sketches (a) and (b).
(g) $R_m/T_r \leq 50$ and $r'_m/R_m \leq 0.5$.
(h) The outer radius r_2 is not required provided an additional multiplier of 2.0 is included in the equations for branch end and run end stress intensification factors. In this case, the calculated value of i for the branch or run shall not be less than 2.1.

(7) The equation applies only if the following conditions are met.
(a) Cone angle α does not exceed 60 deg.
(b) The larger of D_1/t_1 and D_2/t_2 does not exceed 100.
(c) The wall thickness is not less than t_1 throughout the body of the reducer, except in and immediately adjacent to the cylindrical portion on the small end, where the thickness shall not be less than t_2.
(d) For eccentric reducers, α is the maximum cone angle.

(8) Factors shown apply to bending; flexibility factor for torsion equals 0.9.

(9) The designer is cautioned that cast butt welding elbows may have considerably heavier walls than that of the pipe with which they are used. Large errors may be introduced unless the effect of these greater thicknesses is considered.

(10) The stress intensification factor i shall in no case be taken as less than 2.1.

(11) In Fig. NC-4427-1(c-1) and (c-2), C_x shall be taken as X_{min} and $C_x \geq 1.25\ t_n$. In Fig. NC-4427-1 (c-3), $C_x \geq 0.75\ t_n$. For unequal leg lengths use the smaller leg length for C_x.

Figure 5-2
Flexibility and Stress Intensification Factors ($D_o/t_n \leq 100$) - Figure NC-3673.2(b)-1

5.3 Requirements for Applicability of SIF and Flexibility Expressions

The requirements of Note (6) of Figure NC-3673.2(b)-1 will serve as the basis of the conditions of applicability of the expressions for SIFs and flexibility factors. These requirements have been revised following the discussion of WRC 329 [9]. Each of these conditions is discussed below:

Reinforcement requirements:

As noted in [9], this condition is redundant with other parts of the Code and as such is not required.

Axis of branch normal to pipe run:

This requirement is applicable to the configurations covered by this study.

Distance between branches:

This requirement is applicable to the configurations covered by this study.

Requirement on inside radius, r_1:

This requirement is not included since the inside corner radius is “not a critical consideration” for fatigue [9].

Requirements on the outer radius, r_2:

The configurations covering the analysis and testing correspond to sketch (d) in an “as welded” condition. As such, there is no specification of r_2 and the equations for SIFs are to be used directly. Pending further investigation, this report does not recommend dividing the i-factors by two even if r_2 is provided and meets the minimum requirements of Note (6) of Figure NC-3673.2(b)-1.

Requirements on the outer radius, r_3:

This requirement has been dropped per WRC 329 [9].

Requirements on R_m/T_r and r'_m/R_m:

These requirements are not applicable to this study. The limitations on geometric parameters are specified below.

Requirement on the outer radius, r_2:

This requirement has been dropped.

It should be noted that the nomenclature of Figure NC-3673(b)-2 differs from that used in this study. R_m of Figure NC-3673(b)-2 corresponds to R, T_r to T, T_b to t, and so on.

5.4 Limitations of Equations

Equations 2-1 to 2-6 provide expressions for the stress intensity indices. The expressions are presented as functions of the parameters R / T, r / t, and r / R. These expressions are based on FEA with the following range of parameters:

$$9.0 \le R/T \le 49.5$$

$$8.1 \le r/t \le 99$$

$$0.125 \le r/R \le 1.0$$

These ranges were based upon the limitations of the FEA models and the availability of test data. An investigation of the equations at the lower limits of R / T and r / t was performed to determine if an extension of these limits was reasonable. It is desirable to extend the limits to approximately:

$$3.75 \le R/T \le 49.5 \quad \text{(eq. 5-1)}$$

$$3.75 \le r/t \le 99 \quad \text{(eq. 5-2)}$$

$$0.125 \le r/R \le 1.0 \quad \text{(eq. 5-3)}$$

To investigate this, three additional FEA models were developed and the stress intensities generated. Table 5-1 shows the values of the equations for Cxx (the stress intensity index) and the FEA results, and provides a comparison. A review of this indicates that the equations yield reasonable results for these cases. The values of Cxx have a lower limit of 1.0, which is considered in the comparison (see the note in Table 5-1).

In addition, the effects of the combination of limits of the ranges of parameters of R / T, r / t and r / R were also investigated. Using the various limits of the ranges of Equations 5-1 to 5-3, the values from the regression equation were calculated. The results appeared to be reasonable. It should be noted that the exponents in the expressions for these parameters are less then 1.5.

Table 5-2 shows the results of flexibility for the three models for loading of the branch. The d / D ratio for these additional models is such that the additional flexibility of the run is negligible. The results from the FEA and the regression equations are presented.

It should be noted that the regression equations are based on the average of two sets of boundary conditions, however, only one condition was considered here. Considering the range of flexibilities between the two boundary conditions, this is considered acceptable.

Based on this review, it is concluded that regression equations are applicable to the range of parameters R/T, r/t, and r/R of Equations 5-1 to 5-3. Consequently, it is concluded that the equations provided for the stress intensification factors, 2-7 to 2-12, are valid for the range of parameters listed in Equations 5-1 to 5-3.

Table 5-1
Comparison of FEA and Regression Equations for Stress Indices

Table 5-1 Comparison of FEA and Regression Equations For Stress Indices				
	Model	1	2	3
Dimensions	D_o =	10.00	10.00	10.00
	T =	0.34	0.80	0.34
	d_o =	2.38	2.38	2.38
	t =	0.22	0.15	0.32
	R/T =	14.25	5.75	14.25
	r/t =	4.95	7.21	3.25
	r/R =	0.22	0.24	0.21
Regression	C_{ib} =	4.33	1.50	4.98
Equation:	C_{ob}=	6.83	1.72	8.10
(Note 1)	C_{tb} =	0.47	0.18	0.52
	C_{ir} =	2.06	2.85	1.66
	C_{or} =	0.18	0.30	0.13
	C_{ir} =	1.46	1.96	1.13
FEA:	C_{ib} =	4.37	1.42	4.10
	C_{ob}=	6.61	1.52	6.17
	C_{tb} =	1.23	1.15	1.26
	C_{ir} =	2.84	3.02	2.40
	C_{or} =	1.19	1.29	1.19
	C_{ir} =	2.12	2.19	1.72
% Difference:	C_{ib} =	-0.91	5.61	21.50
	C_{ob}=	3.33	12.89	31.24
	C_{tb} =	-61.79	-84.35	-58.73
	C_{ir} =	-27.42	-5.55	-30.69
	C_{or} =	-85.01	-76.63	-88.78
	C_{ir} =	-31.31	-10.67	-34.56
Note 1: The values listed for the regression equation do not include the lower limit of 1.0. With this limit, the % differences for C_{ib} are -18.7,-13.0 &-20.6%. and for C_{or}. they are -16.0, -22.5, & -16.0% respectively for Models 1, 2 and 3.				

Table 5-2
Comparison of FEA and Regression Equations for Flexibility Factors

TABLE 5-2. Comparison of FEA and Regression Equations for Flexibility Factors							
Model	D_o	T	d_o	t	D/T	d/D	d/t
	(in.)	(in.)	(in.)	(in.)			
1	10.0	0.339	2.38	0.22	28.50	0.22	9.89
2	10.0	0.800	2.38	0.15	11.50	0.24	14.42
3	10.0	0.339	2.38	0.32	28.50	0.21	6.49
			Load Case - 1				
			In-Plane Moment				
			on Branch				
Model	ϕ_{5-4}	ϕ_{2-1}	ϕ_{fea}	k	k -Regr	% Dif	
	(rad.)	(rad.)	(rad.)		Eq. (4-11)	%	
1	4.44E-03	4.31E-05	7.39E-03	4.01	4.96	-23.69	
2	4.33E-03	1.57E-05	5.06E-03	1.00	1.28	-27.72	
3	4.59E-03	5.70E-05	8.07E-03	4.56	6.27	-37.58	
Model			Load Case - 2				
			Out-of-Plane Moment				
			on Branch				
	ϕ_{5-4}	ϕ_{2-1}	ϕ_{fea}	k	k -Regr	% Dif	
	(rad.)	(rad.)	(rad.)		Eq. (4-18)	%	
1	4.44E-03	5.60E-05	1.05E-02	8.23	11.78	-43.10	
2	4.33E-03	2.04E-05	5.33E-03	1.38	2.07	-49.34	
3	4.59E-03	7.41E-05	1.17E-02	9.36	15.07	-61.11	
			Load Case - 3				
			Torsion				
			on Branch				
	ϕ_{5-4}	ϕ_{2-1}	ϕ_{fea}	k	k -Regr	% Dif	
	(rad.)	(rad.)	(rad.)		Eq. (4-25)	%	
1	5.77E-03	4.31E-05	6.16E-03	0.48	0.36	-25.57	
2	5.63E-03	1.57E-05	5.90E-03	0.35	0.17	-50.56	
3	5.96E-03	5.70E-05	6.52E-03	0.69	0.41	-40.53	

6

CONCLUSIONS

There are several configurations that are categorized as branch connections. Figure NC-3673.2(b)-1 (included in Section 5 as Figure 5-1) indicates these configurations. This study focused on the configuration indicated as sketch (d). The extension to other configurations is discussed in Section 5 and summarized below. The conclusions derived from the tests and analysis described in this report are listed below.

6.1 Stress Intensification Factors

For the geometry indicated in Figure NC-3673.2(a)-1 for an "as welded" configuration, for individual loadings, for example, torsion, in-plane and out-of-plane bending, the stress intensification factors for the branch and run pipe ends are given by:

$$i_{xy} = A_0 (R/T)^{n1} (r/t)^{n2} (r/R)^{n3} \geq 1.0$$

	Part	SIF	A_0	n_1	n_2	n_3
In-plane	Branch	i_{ib}	0.515	1.05	-0.387	0.49
bending	Run	i_{ir}	0.985	-0.137	0.482	0.241
Out-of-plane	Branch	i_{ob}	Note 1	1.40	-0.558	0.406
bending	Run	i_{or}	0.605	-0.237	0.528	1.42
Torsion	Branch	i_{tb}	0.850	1.00	-0.50	2.10
	Run	i_{tr}	0.864	-0.0473	0.543	0.609

Note 1: Replace A_0 with $1.28[1.28(r/R)-(r/R^4)]$

6.2 Combination Of Moments

For combination of stresses due to different moments, the various code committees are considering changes at this time. Until these changes are finalized, the evaluation of the stresses must be based on the maximum i factor for the branch and the maximum i factor of the run. If Section III is the Code of record (for Class 2 or 3 piping), Equation 3-1 should be used for evaluating the branch connections.

$$S = \frac{i(M_i^2 + M_o^2 + M_t^2)^{1/2}}{Z_i} \quad \text{(eq. 3-1)}$$

where the branch and each end of the run pipe are evaluated. The values of the moments and section modulus are appropriate for the location. The value of Z_i for the branch is given by Equation :

$$z = \pi r^2 t \quad \text{(eq. 3-2)}$$

(See Section 5 for a definition of r and t for reinforced branches.) For the run pipe, Z_i is:

$$Z = \pi R^2 T \quad \text{(eq. 3-3)}$$

For the branch, the value of i is the maximum of i_{ib}, $i_{ob,}$ or i_{tb}. For the run, the value of i is the maximum of i_{ir}, i_{or}, or i_{tr}.

If B31.1 is the Code of record, a less conservative approach is permitted. This is discussed in Section 3.

6.3 Flexibility Factors

For the geometry indicated in Figure NB-3643.3(a)-1, the flexibility modeling of the branch connection should be based on Figures 4-1 and 4-4 for the branch and pipe run respectively:

Figure 4-1 shows the model for branch loading where it is assumed there is a rigid link from the centerline of the run pipe to its outer surface. At this point, it is assumed that a point spring exists. The flexibility factors of the point spring are given by:

$$k_{xy} = B_0\,(D/T)^{n1}(d/D)^{n2}(d/t)^{n3}$$

	Part	k	B_0	n_1	n_2	n_3
In-plane	Branch	k_{ib}	0.488	1.279	0.391	-0.602
bending	Run	k_{ir}	0.995	0.675	3.78	-0.250
Out-of-plane	Branch	k_{ob}	Note 1	1.72	0.5057	-0.717
bending	Run	k_{or}	0.0771	-0.159	4.096	1.305
Torsion	Branch	k_{tb}	2.43	0.751	2.11	-0.553
	Run	k_{tr}	0.813	0.982	4.328	-0.349

Note 1. Replace B_o with $0.828\,(3.0\,(d/D)-3.75(d/D)^2+(d/D)^3)$

Note 2. For $d/D<0.5$, values of k_{ir}, k_{or} and k_{tr} are small and should be set to zero. The equations for k_{ir}, k_{or} and k_{tr} are valid only for $d/D \geq 0.5$.

6.4 Applicability of Results

The equations specified above in Sections 6.1 and 6.3 are applicable to the following range of parameters:

$$3.75 \leq R/T \leq 49.5 \qquad \text{(eq. 5-1)}$$

$$3.75 \leq r/t \leq 99 \qquad \text{(eq. 5-2)}$$

$$0.125 \leq r/R \leq 1.0 \qquad \text{(eq. 5-3)}$$

This report focused on the branch connection configuration depicted in Figure NC-3673.2(b)-1, sketch (d) (Figure 5-2 in Section 5). The equations presented above are also applicable to the configurations of sketches (a) and (b) of Figure NB-3643.3(d)-1 when the effective values of branch thickness and radius are used as specified in Section 5. As discussed in Section 5, for configurations corresponding to sketches (a) and (b), the transition at the end of the reinforced branch to the branch pipe might require additional qualification.

6.5 B Indices

This report is focused on SIFs and flexibility factors for ASME Section III Class 2 or 3 and ANSI B31.1 piping. Certain editions of ASME Section III require the use of B indices for the qualification of Class 2 or 3 piping. The scope of this report did not address the B indices for the branch connections.

If B indices are required in the qualification process, it is suggested that the existing plant-specific Code of record be followed.

6.6 Comparison to Present Code

The present Code yields unconservative results for certain ranges of the parameters. This unconservatism has been addressed by the equations herein. The use of the flexibility factors suggested herein will tend to offset this increase in the indices. This unconservatism has been documented in various studies previously.

As an example, consider a straight run of pipe (D_o=24”, T=0.374”) 10’ long, fixed at both ends with a branch pipe (d_o= 12.75”, t=0.375”) 2’ long located 4’ from one end of the run pipe. Assume the material is A106 Grade B, with E = 30,000 ksi. Assume there is an in-plane moment on the branch such that the rotation is 0.001 radians. The moment calculated to obtain this rotation, assuming no local flexibility of the branch, would be 19 times that calculated using the flexibilities defined in this report. In other words, ignoring this flexibility would result in over-estimating the stresses by a factor of 19. If the lengths were doubled, the factor would change to 10.

Reference [27] contains a discussion of the potential effects of including the flexibility of the branch connection. Many examples are given where inclusion of the appropriate flexibility will turn a not-Code-acceptable piping system into a Code-acceptable system.

The use of the expressions defined in this report will clearly result in a more realistic evaluation of branch connections.

7

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20. "Finite Element Stress Analysis of An Equal Diameter Branch Pipe Intersection Subjected to Out-Of-Plane and Twisting Moments", Kirkwood, M.G., Carmichael, G.D.T., Moffat, D.G., *Journal of Strain Analysis*, Volume 21, No. 1, 1986, I.Mech.E., London, (1986).

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A

MATERIAL CERTIFICATIONS

LTV Steel Tubular Products Company

SHIPPER'S NUMBER 6801-22905 540

CERTIFICATE OF TESTS

SALES ORDER NO. 241757 00

BILL OF LADING NUMBER 6801-22905

PUR. ORD. DATE 12/17/96

PURCHASE ORDER NO. 20-11855

SOLD TO:
MARMON/KEYSTONE CORP
4250 BLUE RIDGE INDUSTRIAL
PARKWAY
NORCROSS GA 30071

CONSIGNED TO:
MARMON/KEYSTONE CORP
4250 BLUE RIDGE INDUSTRIAL
PARKWAY
NORCROSS GA 30071

SHIP DATE 1/06/97 FROM COUNCE

I HEREBY CERTIFY THAT THE MATERIAL LISTED HEREIN HAS BEEN INSPECTED AND TESTED IN ACCORDANCE WITH THE METHODS PRESCRIBED IN THE GOVERNING SPECIFICATIONS AND BASED UPON THE RESULTS OF SUCH INSPECTION AND TESTING HAS BEEN APPROVED FOR CONFORMANCE TO THE SPECIFICATIONS.

L. J. Deeb
Product/Process Metallurgist
By S King
Metallurgical Technician

ITEM	ITEM DESCRIPTION / SPECIFICATION	QTY SHIPPED
03	ERW STANDARD PIPE 8.625 OD .188W DRL PE BEV REC MILL COAT Itm-003 P/N: 001664 API 5L ASTM A53-95 GRADE B ASME SA53-92 GRADE B A93 ADDENDA	28 PC 1205.0 FT 20413 LB

HEAT NO.	LOT	√		C	MN	P	S	SI	CU	NI	CR	MO	V	AL	CB	CA	SN	B	CO	N	TI
070214				190	106	013	007	200	01	02	032	011	000	046	.		006		.		.

HEAT NO.	LOT NO.	I/O	YIELD STR PSI	TENSILE STR PSI	WELD UTS PSI	TENSILE SAMPLE		SZ (IN)	ELONG % IN 2"	HARDNESS	HYDRO PSI	
070214	8	1	52500	73300	76800	T	S	1.50	35.0		1370	5 Sec Hydro Flatten Test OK

8625 x .188 LT

TEST REPORT OK'D
INT. L
DATE 1-8-97

MARMON/KEYSTONE CORPORATION
This report, to which this stamp is affixed, is a copy of the original supplier's test report. There is indicated, not only the complete identification of this material but also a record of tests made in accordance with specification requirements. If several items are shown in this report, those items which are shipped to you are checked (✓) as being pertinent. We certify herewith that the material supplied to you is completely identifiable by this document.
Cust. P O 41606
MKC Order No. 28152
Date 2-11-97
Signed L
FOR THE QUALITY CONTROL DEPARTMENT

MET 0040 (11/92) T = TRANSVERSE L = LONGITUDINAL T = TUBE S = STRIP

(Pg 03-Last) 970106 00080 THE01 THE001 1/06/97 18:15:18

210 T 2.500 X .065 SH

SHARON TUBE COMPANY P.O. BOX 492, SHARON, PENNA. 16146

REPORT OF ANALYSIS AND MECHANICAL PROPERTIES FOR: MARMON KEYSTONE
NORCROSS GA

January 11, 1997

Sharon Tube
Order No. 547017

Customer
Order No. 20M11716*

DESCRIPTION	ANALYSIS, % C	Mn	P	S	Si	Al	Cu	Ni	Cr	Mo	V	Sn	YIELD PSI	TENSILE PSI	2" % ELG.	BEND TEST
2.5000" O.D., .0650" Wall	0.170	0.470	0.010	0.005	0.024	0.040	0.020	0.010	0.030	0.010	0.000	0.001	72740	12310	28.0	N/A

Heat No. 2115611
Grade 1020
Stress Relieved
Hardness Rb: 90
Tag:

Cold Drawn Electric Weld Carbon Steel Mechanical Tubing Meeting the Requirements of ASTM A513-95 TYPE 5.

Steven M. Grabert, Manager, Technical Services, being duly sworn according to law, deposes and says that the figures set forth above are correct as contained in the records of Sharon Tube Co.

B

CALIBRATION RECORD

Calibration Record

MTS Systems Corporation
14000 Technology Drive
Eden Prairie, MN 55344-2290

Calibration Report

Page 1 of 2

Customer Name Ohio State University System No. 870.54
System ID Axial-torsion Location Composite lab Site No. C84009-M05

Equipment Device Type: x Displacement _ Force _ Pressure _ Extensometer: Gage Length n/a _ Other n/a
Device Model No. 309.30 Serial No. 148
Controller/Conditioner Model 458.13 Serial No. 191 Calibration Data File Name n/a
Readout Device Model No. n/a Serial No. n/a Channel n/a

Procedure MTS Procedure No. 1254 Rev A
Calibration has been performed in accordance with: _ ASTM E4- _ Other n/a _ Not Required
Method of verification Set the displacement

Calibration Equipment Asset NO.* DVM 13475 Indicator 12089 Standardizer n/a Temp Readout 13477
Additional Equipment n/a

Conditions Ambient Temperature 68 deg. F Retraction x Positive _ Negative Bidirectional: _ Yes X No
Ref Voltage: Initial 10.000 V Final 10.000 V Other n/a

Range 1 Full Scale 100 Percent

Run No. 1 - As Found — Within Tolerance: x yes _ no
Run No. 1 - As Adjusted (If required)
Run No. 2

Asset No. (Standard)		12089
Class A Loading Range		n/a
Data Mode	X Ascending	Decending
	Initial	Final
Excitation	n/a	n/a
Gain	n/a	n/a
ΔK	_ On In / _ Off	_ On In / _ Off
Shunt Cal	+ n/a / - n/a	+ n/a / - n/a
Cal Factor	x0x000	x0x000
Phase	n/a	n/a
Zero Offset	0	0

Percent	Custom Percent	Run No. 1 - As Found Indicated Reading	Run No. 1 - As Found Error % of Reading	Run No. 1 - As Adjusted Indicated Reading	Run No. 1 - As Adjusted Error % of Reading	Run No. 2 Indicated Reading	Run No. 2 Error % of Reading
100							
80							
60		6.006 V	+0.10%				
40		3.999 V	-0.02%				
20		2.002 V	+0.10%				
Start 0		0.000 V					
Ret 0		0.000 V					
Ret 0		0.000 V					
Start 0		0.000 V					
-20		-1.990 V	-0.50%				
-40		-4.003 V	+0.08%				
-60		-6.019 V	+0.32%				
-80							
-100							

Range 2 Full Scale 50 Percent

Run No. 1 - As Found — Within Tolerance: x yes _ no
Run No. 1 - As Adjusted (If required)
Run No. 2

Asset No. (Standard)		12089
Class A Loading Range		n/a
Data Mode	X Ascending	Decending
	Initial	Final
Excitation	n/a	n/a
Gain	n/a	n/a
ΔK	_ On In / _ Off	_ On In / _ Off
Shunt Cal	+ n/a / - n/a	+ n/a / - n/a
Cal Factor	x0x000	x0x000
Phase	n/a	n/a
Zero Offset	n/a	n/a

Percent	Custom Percent	Run No. 1 - As Found Indicated Reading	Run No. 1 - As Found Error % of Reading	Run No. 1 - As Adjusted Indicated Reading	Run No. 1 - As Adjusted Error % of Reading	Run No. 2 Indicated Reading	Run No. 2 Error % of Reading
100		10.013 V	+0.13%				
80		8.017 V	+0.21%				
60		6.012 V	+0.20%				
40		4.013 V	+0.32%				
20		2.003 V	+0.16%				
Start 0		0.000 V					
Ret 0		0.000 V					
Ret 0		0.000 V					
Start 0		0.000 V					
-20		-2.010 V	+0.60%				
-40		-3.994 V	-0.15%				
-60		-6.003 V	+0.05%				
-80		-8.015 V	+0.19%				
-100		-10.040 V	+0.40%				

Performed by: Don BERNOW — Print
Signature: Don Bernow
Date: 6/29/95
Next Recommended Calibration Due Date: 6/28/96

* MTS Measurement Standards are Traceable to the National Institute of Standards and Technology.
MTS Force Standards are temperature compensated in the range specified by the manufacturer.

Form Number 114093-11D (04-94)-PC

MTS Systems Corporation
14000 Technology Drive
Eden Prairie, MN 55344-2290

Calibration Report

Page 2 of 2.

Customer Name: Ohio State University System No.: 870.64
System ID: Axial-torsion Location: Composite lab Site No.: C84009-M05

Equipment Device Type: Displacement X Force _ Pressure _ Extensometer: Gage Length n/a _ Other n/a
Device Model No. 8468 Serial No. 175
Controller/Conditioner Model 458.11 Serial No. 107 Calibration Data File Name n/a
Readout Device Model No. n/a Serial No. n/a Channel n/a

Procedure MTS Procedure No. 1234 Rev B
Calibration has been performed in accordance with: _ ASTM E4- 94 _ Other n/a _ Not Required
Method of verification: Set the force

Calibration Equipment Asset NO.* DVM 13475 Indicator 10976 Standardizer 10559 Temp Readout 13477
Additional Equipment n/a

Conditions Ambient Temperature 68 deg. F Retraction x Positive _ Negative Bidirectional: _ Yes X No
Ref Voltage: Initial 10.000 V Final 10.000 V Other n/a

Range 2 Full Scale 50 Percent

Asset No. (Standard): 10575
Class A Loading Range: 3402.02
Data Mode: X Ascending _ Descending

	Initial	Final
Excitation	10.990	10.990
Gain	n/a	n/a
ΔK _ On	In	In
_ Off		
Shunt Cal +	8.345	8.345
-	n/a	n/a
Cal Factor	n/a	n/a
Phase	n/a	n/a
Zero Offset	n/a	n/a

Run No. 1 - As Found, Within Tolerance: x yes _ no; Run No. 1 - As Adjusted (If required); Run No. 2

Percent	Custom Percent	Run No. 1 - As Found: Indicated Reading	Run No. 1 - As Found: Error % of Reading	Run No. 1 - As Adjusted: Indicated Reading	Run No. 1 - As Adjusted: Error % of Reading	Run No. 2: Indicated Reading	Run No. 2: Error % of Reading
100		9.974 V	-0.26%			9.978 V	-0.22%
80		7.989 V	-0.14%			7.991 V	-0.11%
60		5.992 V	-0.13%			5.999 V	-0.02%
40		4.002 V	+0.05%			4.001 V	+0.03%
20		2.005 V	+0.25%			2.005 V	+0.25%
Start 0		0.000 V				0.000 V	
Ret 0		0.000 V				0.000 V	
Ret 0		0.000 V				0.000 V	
Start 0		0.000 V				0.000 V	
-20		-2.013 V	+0.65%			-2.013 V	+0.66%
-40		-4.013 V	+0.32%			-4.014 V	+0.35%
-60		-6.012 V	+0.20%			-6.012 V	+0.20%
-80		-8.012 V	+0.15%			-8.009 V	+0.11%
-100		-10.017 V	+0.17%			-10.012 V	+0.12%

Range 1 Full Scale 100 Percent

Asset No. (Standard): 10576
Class A Loading Range: 3402.02
Data Mode: X Ascending _ Descending

	Initial	Final
Excitation	10.993	10.993
Gain	n/a	n/a
ΔK _ On	In	In
_ Off		
Shunt Cal +	6.962	[illegible]
-	n/a	n/a
Cal Factor	n/a	n/a
Phase	n/a	n/a
Zero Offset	n/a	n/a

Run No. 1 - As Found, Within Tolerance: X yes _ no; Run No. 1 - As Adjusted (If required); Run No. 2

Percent	Custom Percent	Run No. 1 - As Found: Indicated Reading	Run No. 1 - As Found: Error % of Reading	Run No. 1 - As Adjusted: Indicated Reading	Run No. 1 - As Adjusted: Error % of Reading	Run No. 2: Indicated Reading	Run No. 2: Error % of Reading
100		—				—	—
80		—				—	—
60		6.004 V	+0.07%			5.994 V	-0.10%
40		4.006 V	+0.15%			4.005 V	+0.12%
20		2.002 V	+0.10%			2.004 V	+0.20%
Start 0		0.000 V				0.000 V	
Ret 0		0.000 V				0.000 V	
Ret 0		0.000 V				0.000 V	
Start 0		0.000 V				0.000 V	
-20		-2.015 V	+0.75%			-2.017 V	+0.85%
-40		-4.017 V	+0.43%			-4.014 V	+0.35%
-60		-6.007 V	+0.12%			-6.009 V	+0.15%
-80		—				—	—
-100		—				—	—

Notes: System inserts used in collet grips. Grips not removed.....Fully preloaded. Could not achieve greater than 30,000 without slippage.

Performed by: Don BERNOW (Print)
[signature] (Signature)

Date: 6/29/95
Next Recommended Calibration Due Date: 6/28/96

* MTS Measurement Standards are Traceable to the National Institute of Standards and Technology.
MTS Force Standards are temperature compensated in the range specified by the manufacturer.

Form Number 1140-…-11D (04-94)-PC

C

TEST DATA AND RESULTS

Overview of Appendix C

The description of the testing is contained in Section 2. Table 2-2 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 includes 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 indicates 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 Specimen A
Test Report

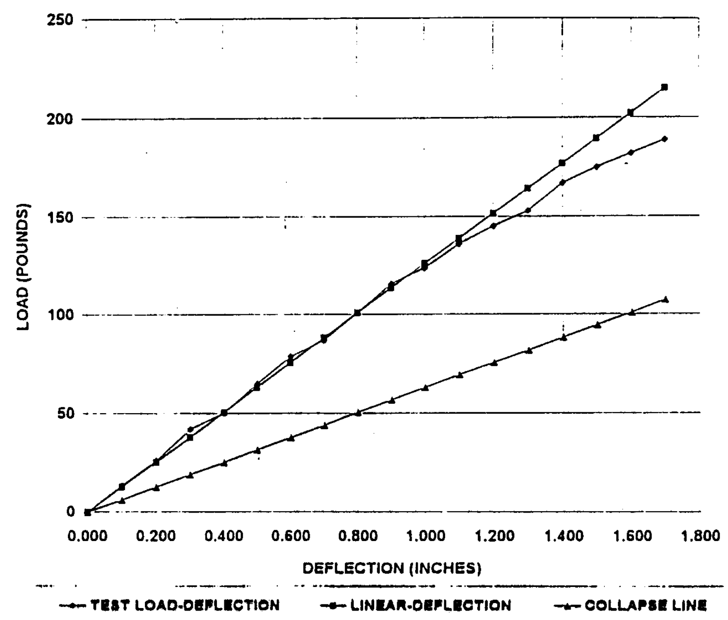
TEST #: UNREINFORCED BRANCH-A TYPE: FATIGUE - LOAD DEFLECTION CURVE

F = Fo + m δ "m" TO BE BASED ON N DATA POINTS, N = 8
THE VALUE OF "m" = 126 87 0

NOMINAL STRESS = M/Z KSI, M=F x L, L(IN) = 46.5 Z(IN³) =πr²t= 0.303

DATA POINT	MEASURED DEFLECTION δ	LOAD F	MODIFIED DEFLECTION δ	LOAD F	SLOPE FOR START TO DATA POINT	F BASED ON "m"	NOMINAL STRESS
#	(INCHES)	(LBS)	(INCHES)	(LBS)	(LBS/INCH)	(LBS)	(KSI)
1	0	0	0.000	0	N/A	0	
2	0.1	13.56	0.100	14	136	13	1.9
3	0.2	26	0.200	26	130	25	3.9
4	0.3	42	0.300	42	138	38	5.8
5	0.4	50.2	0.400	50	129	51	7.8
6	0.5	65	0.500	65	129	63	9.7
7	0.6	79	0.600	79	130	76	11.6
8	0.7	87	0.700	87	126	88	13.6
9	0.8	101	0.800	101	126	101	15.5
10	0.9	116	0.900	116	126	114	17.5
11	1	124	1.000	124	125	126	19.4
12	1.1	136	1.100	136	124	139	21.4
13	1.2	145	1.200	145	122	152	23.3
14	1.3	153	1.300	153	120	164	25.2
15	1.4	167	1.400	167	119	177	27.2
16	1.5	175	1.500	175	117	190	29.1
17	1.6	182	1.600	182	115	202	31.1
18	1.7	189	1.700	189	113	215	33.0
19							
20							
21							
22							
23							
24							
25							

POSITIVE LOAD - LOADING CONDITION



NOTES:
1. Load in upward direction.
2. Inital load of .81 lbs.

TEST #: UNREINFORCED BRANCH-A **TYPE:** FATIGUE - LOAD DEFLECTION CURVE

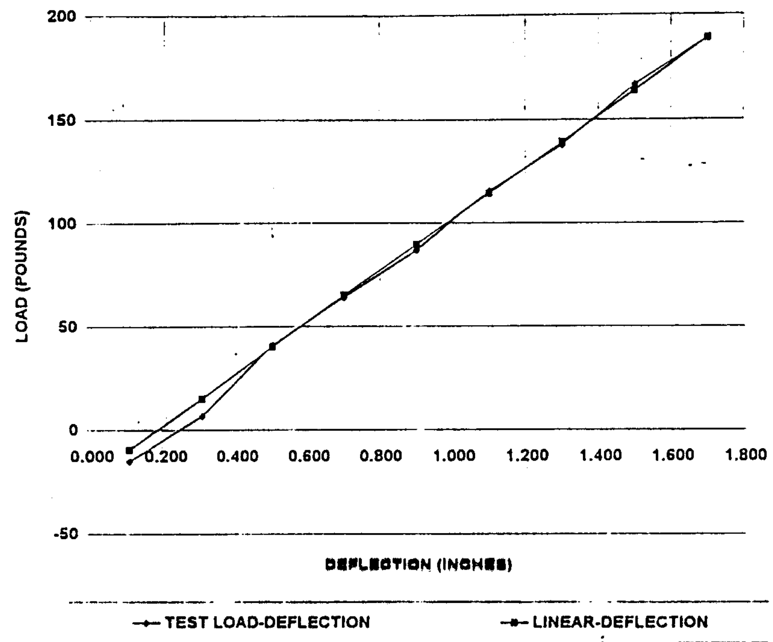
F = Fo + m δ "m" TO BE BASED ON N DATA POINTS, N = 4
THE VALUE OF "m" = 124 Fo (LBS) = 189

NOMINAL STRESS = M/Z KSI, M=F x L, L(IN) = 46.5 $Z(IN^3) = \pi r_n^2 t =$ 0.303

DATA POINT	MEASURED DEFLECTION δ	MEASURED LOAD F	MODIFIED DEFLECTION δ	MODIFIED LOAD F	SLOPE FOR START TO DATA POINT	F BASED ON "m"	NOMINAL STRESS
#	(INCHES)	(LBS)	(INCHES)	(LBS)	(LBS/INCH)	(LBS)	(KSI)
1	1.7	189	1.700	189	N/A	189	29.0
2	1.500	167	1.500	167	110	164	25.2
3	1.300	138	1.300	138	128	139	21.4
4	1.100	116	1.100	116	124	115	17.6
5	0.900	87	0.900	87	127	90	13.8
6	0.700	64	0.700	64	127	65	10.0
7	0.500	41	0.500	41	125	40	6.2
8	0.300	7	0.300	7	128	15	2.4
9	0.100	-15	0.100	-15	129	-9	-1.4
10							
11							
12							
13							
14							
15							
16							
17							
18							
19							
20							
21							
22							
23							
24							
25							

NOTES.

POSITIVE LOAD - UNLOADING CONDITION



TEST #: UNREINFORCED BRANCH-A

TYPE: FATIGUE - LOAD DEFLECTION CURVE

NEGATIVE LOAD - LOADING CONDITION

$F = Fo + m\delta$

"m" TO BE BASED ON N DATA POINTS, N = 4

THE VALUE OF "m" = 112

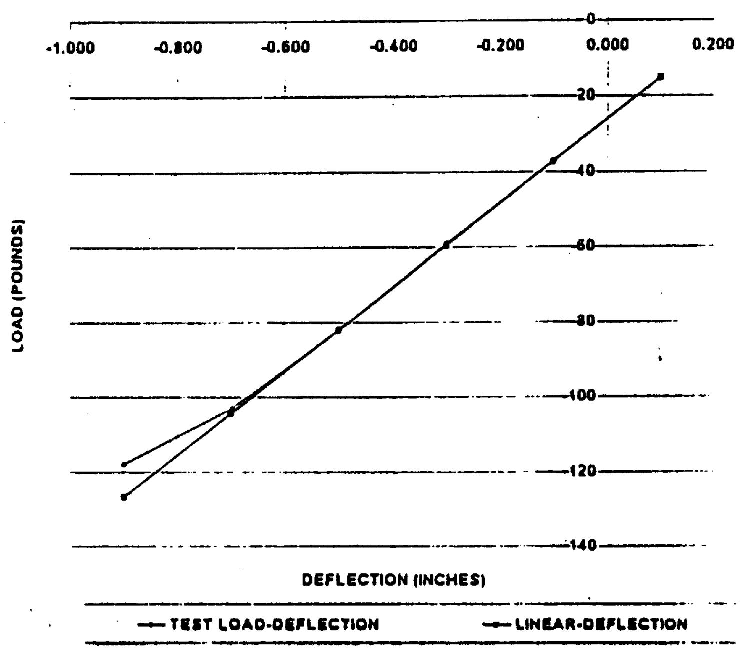
Fo (LBS) = -15

NOMINAL STRESS = M/Z KSI, M=F x L,

L(IN) = 48.5

$Z(IN^3) = \pi r_n^2 t$ = 0.303

DATA POINT #	MEASURED DEFLECTION δ (INCHES)	MEASURED LOAD F (LBS)	MODIFIED DEFLECTION δ (INCHES)	MODIFIED LOAD F (LBS)	SLOPE FOR START TO DATA POINT (LBS/INCH)	F BASED ON "m" (LBS)	NOMINAL STRESS (KSI)
1	0.100	-15	0.100	-15	N/A	-15	-2.3
2	-0.100	-37.000	-0.100	-37	110	-37	-5.7
3	-0.300	-59.000	-0.300	-59	110	-60	-9.2
4	-0.500	-82.000	-0.500	-82	112	-82	-12.6
5	-0.700	-103.000	-0.700	-103	111	-104	-16.0
6	-0.900	-118.000	-0.900	-118	105	-127	-19.4
7			0.000				
8			0.000				
9			0.000				
10			0.000				
11			0.000				
12			0.000				
13			0.000				
14			0.000				
15			0.000				
16			0.000				
17			0.000				
18			0.000				
19			0.000				
20			0.000				
21			0.000				
22			0.000				
23			0.000				
24							
25							



NOTES:

TEST #: UNREINFORCED BRANCH-A TYPE: FATIGUE - LOAD DEFLECTION CURVE

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

THE VALUE OF "m" = 133 Fo (LBS) = 6

NEGATIVE LOAD - UNLOADING CONDITION

NOMINAL STRESS = M/Z KSI, M=F x L, L(IN) = 46.5 $Z(IN^3) = \pi r_n^2 t =$ 0.303

DATA POINT	MEASURED DEFLECTION δ	MEASURED LOAD F	MODIFIED DEFLECTION δ	MODIFIED LOAD F	SLOPE FOR START TO DATA POINT	F BASED ON "m"	NOMINAL STRESS
#	(INCHES)	(LBS)	(INCHES)	(LBS)	(LBS/INCH)	(LBS)	(KSI)
1	-0.900	-118.000	-0.9	-118	137	-113	-17.4
2	-0.600	-75	-0.6	-75	133	-74	-11.3
3	-0.500	-59	-0.5	-59	128	-60	-9.3
4	-0.300	-30	-0.3	-30	119	-34	-5.2
5	-0.100	-8	-0.1	-8	140	-7	-1.1
6	0.000	6	0	6	N/A	6	0.9
7							
8							
9							
10							
11							
12							
13							
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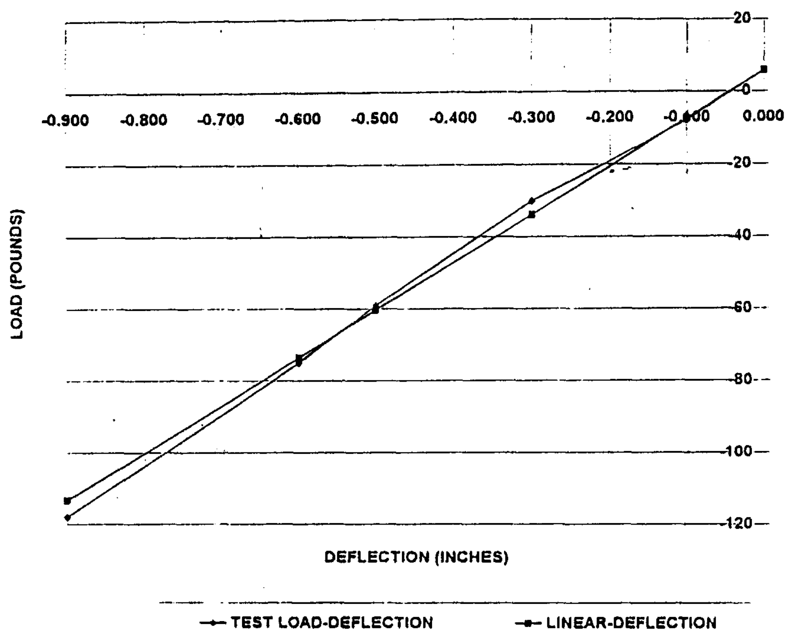
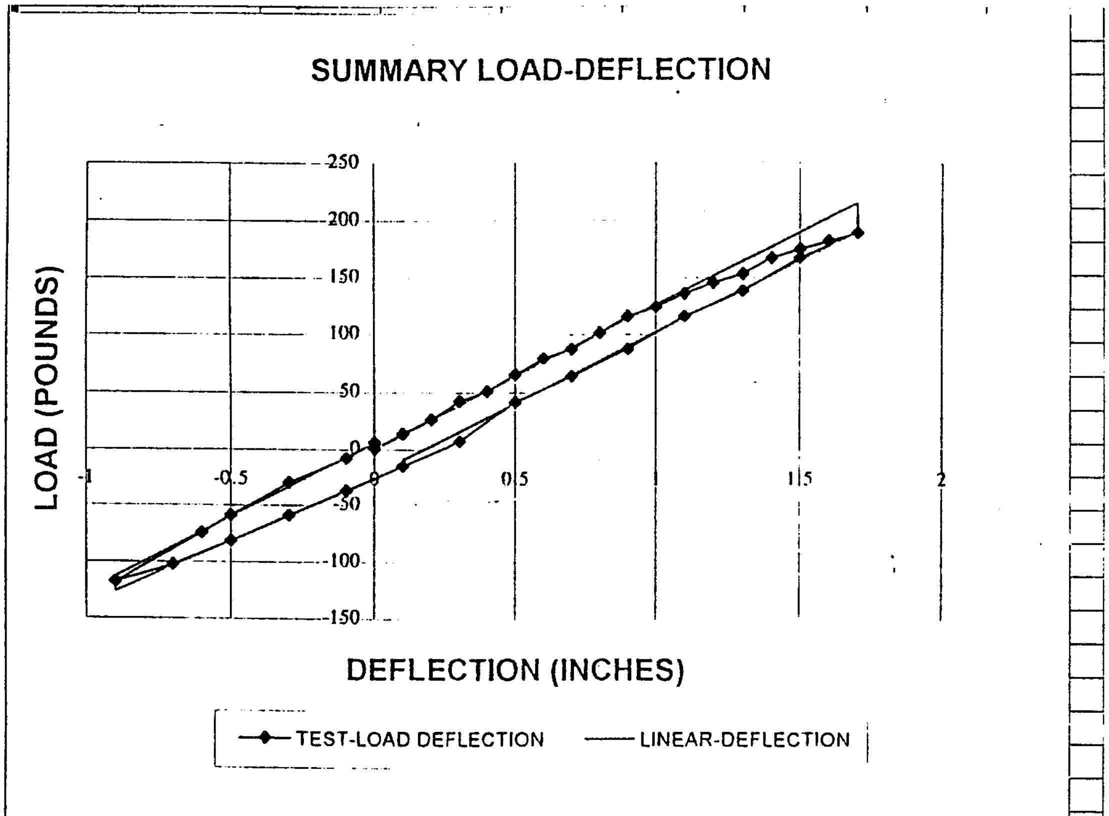


NOTES:


SUMMARY LOAD-DEFLECTION
LOAD (POUNDS)
250
200
150
100
50
0
-50
-100
-150
-1
-0.5
0
0.5
1.5
2
DEFLECTION (INCHES)
TEST-LOAD DEFLECTION
LINEAR-DEFLECTION

FATIGUE TEST DATA ANALYSIS

TEST #: **UNREINFORCED BRANCH-A**

COMPONENT: UNREINFORCED BRANCH CONNECTION

STIFFNESS (lbs/in) = 124 MOMENT ARM (in)= 46.5

D (in) = 2.5 t (in) = 0.065 $Z(IN^3) = \pi r_n^2 t =$ 0.303

TEST DISPLACEMENT/CYCLE DATA:

CONDITION #	DISPLACEMENT AMPLITUDE (+/-) (in.) δ_i	EFFECTIVE APPLIED LOAD (lbs)	NOMINAL STRESS (+/-) (psi) S	NUMBER OF TEST CYCLES N_i
1	1.20	148	22,792	459
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:	459

THE EQUIVALENT NUMBER OF CYCLES, BASED ON A DISPLACEMENT: $\delta_{max} =$ 1.2

IS: $N_{eq} = SUM(\delta_i/\delta_{max})^5 * N_i = 459$

FOR MEASURED DIMENSIONS: $i = 245{,}000 * N_{eq}^{(-0.2)}/S =$ **3.155**

FOR NOMINAL DIMENSIONS: $Z(IN^3) =$ 0.303 i = **3.152**

COMMENTS:

1. Failure occured at bottom of branch at the end of the weld.
2. Stand pipe 19.5 Inches long.
3. Moment arm = 46.5 inches.

Test Specimen B
Test Report

TEST #: UNREINFORCED BRANCH-B   TYPE: FATIGUE - LOAD DEFLECTION CURVE

$F = Fo + m\,\delta$ "m" TO BE BASED ON N DATA POINTS, N = 8
THE VALUE OF "m" = 134   87 0

NOMINAL STRESS = M/Z KSI, M=F x L,   L(IN) = 46.5 $Z(IN^3) = \pi r_n^2 t$ = 0.303

DATA POINT #	MEASURED DEFLECTION δ (INCHES)	MEASURED LOAD F (LBS)	MODIFIED DEFLECTION δ (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	16.6	0.100	17	166	13	2.1
3	0.2	31.2	0.200	31	156	27	4.1
4	0.3	45.9	0.300	46	152	40	6.2
5	0.4	53.2	0.400	53	136	54	8.2
6	0.5	67.9	0.500	68	133	67	10.3
7	0.6	82.5	0.600	83	133	80	12.4
8	0.7	97	0.700	97	134	94	14.4
9	0.8	105	0.800	105	131	107	16.5
10	0.9	119	0.900	119	130	121	18.5
11	1	133	1.000	133	130	134	20.6
12	1.1	141	1.100	141	128	147	22.6
13	1.2	148	1.200	148	125	161	24.7
14	1.3	153	1.300	153	121	174	26.8
15	1.4	163	1.400	163	117	188	28.8
16	1.5	178	1.500	178	116	201	30.9
17	1.6	185	1.600	185	114	214	32.9
18	1.7	192	1.700	192	112	228	35.0
19							
20							
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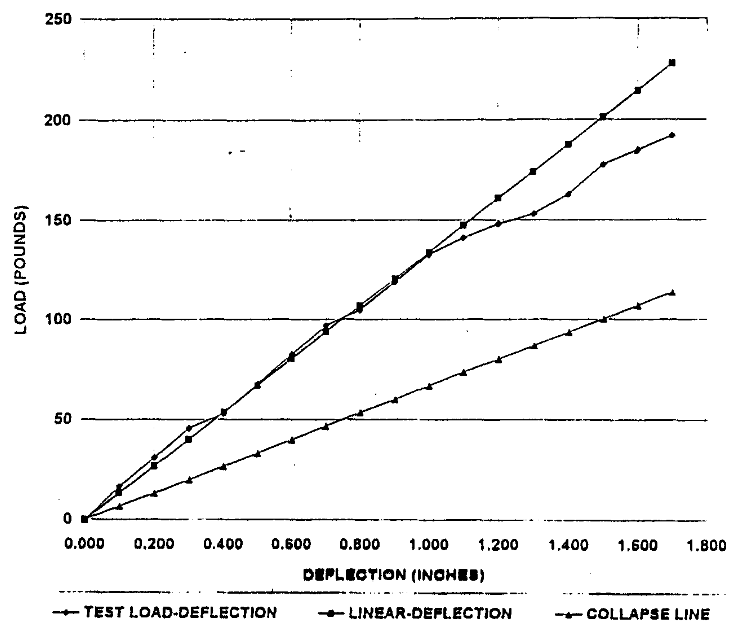
23							
24							
25							

POSITIVE LOAD - LOADING CONDITION



NOTES:
1. Load in upward direction.
2. Inital load of .81 lbs.

TEST #: UNREINFORCED BRANCH-B TYPE: FATIGUE - LOAD DEFLECTION CURVE

$F = F_o + m\,\delta$ "m" TO BE BASED ON N DATA POINTS, N = 5

THE VALUE OF "m" = 125 Fo (LBS) = 192

NOMINAL STRESS = M/Z KSI, M=F x L, L(IN) = 46.5 $Z(IN^3) = \pi r_n^2 t$ = 0.303

DATA POINT	MEASURED DEFLECTION δ	MEASURED LOAD F	MODIFIED DEFLECTION δ	MODIFIED LOAD F	SLOPE FOR START TO DATA POINT	F BASED ON "m"	NOMINAL STRESS
#	(INCHES)	(LBS)	(INCHES)	(LBS)	(LBS/INCH)	(LBS)	(KSI)
1	1.7	192	1.700	192	N/A	192	29.5
2	1.500	163	1.500	163	145	167	25.7
3	1.300	134	1.300	134	145	142	21.8
4	1.100	119	1.100	119	124	117	18.0
5	0.900	88.9	0.900	89	125	92	14.1
6	0.700	67.9	0.700	68	123	67	10.3
7	0.500	45.9	0.500	46	120	42	6.4
8	0.300	16.6	0.300	17	122	17	2.6
9	0.100	-5.4	0.100	-5	121	-8	-1.3
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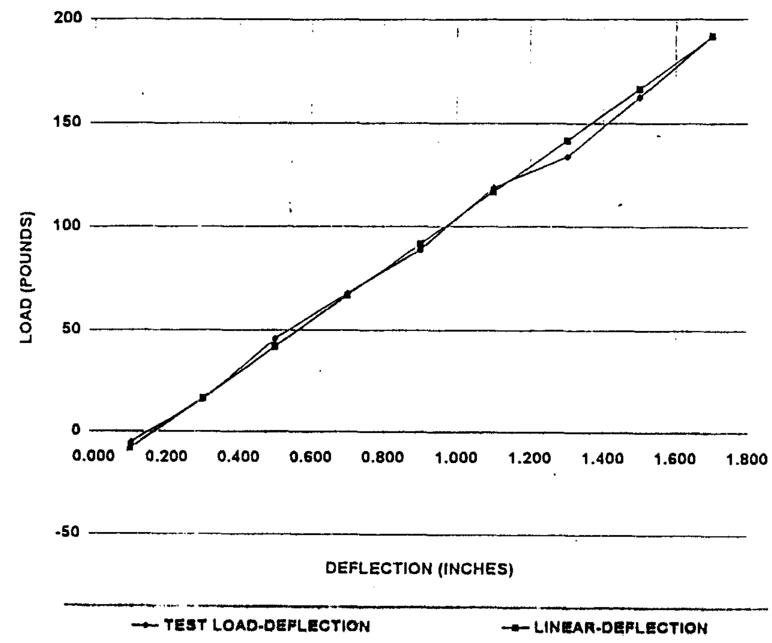
NOTES:

POSITIVE LOAD - UNLOADING CONDITION



TEST #: **UNREINFORCED BRANCH-B** **TYPE:** **FATIGUE - LOAD DEFLECTION CURVE**

F = Fo + m δ

"m" TO BE BASED ON N DATA POINTS, N = 2

THE VALUE OF "m" = 110 Fo (LBS) = -5.4

NOMINAL STRESS = M/Z KSI, M=F x L, L(IN) = 46.5 Z(IN³) = πr²t = 0.303

DATA POINT #	MEASURED DEFLECTION δ (INCHES)	MEASURED LOAD F (LBS)	MODIFIED DEFLECTION δ (INCHES)	MODIFIED LOAD F (LBS)	SLOPE FOR START TO DATA POINT (LBS/INCH)	F BASED ON "m" (LBS)	NOMINAL STRESS (KSI)
1	0.100	-5.4	0.100	-5	N/A	-5	-0.8
2	-0.100	-27.300	-0.100	-27	110	-27	-4.2
3	-0.300	-49.300	-0.300	-49	110	-49	-7.6
4	-0.500	-71.300	-0.500	-71	110	-71	-10.9
5	-0.700	-93.300	-0.700	-93	110	-93	-14.3
6	-0.900	-107.900	-0.900	-108	105	-115	-17.7
7	-1.100	-122.600	-1.100	-123	99	-137	-21.0
8	-1.200	-129.900	-1.200	-130	96	-148	-22.7
9	-1.300	-138.000	-1.300	-138	94	-159	-24.4
10	-1.400	-151.900	-1.400	-152	94	-170	-26.1
11	-1.500	-159.200	-1.500	-159	93	-181	-27.7
12							
13							
14							
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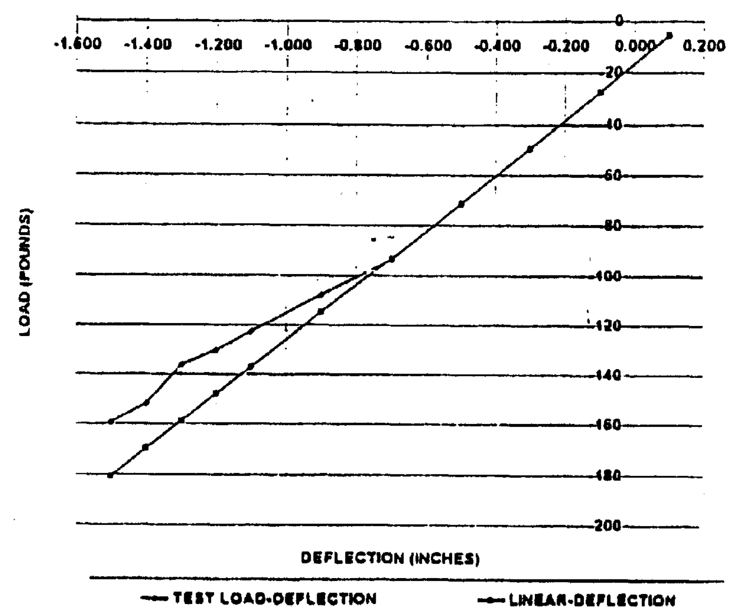
NOTES.

NEGATIVE LOAD - LOADING CONDITION



TEST #: UNREINFORCED BRANCH-B

TYPE: FATIGUE - LOAD DEFLECTION CURVE

$F = F_o + m\,\delta$

"m" TO BE BASED ON N DATA POINTS, N = 2

THE VALUE OF "m" = 134

F_o (LBS) = 19

NOMINAL STRESS = M/Z KSI, M=F x L,

L(IN) = 46.5

$Z(IN^3) = \pi r_n^2 t =$ 0.303

DATA POINT	MEASURED DEFLECTION δ	MEASURED LOAD F	MODIFIED DEFLECTION δ	MODIFIED LOAD F	SLOPE FOR START TO DATA POINT	F BASED ON "m"	NOMINAL STRESS
#	(INCHES)	(LBS)	(INCHES)	(LBS)	(LBS/INCH)	(LBS)	(KSI)
1	-1.500	-159.200	-1.5	-159.2	134	-154	-23.7
2	-1.400	-144.5	-1.4	-144.5	134	-141	-21.7
3	-1.200	-115.2	-1.2	-115.2	134	-114	-17.6
4	-1.000	-93.3	-1	-93.3	138	-88	-13.5
5	-0.800	-64	-0.8	-64	140	-61	-9.4
6	-0.600	-42	-0.6	-42	153	-34	-5.2
7	-0.400	-12.4	-0.4	-12.4	159	-7	-1.1
8	-0.200	19.3	-0.2	19.3	N/A	19	3.0
9							
10							
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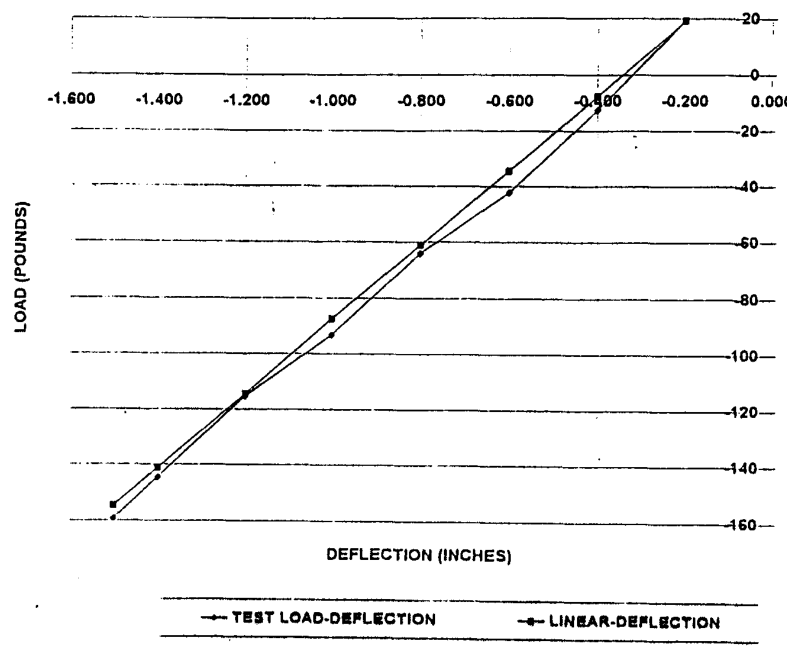
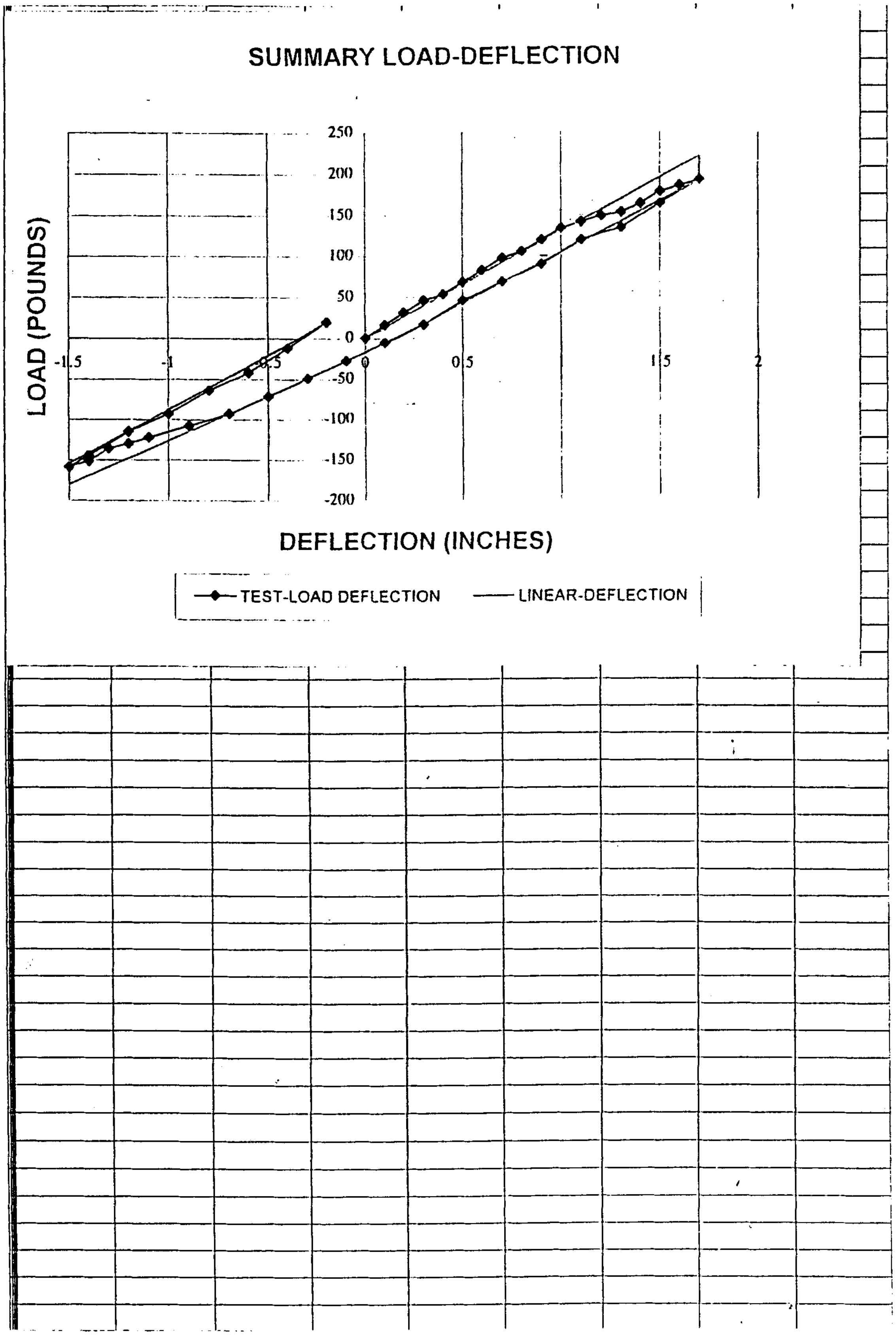
NOTES

NEGATIVE LOAD - UNLOADING CONDITION




SUMMARY LOAD-DEFLECTION
LOAD (POUNDS)
250
200
150
100
50
0
-50
-100
-150
-200
-1.5
-1
-0.5
0
0.5
1.5
2
DEFLECTION (INCHES)
TEST-LOAD DEFLECTION
LINEAR-DEFLECTION

FATIGUE TEST DATA ANALYSIS

TEST #: **UNREINFORCED BRANCH-B**

COMPONENT: UNREINFORCED BRANCH CONNECTION

STIFFNESS (lbs/in) = 125 MOMENT ARM (in)= 45.875

D (in) = 2.5 t (in) = 0.065 $Z(IN^3) = \pi r_n^2 t =$ 0.303

TEST DISPLACEMENT/CYCLE DATA:

CONDITION #	DISPLACEMENT AMPLITUDE (+/-) (in.) δ_i	EFFECTIVE APPLIED LOAD (lbs)	NOMINAL STRESS (+/-) (psi) S	NUMBER OF TEST CYCLES N_i
1	1.00	125	18,873	754
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:	754

THE EQUIVALENT NUMBER OF CYCLES, BASED ON A DISPLACEMENT: δ_{max} = 1 INCHES

IS: $N_{eq} = SUM(\delta_i/\delta_{max})^5 * N_i$ = 754

FOR MEASURED DIMENSIONS: $i = 245{,}000 * N_{eq}^{(-0.2)}/S$ = **3.450**

FOR NOMINAL DIMENSIONS: $Z(IN^3)$ = 0.303 i = **3.447**

COMMENTS:

1. Failure occured at bottom of branch at the end of the weld. This was followed by failure at the top.
2. Stand pipe 19.5 Inches long.
3. Moment arm = ~~46.5~~ 45.875 inches.

Test Specimen C
Test Report

TEST #: UNREINFORCED BRANCH-C

TYPE: FATIGUE - LOAD DEFLECTION CURVE

$F = Fo + m\delta$

"m" TO BE BASED ON N DATA POINTS, N = 10
THE VALUE OF "m" = 130 87 0

POSITIVE LOAD - LOADING CONDITION

NOMINAL STRESS = M/Z KSI, M=F x L, L(IN) = 46.5 $Z(IN^3) = \pi r_n^2 t =$ 0.303

DATA POINT #	MEASURED DEFLECTION δ (INCHES)	MEASURED LOAD F (LBS)	MODIFIED DEFLECTION δ (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	16.6	0.100	17	166	13	2.0
3	0.2	31.2	0.200	31	156	26	4.0
4	0.3	45.9	0.300	46	152	39	6.0
5	0.4	53.2	0.400	53	136	52	8.0
6	0.5	67.9	0.500	68	133	65	10.0
7	0.6	82.5	0.600	83	133	78	12.0
8	0.7	97.2	0.700	97	134	91	14.0
9	0.8	105	0.800	105	131	104	16.0
10	0.9	119.4	0.900	119	130	117	18.0
11	1	133.8	1.000	134	130	130	20.0
12	1.1	141.1	1.100	141	128	143	22.0
13	1.2	155.8	1.200	156	128	156	24.0
14	1.3	163.1	1.300	163	126	169	26.0
15	1.4	177	1.400	177	125	182	28.0
16	1.5	185	1.500	185	123	195	30.0
17	1.6	192	1.600	192	121	208	32.0
18	1.7	200	1.700	200	119	221	34.0
19	1.8	207	1.800	207	116	234	36.0
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21							
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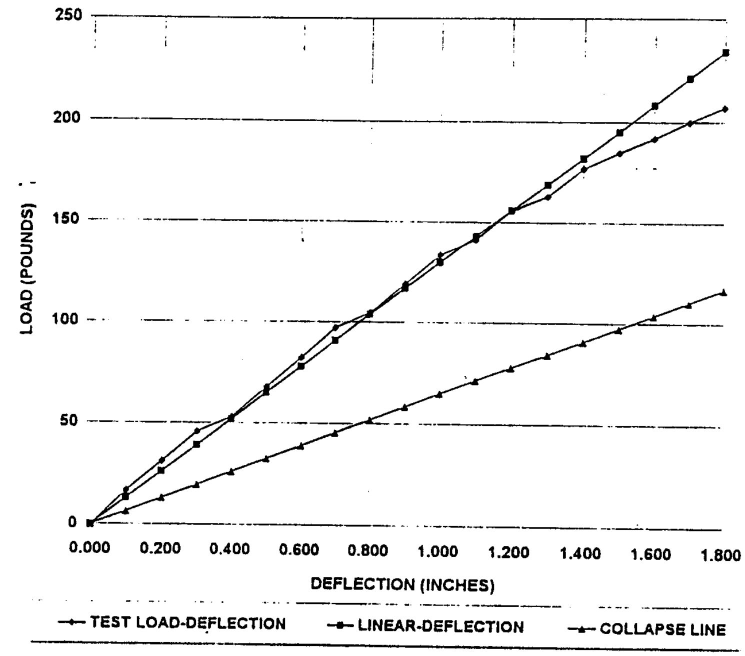

NOTES:
1. Load in upward direction.
2. Inital load of .81 lbs.

TEST #: UNREINFORCED BRANCH-C TYPE: FATIGUE - LOAD DEFLECTION CURVE

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

THE VALUE OF "m" = 128 Fo (LBS) = 207

NOMINAL STRESS = M/Z KSI, M=F x L, L(IN) = 46.5 $Z(IN^3) = \pi r_n^2 t =$ 0.303

DATA POINT #	MEASURED DEFLECTION δ (INCHES)	MEASURED LOAD F (LBS)	MODIFIED DEFLECTION δ (INCHES)	MODIFIED LOAD F (LBS)	SLOPE FOR START TO DATA POINT (LBS/INCH)	F BASED ON "m" (LBS)	NOMINAL STRESS (KSI)
1	1.8	207	1.800	207	N/A	207	31.8
2	1.600	177.7	1.600	178	147	181	27.9
3	1.400	148	1.400	148	148	156	23.9
4	1.200	126.5	1.200	127	136	130	20.0
5	1.000	97.2	1.000	97	135	105	16.1
6	0.800	75.2	0.800	75	132	79	12.1
7	0.600	53.2	0.600	53	128	53	8.2
8	0.400	23.9	0.400	24	128	28	4.3
9	0.200	2	0.200	2	127	2	0.3
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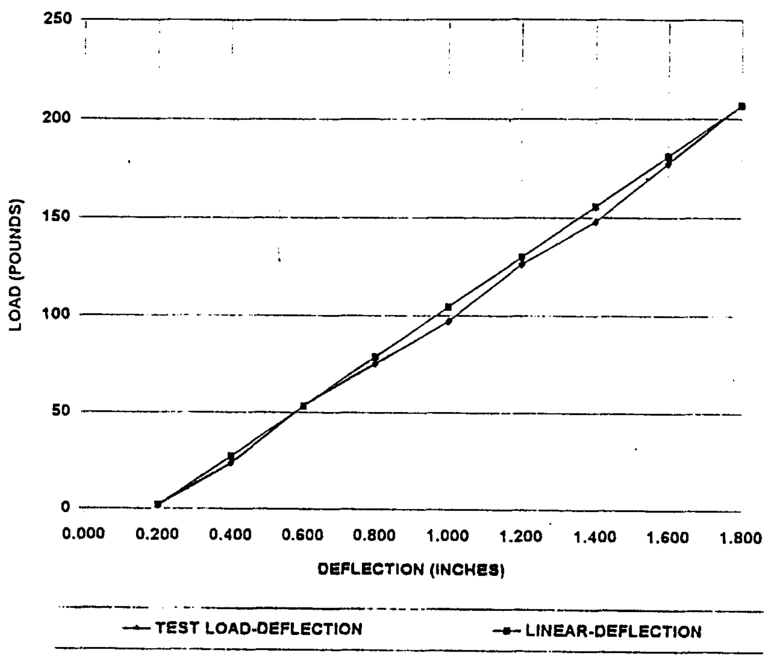
NOTES:

POSITIVE LOAD - UNLOADING CONDITION



TEST #: UNREINFORCED BRANCH-C

TYPE: FATIGUE - LOAD DEFLECTION CURVE

NEGATIVE LOAD - LOADING CONDITION

$F = Fo + m\delta$ — "m" TO BE BASED ON N DATA POINTS, N = 4

THE VALUE OF "m" = 109 — Fo (LBS) = 2

NOMINAL STRESS = M/Z KSI, M=F x L, — L(IN) = 46.5 — $Z(IN^3) = \pi r_n^2 t$ = 0.303

DATA POINT #	MEASURED DEFLECTION δ (INCHES)	MEASURED LOAD F (LBS)	MODIFIED DEFLECTION δ (INCHES)	MODIFIED LOAD F (LBS)	SLOPE FOR START TO DATA POINT (LBS/INCH)	F BASED ON "m" (LBS)	NOMINAL STRESS (KSI)
1	0.200	2	0.200	2	N/A	2	0.3
2	0.000	-20.000	0.000	-20	110	-20	-3.0
3	-0.200	-42.000	-0.200	-42	110	-41	-6.4
4	-0.400	-63.000	-0.400	-63	109	-63	-9.7
5	-0.600	-78.600	-0.600	-79	102	-85	-13.0
6	-0.800	-100.600	-0.800	-101	101	-107	-16.4
7	-1.000	-115.000	-1.000	-115	98	-128	-19.7
8	-1.100	-123.000	-1.100	-123	96	-139	-21.4
9	-1.200	-130.000	-1.200	-130	94	-150	-23.0
10	-1.300	-137.000	-1.300	-137	92	-161	-24.7
11	-1.400	-145.000	-1.400	-145	91	-172	-26.4
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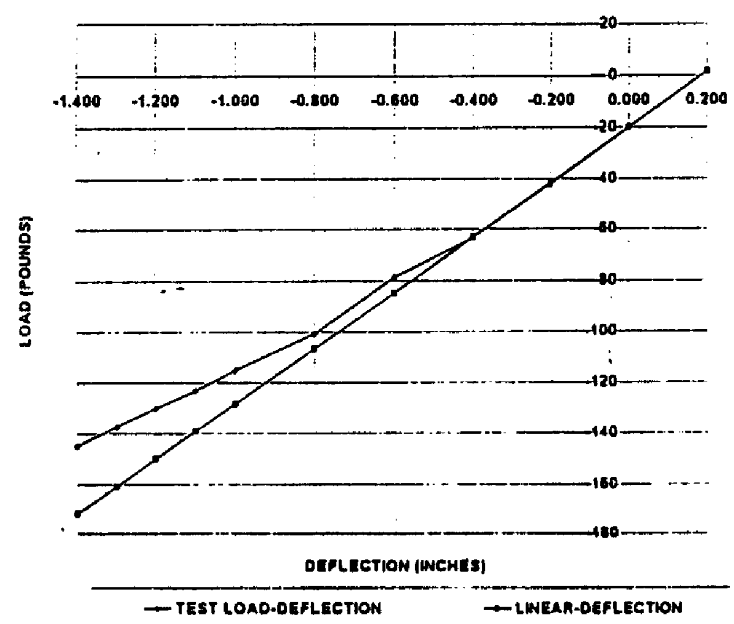
NOTES:



TEST #: UNREINFORCED BRANCH-C

TYPE: FATIGUE - LOAD DEFLECTION CURVE

F = Fo + m δ

"m" TO BE BASED ON N DATA POINTS, N = 2

THE VALUE OF "m" = 127

Fo (LBS) = 31

NOMINAL STRESS = M/Z KSI, M=F x L,

L(IN) = 46.5

$Z(IN^3) = \pi r_n^2 t =$ 0.303

DATA POINT #	MEASURED DEFLECTION δ (INCHES)	MEASURED LOAD F (LBS)	MODIFIED DEFLECTION δ (INCHES)	MODIFIED LOAD F (LBS)	SLOPE FOR START TO DATA POINT (LBS/INCH)	F BASED ON "m" (LBS)	NOMINAL STRESS (KSI)
1	-1.400	-145.000	-1.4	-145	127	-146	-22.5
2	-1.200	-122	-1.2	-122	127	-121	-18.6
3	-1.000	-93.3	-1	-93.3	124	-96	-14.7
4	-0.800	-64	-0.8	-64	121	-70	-10.8
5	-0.600	-42	-0.6	-42	124	-45	-6.9
6	-0.400	-20	-0.4	-20	128	-20	-3.0
7	-0.200	9.9	-0.2	9.9	106	6	0.9
8	0.000	31	0	31	N/A	31	4.8
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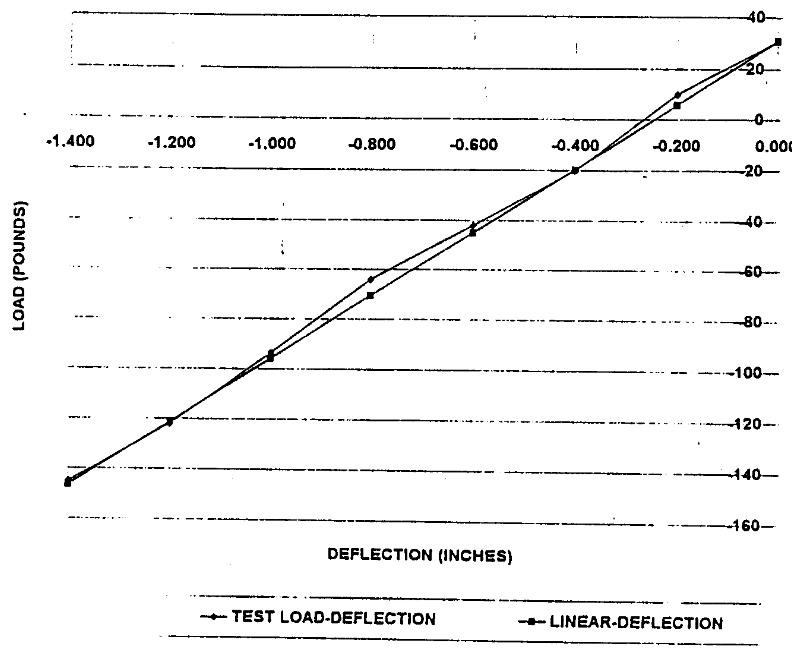
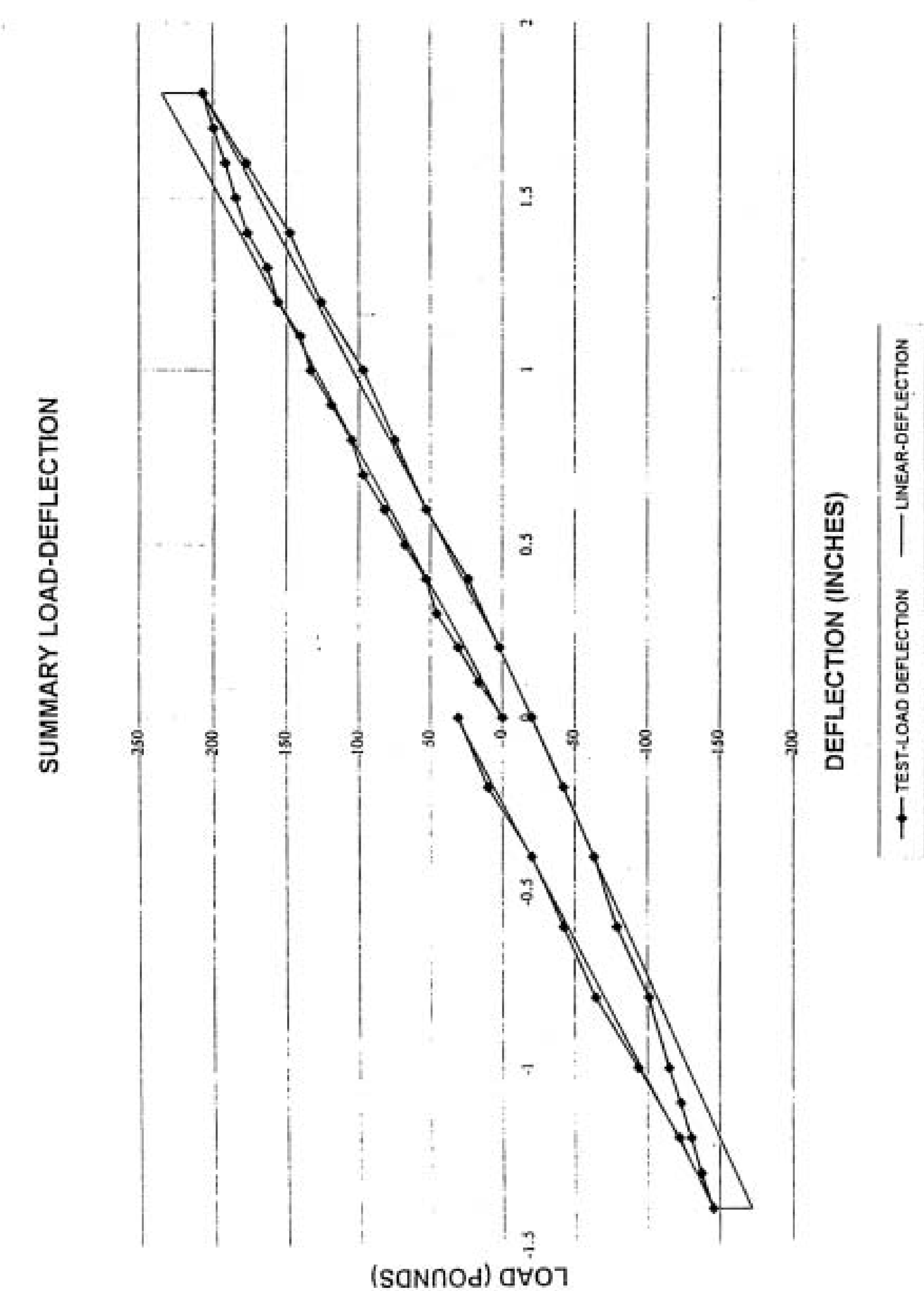
NOTES:

NEGATIVE LOAD - UNLOADING CONDITION




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

FATIGUE TEST DATA ANALYSIS

TEST #: **UNREINFORCED BRANCH-C**

COMPONENT: UNREINFORCED BRANCH CONNECTION

STIFFNESS (lbs/in) = 123 MOMENT ARM (in)= 46.5

D (in) = 2.5 t (in) = 0.065 $Z(IN^3) = \pi r_n^2 t =$ 0.303

TEST DISPLACEMENT/CYCLE DATA:

CONDITION #	DISPLACEMENT AMPLITUDE (+/-) (in.) δ_i	EFFECTIVE APPLIED LOAD (lbs)	NOMINAL STRESS (+/-) (psi) S	NUMBER OF TEST CYCLES N_i
1	0.85	105	16,108	923
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:	923

THE EQUIVALENT NUMBER OF CYCLES, BASED ON A DISPLACEMENT: $\delta_{max} =$ 0.9 INCHES

IS: $N_{eq} = SUM(\delta_i/\delta_{max})^5 * N_i = 923$

FOR MEASURED DIMENSIONS: $i = 245{,}000 * N_{eq}^{(-0.2)}/S =$ **3.882**

FOR NOMINAL DIMENSIONS: $Z(IN^3) =$ 0.303 $i =$ **3.878**

COMMENTS:

1. Failure occured at bottom of branch at the end of the weld. This was followed by failure at the top @ 1037 cycles.
2. Stand pipe 19.5 Inches long.
3. Moment arm =46.5 inches.

Test Specimen D
Test Report

TEST #: UNREINFORCED BRANCH-D

TYPE: FATIGUE - LOAD DEFLECTION CURVE

$F = F_o + m\,\delta$

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

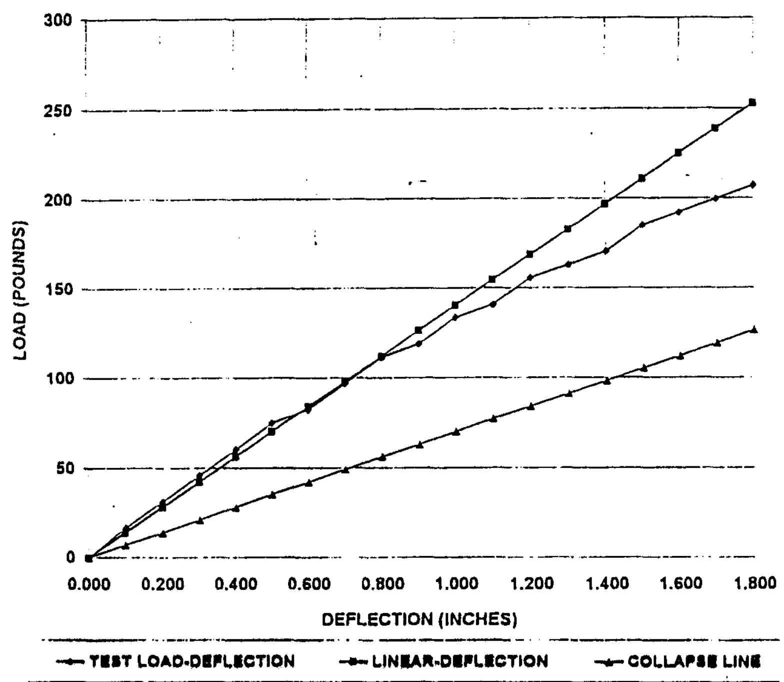
THE VALUE OF "m" = 141   87 0

NOMINAL STRESS = M/Z KSI, M=F x L,   L(IN) = 46.5 $Z(IN^3) = \pi r_n^2 t =$ 0.303

DATA POINT #	MEASURED DEFLECTION δ (INCHES)	MEASURED LOAD F (LBS)	MODIFIED DEFLECTION δ (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	16.5	0.100	17	165	14	2.2
3	0.2	31.1	0.200	31	156	28	4.3
4	0.3	45.8	0.300	46	152	42	6.5
5	0.4	60.4	0.400	60	150	56	8.6
6	0.5	75	0.500	75	149	70	10.8
7	0.6	82.4	0.600	82	141	84	13.0
8	0.7	97	0.700	97	137	98	15.1
9	0.8	111.7	0.800	112	137	112	17.3
10	0.9	119	0.900	119	133	126	19.4
11	1	133.6	1.000	134	131	141	21.6
12	1.1	141	1.100	141	128	155	23.7
13	1.2	155.6	1.200	156	127	169	25.9
14	1.3	162.9	1.300	163	125	183	28.1
15	1.4	170.3	1.400	170	122	197	30.2
16	1.5	184.9	1.500	185	120	211	32.4
17	1.6	192.2	1.600	192	119	225	34.5
18	1.7	199.6	1.700	200	117	239	36.7
19	1.8	206.9	1.800	207	114	253	38.9
20							
21							
22							
23							
24							
25							

NOTES:
1. Load in upward direction.
2. Inital load of .81 lbs.

POSITIVE LOAD - LOADING CONDITION



TEST #: UNREINFORCED BRANCH-D

TYPE: FATIGUE - LOAD DEFLECTION CURVE

$F = Fo + m\,\delta$

"m" TO BE BASED ON N DATA POINTS, N = 5

THE VALUE OF "m" = 128

Fo (LBS) = 207

NOMINAL STRESS = M/Z KSI, M=F x L, L(IN) = 46.5 $Z(IN^3) = \pi r_m^2 t =$ 0.303

DATA POINT #	MEASURED DEFLECTION δ (INCHES)	MEASURED LOAD F (LBS)	MODIFIED DEFLECTION δ (INCHES)	MODIFIED LOAD F (LBS)	SLOPE FOR START TO DATA POINT (LBS/INCH)	F BASED ON "m" (LBS)	NOMINAL STRESS (KSI)
1	1.8	206.9	1.800	207	N/A	207	31.8
2	1.600	177.6	1.600	178	147	181	27.8
3	1.400	148.3	1.400	148	147	156	23.9
4	1.200	126.3	1.200	126	136	130	20.0
5	1.000	104.3	1.000	104	128	104	16.0
6	0.800	75	0.800	75	129	79	12.1
7	0.600	53	0.600	53	127	53	8.1
8	0.400	23.8	0.400	24	128	27	4.2
9	0.200	0	0.200	0	128	2	0.3
10							
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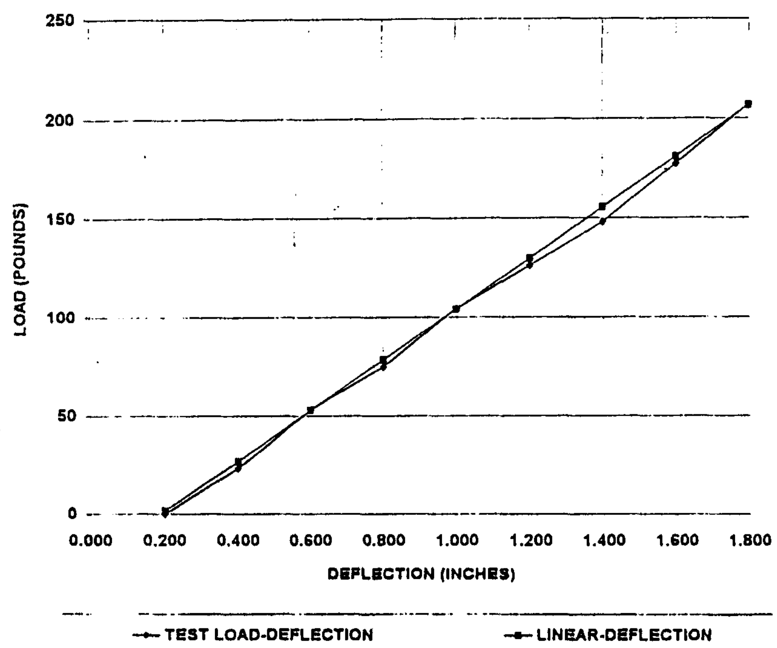
25							

NOTES:

POSITIVE LOAD - UNLOADING CONDITION



TEST #: UNREINFORCED BRANCH-D **TYPE:** FATIGUE - LOAD DEFLECTION CURVE

F = Fo + m δ "m" TO BE BASED ON N DATA POINTS, N = 6

THE VALUE OF "m" = 103 Fo (LBS) = 0

NOMINAL STRESS = M/Z KSI, M=F x L, L(IN) = 48.5 $Z(IN^3) = \pi r_m^2 t$ = 0.303

DATA POINT #	MEASURED DEFLECTION δ (INCHES)	MEASURED LOAD F (LBS)	MODIFIED DEFLECTION δ (INCHES)	MODIFIED LOAD F (LBS)	SLOPE FOR START TO DATA POINT (LBS/INCH)	F BASED ON "m" (LBS)	NOMINAL STRESS (KSI)
1	0.200	0	0.200	0	N/A	0	0.0
2	0.000	-20.200	0.000	-20	101	-21	-3.2
3	-0.200	-42.100	-0.200	-42	105	-41	-6.3
4	-0.400	-64.100	-0.400	-64	107	-62	-9.5
5	-0.600	-86.100	-0.600	-86	108	-83	-12.7
6	-0.800	-100.700	-0.800	-101	103	-103	-15.9
7	-1.000	-122.700	-1.000	-123	102	-124	-19.0
8	-1.100	-130.000	-1.100	-130	101	-134	-20.6
9	-1.200	-137.400	-1.200	-137	99	-145	-22.2
10	-1.300	-144.700	-1.300	-145	98	-155	-23.8
11	-1.400	-152.000	-1.400	-152	98	-165	-25.4
12	-1.500	-159.300	-1.500	-159	94	-176	-27.0
13							
14							
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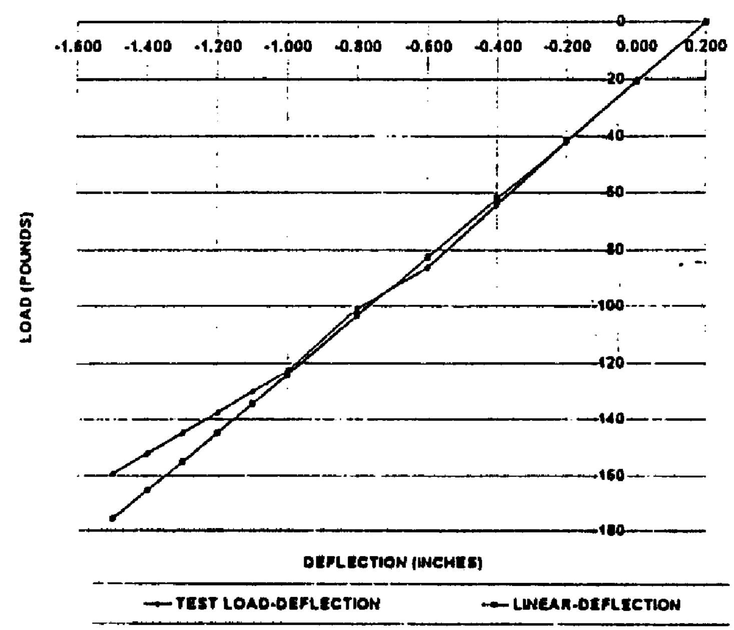
NOTES:

NEGATIVE LOAD - LOADING CONDITION



TEST #: UNREINFORCED BRANCH-D TYPE: FATIGUE - LOAD DEFLECTION CURVE

$F = Fo + m\,\delta$ "m" TO BE BASED ON N DATA POINTS, N = 2
THE VALUE OF "m" = 122 Fo (LBS) = 17

NOMINAL STRESS = M/Z KSI, M=F x L, L(IN) = 46.5 $Z(IN^3) = \pi r_n^2 t =$ 0.303

DATA POINT	MEASURED DEFLECTION	LOAD	MODIFIED DEFLECTION	LOAD	SLOPE FOR START TO DATA POINT	F BASED ON "m"	NOMINAL STRESS
	δ	F	δ	F			
#	(INCHES)	(LBS)	(INCHES)	(LBS)	(LBS/INCH)	(LBS)	(KSI)
1	-1.500	-159.300	-1.5	-159.3	124	-154	-23.6
2	-1.300	-130	-1.3	-130	122	-130	-19.9
3	-1.100	-108.1	-1.1	-108.1	121	-105	-16.2
4	-0.900	-78.8	-0.9	-78.8	117	-81	-12.4
5	-0.700	-56.8	-0.7	-56.8	117	-57	-8.7
6	-0.500	-27.5	-0.5	-27.5	110	-32	-4.9
7	-0.300	-12.8	-0.3	-12.8	147	-8	-1.2
8	-0.100	16.5	-0.1	16.5	N/A	17	2.5
9							
10							
11							
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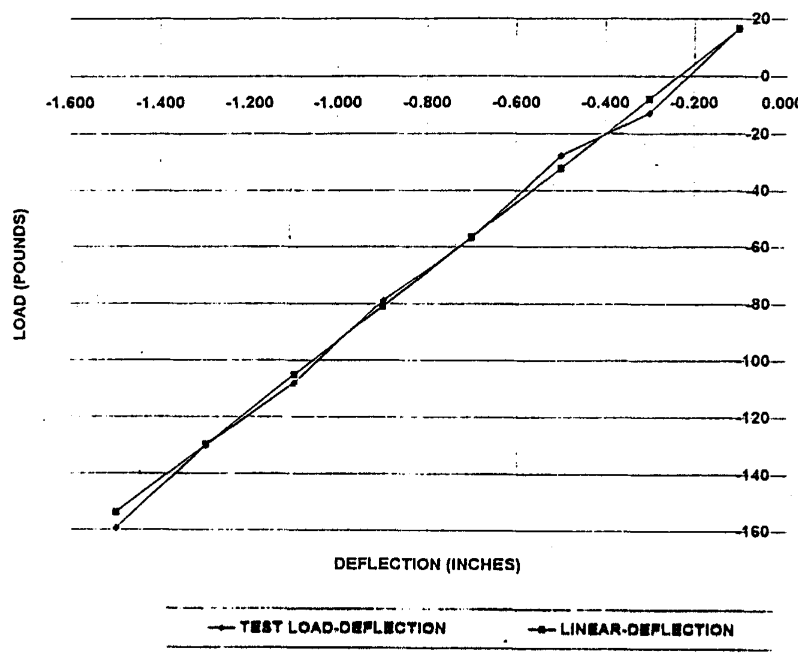
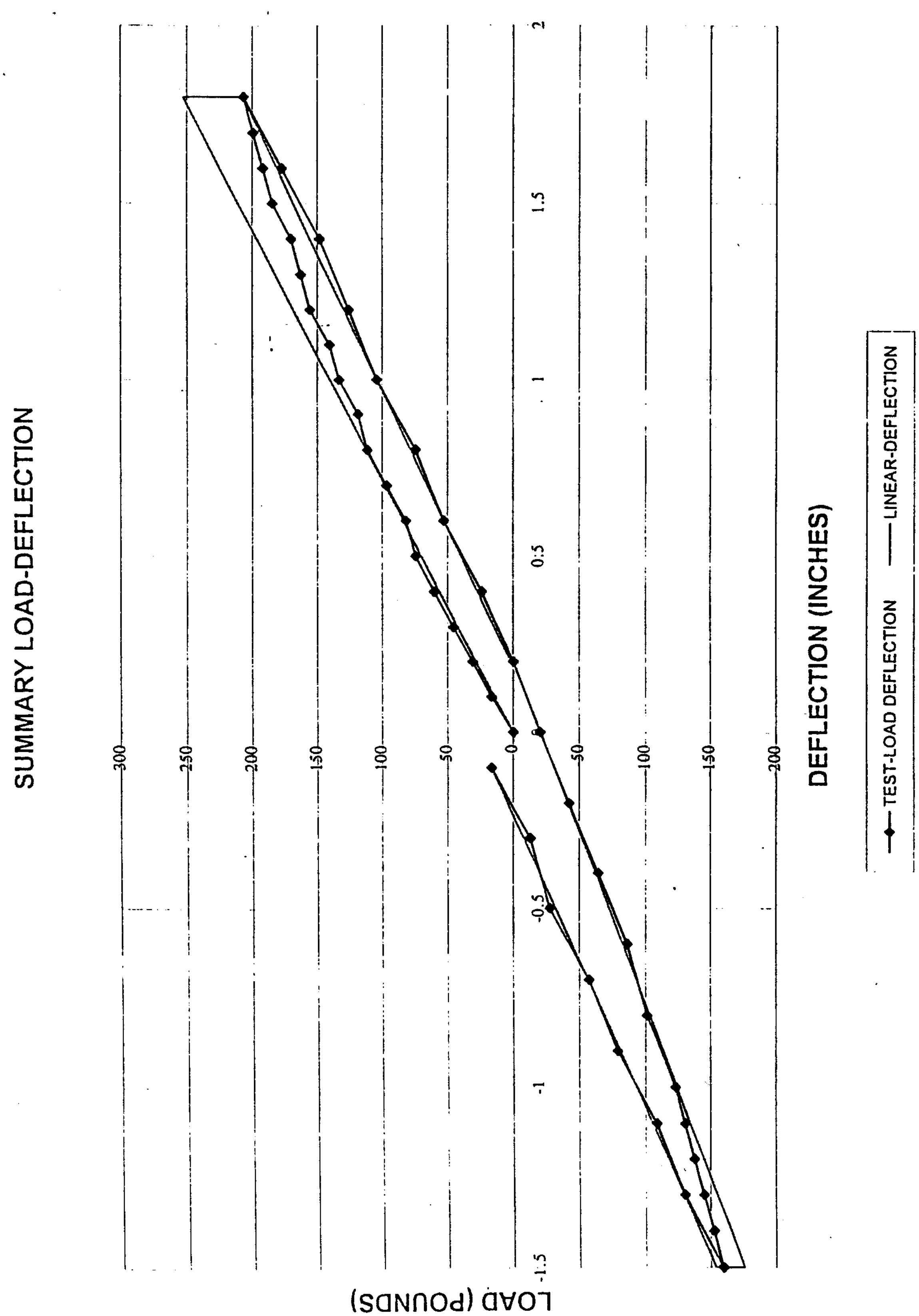
NOTES:

NEGATIVE LOAD - UNLOADING CONDITION




SUMMARY LOAD-DEFLECTION
DEFLECTION (INCHES)
LOAD (POUNDS)
TEST-LOAD DEFLECTION
LINEAR-DEFLECTION
300
250
200
150
100
50
0
50
100
150
200
-1.5
-1
-0.5
0
0.5
1
1.5
2

FATIGUE TEST DATA ANALYSIS

TEST #: **UNREINFORCED BRANCH-D**

COMPONENT: UNREINFORCED BRANCH CONNECTION

STIFFNESS (lbs/in) = 123 MOMENT ARM (in)=.46.5

D (in) = 2.5 t (in) = 0.065 $Z(IN^3) = \pi r_n^2 t =$ 0.303

TEST DISPLACEMENT/CYCLE DATA:

CONDITION #	DISPLACEMENT AMPLITUDE (+/-) (in.) δ_i	EFFECTIVE APPLIED LOAD (lbs)	NOMINAL STRESS (+/-) (psi) S	NUMBER OF TEST CYCLES N_i
1	0.75	93	14,223	1,816
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:	1,816

THE EQUIVALENT NUMBER OF CYCLES, BASED ON A DISPLACEMENT: $\delta_{max} =$ 0.8 INCHES

IS: $N_{eq} = SUM(\delta_i/\delta_{max})^5 * N_i = 1{,}816$

FOR MEASURED DIMENSIONS: $i = 245{,}000 * N_{eq}^{(-0.2)}/S =$ **3.840**

FOR NOMINAL DIMENSIONS: $Z(IN^3) =$ 0.303 i = **3.836**

COMMENTS:

1. Failure occured at top of branch at the end of the weld. Very slow growing crack.
2. Stand pipe 19.5 Inches long.
3. Moment arm =46.5 inches.

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