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Stress Indices for Straight Pipe with Trunnion Attachments

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Technical Report

Stress Indices for Straight Pipe with Trunnion Attachments

TR-110162

Final Report
October 1998

Prepared for
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Palo Alto, California 94304

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This report describes research sponsored by EPRI. The report is a corporate document that should be cited in the literature in the following manner:

Stress Indices for Straight Pipe with Trunnion Attachments, EPRI, Palo Alto, CA: 1998. TR-110162.

REPORT SUMMARY

This report provides equations based on experimental and test data for determining B and C stress indices and the flexibility factor, k, for straight pipe with trunnions (or hollow circular cross-section welded attachments). The report contains explicit modifications to ASME Code Cases 391 and 392 for qualification of trunnions on pipe. It also provides flexibility equations for a more accurate evaluation of these configurations.

Background

Fatigue is a significant consideration in the design and engineering of piping systems. The ASME Section III Code uses factors such as C_2 and K_2 indices to account for fatigue effects produced by reversing loads and the k flexibility factors for evaluation of piping configurations. ASME Code Cases 391 and 392 provide procedures for evaluating the design of trunnion attachments on Classes 1, 2, and 3 pipe.

Objectives

- To derive expressions for B_2, C_2, K_2, and k factors for trunnions on straight pipe.
- To provide modifications to Code Cases 391 and 392 for improved evaluation of trunnions on straight pipe.

Approach

A review of the present approach for evaluation of trunnions on pipe in accordance with the Code provided an understanding of the conservatism in determining the fatigue 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. The present values of A_o, B, and C in Code Cases 391 and 392 were modified as a result of this research and analysis. Equations and parameter limitations were derived for the determination of flexibility factors.

Results

The report summarizes: the available literature in Section 2; the test program in Section 3; the analysis of other test data in Section 4; the comparison to Code Case results in Section 5; the finite element analysis (FEA) investigation of flexibility in Section 6; and the results of the investigation of straight pipe with trunnion attachments in Section 7.

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, root cause failures, and the evaluation of remaining fatigue life of plant designs. The work being conducted under EPRI's stress intensification factor (SIF) optimization program continues to establish the technical justification to all for reductions in current Code stress indices. These reductions and associated reductions in design stresses can provide a basis to reduce the scope of on-going pressure boundary component testing and inspection programs for operating nuclear power plants. Examples include reductions in both the inspection scope of postulated high- and moderate-energy line break locations and snubber testing.

TR-110162

Interest Categories

Piping, reactor vessels, and internals

ABSTRACT

This report was prepared under the auspices of the EPRI project on stress intensification factor (SIF) optimization. SIFs and stress indices are used in the qualification of piping components to ensure that they have an adequate fatigue life under cyclic loading. They are also used for qualification of other loading conditions. In some cases, such as trunnions, stress indices are used in lieu of SIFs.

Generally, trunnions are used on straight pipe as supports; however, they are also used as anchors. The qualification of trunnions is a major concern in the design and qualification of many piping systems. This report presents the results of an investigation of the stress indices and flexibility factors for trunnions on straight pipe subject to bending and twisting moments. The report also reviews existing data and methodologies used for qualification of trunnions. Modified expressions for stress indices are defined, and the results of new testing are included. Finally, flexibility factors are presented for accurately modeling the behavior of a trunnion in a piping system. The information presented in this report should significantly improve the qualification of trunnions on straight pipe.

ACKNOWLEDGMENTS

EPRI expresses appreciation to Edward A. Wais, Royce M. Reinecke, and Everett C. Rodabaugh of Wais and Associates, Incorporated for their assistance in preparing this report.

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1

INTRODUCTION

This report was prepared under the auspices of the EPRI project RP-3921 on stress intensification factor (SIF) optimization. SIFs are used to ensure that piping has an adequate fatigue life under cyclic loading. SIFs are not used explicitly for design of trunnion / pipe configurations; however, the approach is the same.

This report specifically investigates the fatigue behavior of trunnions welded on straight pipe with full penetration welds. Trunnions are used on pipe as pipe supports. They are also referred to as “hollow circular cross-section attachments.”

Trunnions on straight pipe are very similar to unreinforced branch connections. The difference is that there is no opening in the “run” pipe. As such, they are among the most complex of piping components for evaluation. Stress concentration occurs at or near the intersection of the trunnion and pipe similar to branch connections.

The general approach followed in this report is:

1. Review the present approach used for evaluation in accordance with the ASME Code.

2. Perform a literature search on the applicable references.

3. Perform tests, as required, and analyze the results.

4. Develop an updated approach to evaluate the trunnion / pipe configuration using the test data and analysis.

Section 2 of this report summarizes the present Code approaches to addressing trunnions on pipe [1,2]. The approach for Section III is in terms of two Code Cases; one for Class 1 piping, and one for Classes 2 and 3 piping [1,3,4]. The background of the Code Cases is provided. Other references are also discussed.

Section 3 of this report presents the results of fatigue tests on trunnions on straight pipe, conducted under the auspices of the EPRI research project. The test results are used to derive experimentally based expressions for the various indices. Section 4 provides an analysis of test data for use in determining B indices. Section 5 provides a comparison of test data to evaluation methods as presented in Code Case N-391-2 [3]. The flexibility of this assembly is covered in Section 6.

Section 7 of this report summarizes the conclusions of the research effort. These conclusions provide new understanding of the behavior of trunnions and allows the user to more accurately evaluate trunnions on straight pipe.

2

BACKGROUND

Nomenclature

Figure 2-1 shows the configuration and applied moments for evaluation of stress indices for straight pipe with trunnion attachments. The nomenclature includes terminology used in the body of this report and the associated appendices.

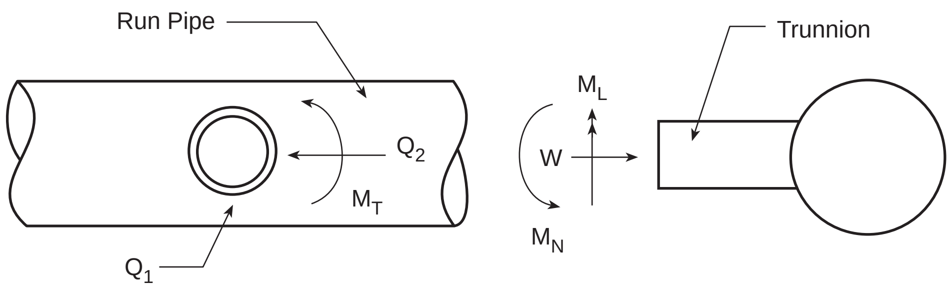

Figure 2-1
Trunnion/Pipe Connection

R_o = run pipe outside radius, inch (in.)
r_o = trunnion outside radius, in.
r_i = trunnion inside radius, in.
T = nominal run pipe wall thickness, in.
t = nominal trunnion wall thickness, in.
$D = D_o - T$
$d = d_o - t$
D_o = outside diameter of the run pipe, in.
d_o = outside diameter of the trunnion, in.
R_m = mean radius of run pipe, in.
$A_T = \pi (r_o^2 - r_i^2)$
$Z_T = I_T / r_o$
$I_p = \pi(R_o^4 - R_i^4) / 4$
$I_T = \pi / 4(r_o^4 - r_i^4)$
$A_m = \pi / 2 (r_o^2 - r_i^2)$
J_m = lesser of $\pi r_o^2 T$ or Z_T
δ = test displacement amplitude

$\gamma = R_o / T$
ϕ_{ij} = rotation at point i with respect to point j
ϕ_x, ϕ_y, ϕ_z = rotations about the x, y, or z axis
$\tau = t / T$
$\beta = d_o / D_o$
$C = A_o (2\gamma)^{n1} \beta^{n2} \tau^{n3}$, but not less than 1.0
k = test specimen stiffness
F = test k * test δ
L = length from test load point to outside diameter (OD) of specimen (in.)
N = test cycles to failure
M = F*L
Ma = $10000*[.7854*(d / 2)^2*t]$
Mb = $10000*[.7854*(D / 2)^2*T]$
M_c = range of resultant moments due to thermal expansion, inch-pounds (in.-lbs.)
M_L = bending moment applied to the trunnion, as shown in Figure 2-1, in.-lbs.
M_N = bending moment applied to the trunnion, as shown in Figure 2-1, in.-lbs.
M_T = torsional moment applied to the trunnion, as shown in Figure 2-1, in.-lbs.
Q_1 = shear load applied to the trunnion, as shown in Figure 2-1, pound (lb.)
Q_2 = shear load applied to the trunnion, as shown in Figure 2-1, lb.
W = thrust load applied to the trunnion, as shown in Figure 2-1, lb.
[These moments and loads are determined at the surface of the pipe.]
n_1, n_2, n_3 are specified in Code Cases N-391 or N-392 (See Appendix A or B.)
$C_T = 1.0$ for $\beta \leq 0.55$
$C_T = C_N$ for $\beta = 1.0$, but not less than 1.0; C_T should be linearly interpolated for $0.55<\beta<1.0$
C_L' = values of C_L based on fatigue test data
$B_W = 0.5(C_W)$, but not less than 1.0
$B_L = 0.5(C_L)$, but not less than 1.0
$B_N = 0.5(C_N)$, but not less than 1.0
$B_T = 0.5(C_T)$, but not less than 1.0
B_T' = values of B_T based on limit load test data
K_e = plasticity factor used in fatigue analysis
$K_T = 1.8$ for full penetration welds
T_T = average temperature of that portion of the trunnion within a distance of 2t from the surface of the pipe, degrees Fahrenheit (°F)
T_w = average temperature of that portion of the pipe under the attachment and within a distance of $(RT)^{0.5}$ from the edge of the attachment, °F
$E\alpha$ = modulus of elasticity, E, times the mean coefficient of thermal expansion, α, both at room temperature, pounds per square inch (psi) / °F
S_{alt} = stress amplitude (psi)
W^{**}, M_N^{**}, M_L^{**}, Q_1^{**}, Q_2^{**}, and M_T^{**} are absolute values of maximum loads occurring simultaneously under all service loading conditions

ASME Section III and B31.1 Power Piping Code Approach

The body of the present Codes, Section III and ANSI B31.1, are silent in regards to specific methodologies for qualification of trunnion / pipe configurations [1,2]. However, Section III has two Code Cases (N-391 for Class 1 piping and N-392 for Classes 2 and 3 piping) that address the evaluation of the design of trunnion attachments on straight pipe [3,4]. These Code Cases are included in Appendix A and Appendix B for reference. For simplicity, this report will refer to both of these Code Cases as the "Code Case" when discussing common items.

N-391 requires the calculation of various stresses:

$$S_{MT} = B_W W / A_T + B_N M_N / Z_T + B_L M_L / Z_T + Q_1 / A_m + Q_2 / A_m + B_T M_T / J_m \qquad \text{(Eq. 2-1)}$$

$$S_{NT} = C_W W / A_T + C_N M_N / Z_T + C_L M_L / Z_T + Q_1 / A_m$$
$$+ Q_2 / A_m + C_T M_T J_m + 1.7E\alpha \left| T_T - T_W \right| \qquad \text{(Eq. 2-2)}$$

$$S_{PT} = K_T(S_{NT}) \qquad \text{(Eq. 2-3)}$$

$$S_{NT}^{**} = C_W W^{**} / A_T + C_N M_N^{**} / Z_T + C_L M_L^{**} / Z_T$$
$$+ Q_1^{**} / A_m + Q_2^{**} / A_m + C_T M_T^{**} / J_m \qquad \text{(Eq. 2-4)}$$

N-392 has similar expressions, except that the $1.7E\alpha \left| T_T - T_W \right|$ term in Equation 2-2 is not included. The stresses calculated by these equations are used in the qualification in modified standard Code equations by the two Code Cases. This report focuses on the B and C indices.

Rodabaugh discusses the background of N-391 and N-392 and is summarized herein [5]. It should be noted that the original objective in developing these Code Cases was to provide a simplified and conservative methodology. The approach used to address the effects of the various mechanical loads (W, Q_1, Q_2, M_N, M_L, and M_T) is discussed below.

The original basis for considering the effects of the W, M_L, and M_N loads was the correlation equations given by Potvin [6]. These correlation equations were considered to correspond to the maximum primary-plus-secondary stresses ($P_L + P_b + Q$). Thus, they corresponded to the C indices of NB-3600 or C_W, C_L, and C_N of the Code Cases [1,3,4].

The form of the Code Case expression for the C indices is:

$$C = A_o(2\gamma)^{n1}\beta^{n2}\tau^{n3} \quad \text{(Eq. 2-5)}$$

where the parameters are defined by $\gamma = R_o / T$, $\beta = d_o / D_o$, and $\tau = t / T$. A_o, n1, n2, and n3 are constants that vary depending upon the loading direction. (See Appendix A or Appendix B.)

The range of the applicable parameters in the Code Cases for C_W, C_L, and C_N has been extended beyond that of Potvin [6]. The applicable range of γ and τ was extended based on Welding Research Council (WRC) Bulletin 198 and WRC Bulletin 297 [7,8]. The range of β was extended based on comparison with the equations derived by Wordsworth [9].

At the time the Code Cases were prepared, data were not available regarding shear loads and torsional moments (Q_1, Q_2, and M_T). Engineering judgment was used in the evaluation of their effects. For the shear loads (Q_1 and Q_2), the stress intensity (twice the shear stress) is Q / A_m, where A_m is one-half the cross-sectional area of the trunnion-pipe interface (where the load is taken) assumed to be $\pi(r_o^2 - r_i^2) / 2$. This is considered reasonable for small trunnions (small d_o / D_o) but is probably very conservative for large trunnions (for example, size-on-size).

The approach used to evaluate the effects of M_T was based on comparisons to data on branch connections [10]. Branch connections are similar to trunnions, except that the run pipe has an opening in it. For branch connections with small d_o / D_o, the stress intensity is about M_t / J_m. For $d_o / D_o = 1.0$, test data indicates that the maximum stress intensity is about the same as for out-of-plane bending (for example, due to M_N) [11]. Based on this information, the value of C_T was taken as 1.0 for $\beta = d_o / D_o \le 0.55$ and equal to C_N for $\beta = 1.0$. Linear interpolation is used in between. The change at $\beta = 0.55$ corresponds to Potvin's data.

Potvin originally suggested a limit on $\gamma = R_o / T \ge 8.33$. Rodabaugh provides a basis for extending that to $\gamma = R_o / T \ge 4.0$ [5]. This was based on a comparison with Wordsworth [9]. This change was made in Code Case N-392 but not in N-391; however, this extension is valid for N-391.

The B indices that are in the Code Cases correspond to those of ASME Section III, NB-3600. The B indices are based upon limit load (or moment) analysis or test. The Code Cases take the B indices as one-half the C indices. Based upon data in Rodabaugh and Kurobane, it is stated that the Code Case B indices are conservative by "a factor of at least 1.5" [5,11,12].

The approach followed by the Code Case is to calculate the stresses due to the trunnion mechanical loads (W, Q_1, Q_2, M_N, M_L, and M_T) and the thermal stresses (if Class 1 piping) and add them to the stresses in the pipe due to loads in the pipe. The stresses are added linearly and then compared to the specific limits dependent upon the piping class and the specific requirement. The linear addition of stresses is generally very conservative. It assumes that all the stresses are maximum at the same point.

Review of References

In addition to the references discussed in the preceding section, there are other references that provide additional information. Slagis, Hankinson, and Hankinson provide general discussions of the subject, including a discussion regarding jurisdictional boundaries [14,15,16].

Melworm, Sadd, Gray, and Basavaraju provide additional information regarding finite element analysis of various configurations and load applications [17,18,19,20].

As discussed earlier, the linear addition of stresses is very conservative. Gray provides such an example [19]. Using this approach, a cumulative usage factor greater than 6 was calculated. Detailed finite element analysis yielded a cumulative usage factor less than 1.0.

3

TEST PROGRAM

Purpose

The purpose of this test program was to obtain some specific data that corresponded to the test methodology followed by Markl [13]. These tests would provide data that could be used to investigate the design approach suggested by Code Cases N-391 or N-392. For simplicity, this report will refer to both of these Code Cases as the “Code Case” when discussing common items.

Methodology

Design Of Test Specimens Four specimens were manufactured by Wilson Welding Service, Incorporated, of Decatur, Georgia. The test specimens consisted of 8-inch NPS Schedule 20 A53-B pipe with a 4-inch Schedule 40 A53-B trunnion. The welds at the interface of the trunnion and pipe were normal full penetration in an as-welded condition. The test specimens were labeled A, B, C, and D. Figure 3-1 indicates the test configuration.

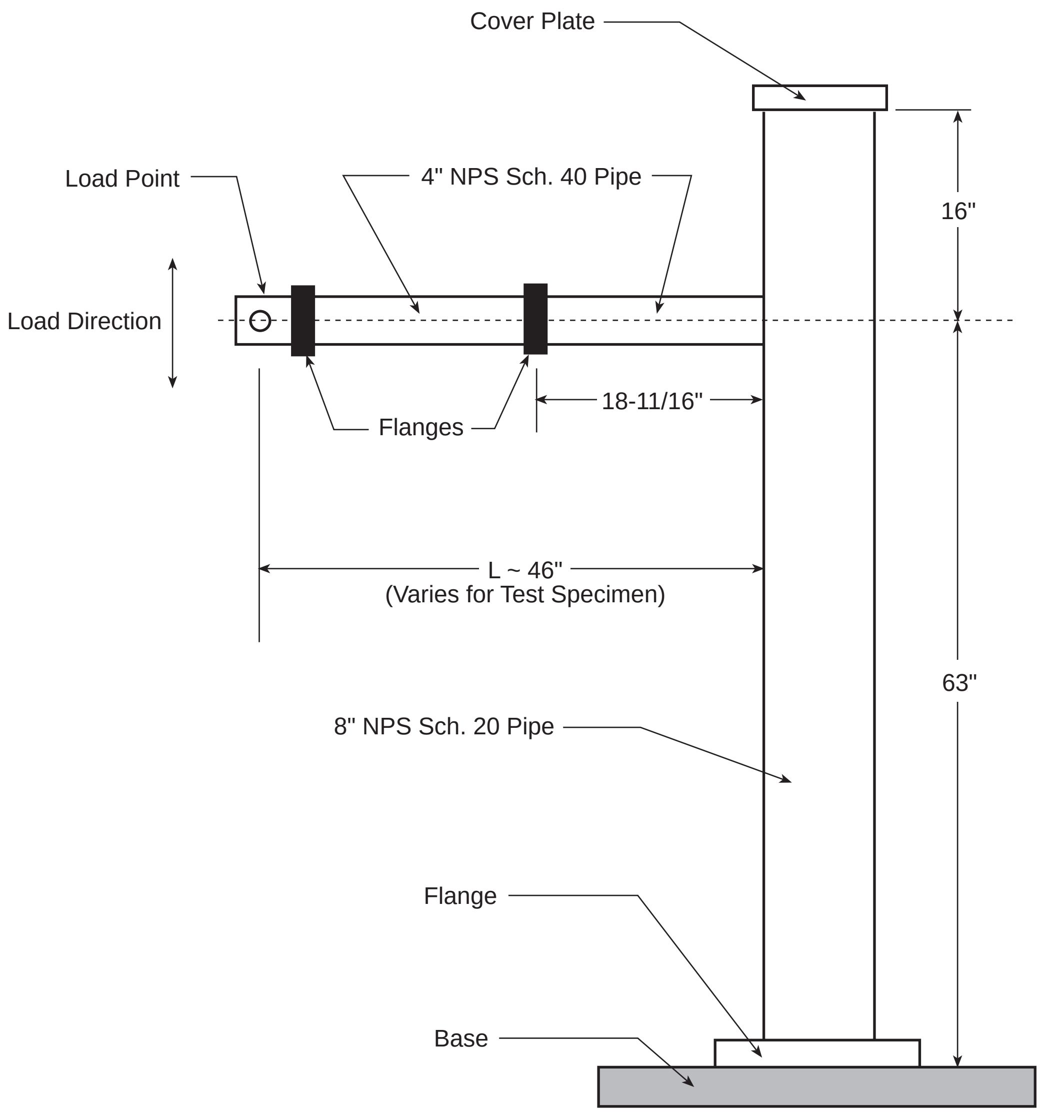

Figure 3-1
Test Configuration

Testing Program The testing was performed at The Ohio State University. The fatigue tests were performed on an MTS Systems Corporation Series 319 dynamically rated Axial/Torsional Load Frame. This unit is designed to accommodate either uniaxial or multiaxial testing. Load frame capacities are 55,000 pounds axial force and 20,000 in.-lb. torsional moment. A computerized control panel provides local, precise operations of the cross head, hydraulic grips, and actuator. The maximum actuator displacement is 6 inches. The loading pattern applied to an attached sample is controlled by programmable servovalves.

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

In these tests, the load was sinusoidal at frequencies ranging from 0.3 Hertz (Hz)–0.5 Hz. Actuator displacement was designated the test control variable. The selection of displacement as the control parameter meant that actuator movement was used by the MTS system for the feedback in the closed loop controls. This resulted in virtually identical cycles of actuator displacement being recorded throughout the duration of each test. The load resulting from the imposition of the specified displacement was measured with a fatigue-rated, 5,000 lb. capacity, tension-compression, electronic load cell manufactured by the Lebow Instrument Company. The output of this load cell was monitored continuously throughout the duration of each test.

Both load and actuator displacement were recorded using a computer program written at OSU, in LabVIEW™[1], specifically for that purpose. LabVIEW is a graphical language developed by National Instruments that allows the user to design, in software, a test control and data collection system adapted to the requirements of each experimental program. In the LabVIEW application developed for the fatigue tests, the signals from the load and displacement transducers were sampled 30 times per second, and the time histories of each were plotted on the computer screen in real time so that the progress of the test could be readily monitored. By combining the load and displacement time histories, a plot of load vs. displacement at any load cycle desired could be constructed. This, too, was done in real time so that changes in the response of the test specimen could be identified while the specimen was still undergoing loading. Any of these presentations of the test data could be printed while the test was still in progress.

Figure 3-1 shows the load application point and direction of loading. Note that the distance from the load point to the surface of the pipe (~46 inches) varies slightly for each test specimen. The measured distance (L) which is dependent on the installation is included in the test data.

The test data, results and other information are provided in Appendix 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

[1] LabVIEW is a trademark of National Instruments Corporation.

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 through-wall cracks formed and water leaked though the cracks.

Test Results Summary Table 3-1 provides a summary of the test results.

Table 3-1
Summary of Test Results

TEST	δ	k	F[1]	L[2]	Z_T	M	N	i_t[3]
	in.	lbs./in.	lbs.	in.	in.^{3}	in.-lbs.	Cycles to Failure	
A	1.05	1741	1828	46.0625	3.21	84099	500	2.700
B	0.90	1732	1559	45.50	3.21	70935	1,280	2.656
C	0.90	1702	1532	46.125	3.21	70664	934	2.839
D	0.80	1841	1473	45.50	3.21	67022	1,866	2.606

Notes: (1) $F = \delta * k$.

(2) Refer to Figure 3-1 for location of L.

(3) The value of i_t is calculated from $i_t = 245{,}000\ N^{-0.2}/S$, where N = cycles to failure and $S = M/Z_T$. Z_T is based on nominal dimensions for the trunnion.

Analysis of Test Data

There are several methods available to analyze the data. In general, for this type of loading condition, the purpose of analysis is to be able to express the results in terms of SIFs (or i-factors), B_2 indices, C_2 indices, and / or K_2 indices. As the applicable Code Cases do not use SIFs in the qualification of trunnion / pipe configurations, the focus will be on B_2, C_2, and K_2. Because the welds were full penetration welds, it is believed that the Code Case specification that $K_2 = 1.8$ is reasonable. Hence, the focus will be on B_2 and C_2. C_2 will be covered first. (Note that the Code uses the terms B_2, C_2, and K_2, and the Code Case uses subscripts that indicate direction of loading, etc.)

C Indices—Markl Approach

As discussed earlier, the tests that were performed as a part of this investigation were fatigue tests. There are two methods that can be used to evaluate the results. The first will be referred to as the Markl approach. The second is the Class 1 fatigue approach used in Class 1 analysis per NB-3600 [1]. The Markl approach will be investigated first.

The fatigue tests on the trunnion / pipe configurations followed the Markl approach [13,21]. Markl used the following expression for Grade B carbon steel:

$$iS = 245{,}000\ N^{-0.2} \qquad \text{(Eq. 3-1)}$$

where S is the nominal stress in the component and N is the number of cycles when through-wall cracks occur and water leaks. This is used as the definition of the SIF (i factor) and is used in the design for fatigue for B31.1 piping and ASME Section III Classes 2 and 3 piping [1,2].

The Code cases differ in that they use C indices (and other indices) in the evaluation of fatigue instead of SIFs [3,4]. The C indices correspond to primary-plus-secondary stresses. The C_2 indices, which are applicable to moment loading in piping, are related to the SIFs. Section NC-3672.2 provides the following equation:

$$i = C_2K_2 / 2 \qquad \text{(Eq. 3-2)}$$

This expression will be used to evaluate the value of C_2, which is used in the Code Cases [1]. The approach follows that developed in Rawls [22].

In N-392, the following equation is provided:

$$S_E = iM_c / Z + S_{PT} / 2 \qquad \text{(Eq. 3-3)}$$

and also:

$$S_{PT} = K_T\, S_{NT} \qquad \text{(Eq. 3-4)}$$

For this application, (neglecting the shear stress term, Q_2 / A, which is about 1 percent (%) of the bending stress):

$$S_{NT} = C_LM_L / Z_T \qquad \text{(Eq. 3-5)}$$

Therefore:

$$S_{PT} = K_T\, C_LM_L / Z_T \qquad \text{(Eq. 3-6)}$$

and:

$$S_E = iM_c / Z + K_T\, C_LM_L / (2Z_T) \qquad \text{(Eq. 3-7)}$$

Substituting Equation 3-2 into Equation 3-7 with $K_2 = K_T$ yields:

$$S_E = (K_T / 2)\, C_2 M / Z + (K_T / 2)\, C_L M_L / Z_T \qquad \text{(Eq. 3-8)}$$

S_E in Equation 3-8 is equivalent to the iS term in Equation 3-1. Substituting and rearranging yields:

$$C_L = \{245{,}000\ N^{-0.2}(2 / K_T) - C_2\ M / Z\}\ Z_T / M \qquad \text{(Eq. 3-9)}$$

As this C_L is derived from fatigue tests, to distinguish it from the C_L from the Code Case, it now will be called C_L'. Additionally, because $C_2 = 1.0$ for straight pipe, Equation 3-9 becomes:

$$C_L' = \{245{,}000\ N^{-0.2}(2 / K_T) - M / Z\}\ Z_T / M \qquad \text{(Eq. 3-10)}$$

C_L' is a fatigue-based value that can be compared to the value of C_L calculated from the Code Case. Table 3-2 provides this comparison.

Table 3-2
Comparison of CL to CL'

TEST	Z_T	Z	M	N	C_L [1]	K_2 [2]	C_L' [3]	C_L/C_L'
	in.^{3}	in.^{3}	in.-lbs.	Cycles to Failure				
A	3.21	13.39	84099	500	3.77	1.8	2.76	1.37
B	3.21	13.39	70935	1,280	3.77	1.8	2.71	1.39
C	3.21	13.39	70664	934	3.77	1.8	2.91	1.30
D	3.21	13.39	67022	1,866	3.77	1.8	2.65	1.42
							Average =	1.37

Notes:
1. From CC N-392, C_L = 3.77 for the pipe, 3.12 for the attachment, where the parameters for C_L are Ro/T=7.25, d_o/D_o=.522, and t/T=0.948.
2. K_2 = 1.8 for full penetration welds.
3. Calculated using Equation 3-10.

Based on this evaluation, it is apparent that the value of C_L calculated in accordance with the Code Case is conservative by about 30%.

C Indices—Class 1 Approach

The second method of evaluating the data follow the fatigue evaluation approach used for Class 1 analysis (NB-3600). Table 3-3 provides a summary of a fatigue analysis of the data using the values for the various stress indices calculated in accordance with the Code Case.

Table 3-3
Trunnion/Pipe—Class 1 CUF Evaluation Using Code Case Indices

Case	M kips	SNT ksi	C2 Mi/Z ksi	Sn ksi	3Sm ksi	Ke	SPT ksi	SP ksi	Salt ksi	N Allowable	N Failure	CUF
A	84.099	197.5	12.6	210.1	60.0	5.00	355.6	361.9	904.6	96	500	5.20
B	70.935	166.6	10.6	177.2	60.0	4.91	299.9	305.2	748.9	142	1280	9.03
C	70.664	166.0	10.6	176.5	60.0	4.88	298.8	304.0	742.6	144	934	6.47
D	67.022	157.4	10.0	167.4	60.0	4.58	283.4	288.4	660.6	184	1866	10.16
											Average =	**7.71**
												↑
Notes:	1. C_2 (pipe) =	1.0										
	2. K_2 (pipe) =	1.0										
	3. K_T (trun) =	1.8										
	4. C_L(trun) =	**3.77**	←									
	5. Z (pipe) =	13.39	in.^{3}									
	6. Z_T(trun) =	3.21	in.^{3}									
	7. $S_{NT} = C_L M_T/Z_T$, where the moment is the range.											
	8. $S_n = C_2 M_i/Z + S_{NT}$											
	9. $S_{PT} = K_T S_{NT}$											
	10. $S_P = K_2 C_2 D_o/2IM_i + S_{PT}$											
	11. Calculations are based on nominal dimensions.											
	12. Ke is the fractor for elastic-plastic analysis defined in NB-3228.5, Reference 1.											
	13. $S_{alt} = S_p K_e/2$											

The test cumulative usage factor, or CUF, is based on an allowable number of cycles from the expression:

$$N_{allowable} = (8{,}664{,}000 / (S_{alt} - 21{,}645))^2 \qquad \text{(Eq. 3-11) [26]}$$

This expression does not include the factors of safety of 2 on stress and 20 on cycles that are part of the Section III Class 1, Appendix I, S-N design curves [1]. If these were included, the calculated CUF would be much greater.

The value of S_m used was 20 kips per square inch (ksi) as specified by the Code. As indicated in Table 3-3, the CUF for the tests is, on the average, 7.99 versus a Code requirement of 1.0. This indicates that the Code is very conservative. Contributors to the conservatism could be the value of the indices and / or the value of K_e. If the Code approach to K_e is changed in the future, the values of C_L based on the Class 1 would need to be reviewed.

Table 3-4 presents the results of a fatigue analysis in which the value of C_L was varied until the average CUF = 1.00. The corresponding value of C_L was 2.36. The ratio of C_L

(Code Case) / C_L(Test) = 3.77 / 2.36 = 1.597, which indicates the Code Case is conservative by about 60%.

Table 3-4
Trunnion/Pipe—Class 1 CUF Evaluation, Average CUF = 1.0

Case	M	S_{NT}	$C_2\ M_i/Z$	S_n	$3S_m$	K_e	S_{PT}	S_P	S_{alt}	N	N	CUF
	kips	ksi	ksi	ksi	ksi		ksi	ksi	ksi	Allowable	Failure	
A	84.099	123.7	12.6	136.2	60.0	3.54	222.6	228.9	405.2	510	500	0.98
B	70.935	104.3	10.6	114.9	60.0	2.83	187.7	193.0	273.2	1186	1280	1.08
C	70.664	103.9	10.6	114.5	60.0	2.82	187.0	192.3	270.7	1209	934	0.77
D	67.022	98.5	10.0	108.6	60.0	2.62	177.4	182.4	238.8	1590	1866	1.17
											Average =	**1.00**
Notes:	1. C_2 (pipe) =	1.0										
	2. K_2 (pipe) =	1.0										
	3. K_T (trun) =	1.8										
	4. C_L(trun) =	**2.36**										
	5. Z (pipe) =	13.39	in.^{3}									
	6. Z_T(trun) =	3.21	in.^{3}									
	7. $S_{NT} = C_L M_T / Z_T$, where the moment is the range.											
	8. $S_n = C_2\ M_i/Z + S_{NT}$											
	9. $S_{PT} = K_T\ S_{NT}$											
	10. $S_P = K_2 C_2 D_o / 2I M_i + S_{PT}$											
	11. Calculations are based on nominal dimensions.											
	12. Ke is the fractor for elastic-plastic analysis defined in NB-3228.5, Reference 1.											
	13. $S_{alt} = S_p\ K_e/2$											

In this case, the value of K_e varies from 2.62 to 3.54, which reduces the potential of contribution to the overall conservatism.

B Indices—From Test Data

The Code Cases specify that the value of the Bindices be taken as one-half the value of the C indices, but not less than 1.0. It is worthwhile to determine if the data obtained in this study can be used for evaluating these indices.

The ASME Code uses limits on the primary stress intensity to limit gross plastic deformation of piping [1]. The Code has specific limits that it applies to stresses calculated using B-indices. The basic equations of the Code are modified to include the effects of the trunnions in the Code case. (Refer to Equation 2-1; the terms in Equation 2-1 can be neglected except for the term with B_L because of the loading.)

Therefore the equation reduces to:

$$S_{MT} = B_L\ M_L / Z_L \qquad \text{(Eq. 3-12)}$$

Using S_Y as the allowable stress and solving for M_L (the limit moment) yields:

$$M_L = S_Y Z_T / B_L \quad \text{(Eq. 3-13)}$$

Or rearranging:

$$B_L = S_Y Z_T / M_L \quad \text{(Eq. 3-14)}$$

As this value of B_L is based on test data, it now will be referred to as B_L' to distinguish it from the value of B_L calculated from the Code case. Hence:

$$B_L' = S_Y Z_T / M_L \quad \text{(Eq. 3-15)}$$

To determine the limit moment (or limit load) experimentally, a load-deflection curve must be developed. The limit moment is defined as when the deflection is equal to twice that predicted, assuming linear behavior. This is explained in Article II-1000, Section II-1430 of the ASME Boiler and Pressure Vessel Code, and it is shown in Figure 3-2 [1].

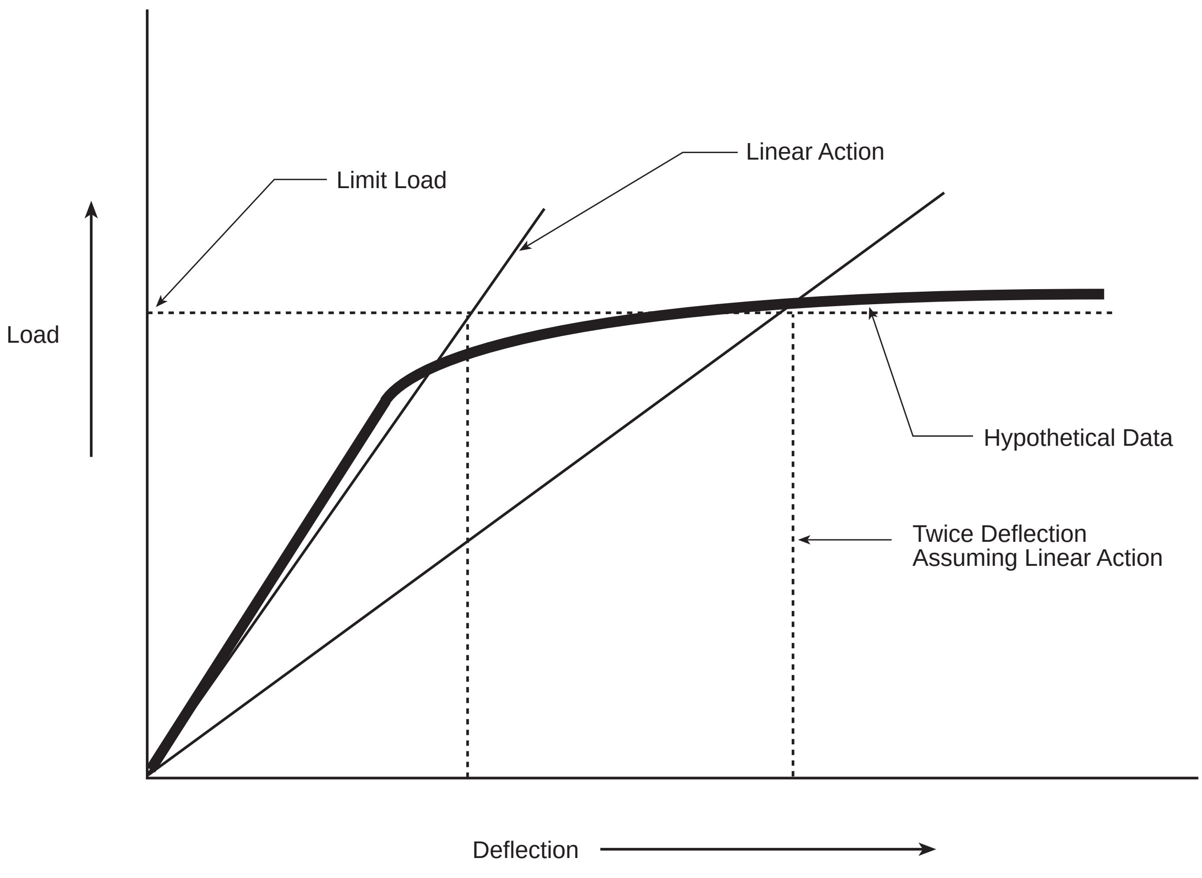

Figure 3-2
Limit Load Definition

The tests performed for this report were directed toward obtaining fatigue data rather than limit moment data. However, the data that was taken during the initial phase of the testing can be used to obtain an estimate of the limit moments.

The first phase of the tests involved determining the stiffness of the test specimen. That was determined by obtaining a load-deflection curve. (See Appendix C for curves.) The loads in these tests were taken slightly into the plastic region. As such, the maximum loads can be used to estimate the limit moment. This would be a lower limit because the deflection was not allowed to go to twice that based on elastic behavior. This maximum load will be used to investigate the value of B_L'.

A review of the curves in Appendix C shows that the specimens were loaded in both the positive and negative direction. Thus B_L' can be estimated for both directions of loading.

Table 3-5 shows the calculation of B_L' based on the maximum force used in determining the load deflection curve. As noted earlier, this force is less than the limit moment; hence, it will underpredict B_L'. Column 5 lists the values of B_L' predicted.

Table 3-5
Trunnion/Pipe—Experimental Evaluation of BL'

TEST SPECIMEN	COLUMN LOADING DIRECTION	m lb./in.	L in.	(1) Fmax lbs.	(2) M=F*L in.-lb.	(3) Z in.^{3}	(4) Sy ksi	(5) $B_L = S_yZ/M$	(6) $B_L = C_L/2$ (N-392)	(7) (6)/(5)	(8) F_{LIM}-EST	(9) $B_L = S_yZ/M$ Using (8)	(10) (6)/(9)
A	POSITIVE	1836	46.0625	2469	113,728	3.215	63.3	1.79	1.89	1.05	2850	1.55	1.22
	NEGATIVE	1566	46.0625	2650	122,066	3.215	63.3	1.67	1.89	1.13	2750	1.61	1.17
							Average for specimen A =	1.73		1.09		1.58	1.19
B	POSITIVE	1797	45.5000	3224	146,692	3.215	63.3	1.39	1.89	1.36	3500	1.28	1.48
	NEGATIVE	1495	45.5000	2560	116,480	3.215	63.3	1.75	1.89	1.08	2400	1.86	1.01
							Average for specimen B =	1.57		1.22		1.57	1.24
C	POSITIVE	1752	46.1250	1984	91,512	3.215	63.3	2.22	1.89	0.85	2450	1.80	1.05
	NEGATIVE	1473	46.1250	2117	97,647	3.215	63.3	2.08	1.89	0.90	2500	1.76	1.07
							Average for specimen C =	2.15		0.88		1.78	1.06
D	POSITIVE	1890	45.5000	2182	99,281	3.215	63.3	2.05	1.89	0.92	2700	1.66	1.14
	NEGATIVE	1766	45.5000	2409	109,610	3.215	63.3	1.86	1.89	1.02	2650	1.69	1.12
							Average for specimen D =	1.95		0.97		1.67	1.13
							Average for all specimens, both loading directions =	1.85		1.04		1.65	1.16
										↑			↑

Note that the value of S_Y is based on the material certification data provided by the test specimen manufacturer.

Column 6 lists the value of B_L calculated from the Code Case. Column 7 is the ratio of B_L / B_L'. As can be seen, this ratio is very close to 1.0. It indicates that the values of B_L (on the average) are only conservative by about 4%.

It should be noted that if S_Y was based on S_m from the Code, where $S_Y = 3/2\ S_m = 3/2\ (20) = 30$ ksi., the ratio of B_L (Code)/B_L(Test) (see Column 7) would increase to 2.19.

In order to obtain more insight into the actual value of B_L', the values of the limit moments were estimated from the load-deflection curves. This was performed by extrapolating the load-deflection curves, assuming that they would continue to follow the shape of the curves beyond the point where the loading was stopped. In other words, it was assumed that there would be no sudden change in the behavior. This is believed to be a reasonable assumption.

Column 8 lists the estimated limit moments (F_{LIM}-EST). Columns 9 lists the associated value of B_L'. Column 10 lists the ratio of B_L/B_L'. It can be seen that the ratio is 1.14 on the average. If S_Y was based on S_m from the Code, the ratio of B_L (Code)/B_L(Test) (see Column 10) would increase to 2.41.

The results will be discussed in the next section.

4

ANALYSIS OF OTHER TEST DATA FOR B INDICES

Introduction

The Code Case specifies that the various B indices be calculated as 0.5 times the corresponding C index. As indicated earlier, the tests performed under this program were not directed toward determination of the maximum collapse load that could lead to evaluating the B indices. An estimate was made, using available test data, that provided some insight into the values of B indices. However, there is additional test data available that could be used to investigate this area further. This is covered in this chapter.

References

The original data to be investigated is from Gibstein, Toprac, and the *Study on Tubular Joints Used for Marine Structures* (hereafter *Tubular Joints*) and is summarized in WRC Bulletin-256 [11,23,24,25]. The data includes dimensions, yield strengths, and the "moment at maximum load." As pointed out in WRC Bulletin-256, the exact definition of maximum load is not clear for all the test data. It could correspond to rupture, cracking, deforming beyond some limit, or the maximum load corresponding to the ultimate strength of a tensile strength test.

It is likely that the definition of "maximum load" does not exactly correspond to the Code definition of "collapse load." As discussed earlier, the Code definition of collapse load is that load when the actual deflection is twice that predicted, assuming elastic behavior. Even though the definitions may be different, the data could be helpful in this investigation.

Table 4-1 lists the data from Gibstein, Toprac, and *Tubular Joints* for in-plane bending tests [23,24,25]. The dimensional data is provided. The yield strengths are also listed (for the pipe). In general, the yield strength for the trunnion is very similar. The "moment at maximum load" is listed. The column labeled B_L' is calculated using Equation 3-15:

$$B_L' = S_Y Z_T / M_L$$

Table 4-1
Gibstein In-Plane Bending Tests (WRC Bulletin 256-Table 2)

D	d	T	t	Sy	Mt				B_L'	CC N-392	
mm.	mm.	mm.	mm.	Kg/mm2	Kg/m	T/D	d/D	t/T	$(S_Y Z_T/ML)$	C_L	B_L'/C_L
298.5	101.2	10.3	5.0	30.0	1420	.03	.34	0.485	0.732	2.73	0.268
298.5	108.2	10.0	6.3	30.0	2080	.03	.36	0.630	0.701	2.96	0.236
298.5	108.2	10.0	8.0	30.0	2580	.03	.36	0.800	0.684	3.25	0.211
219.1	71.6	6.3	18.5	32.0	840	.03	.33	2.937	1.298	10.22	0.127
219.1	71.6	8.9	18.5	43.0	1810	.04	.33	2.079	0.809	6.17	0.131
298.5	101.6	7.2	16.0	30.0	1460	.02	.34	2.222	1.650	8.92	0.185
219.1	101.6	5.5	16.0	31.1	1190	.03	.46	2.909	2.098	10.84	0.194
219.1	101.6	8.4	16.0	37.4	2630	.04	.46	1.905	1.142	5.84	0.195
219.1	101.6	10.0	16.0	37.5	3560	.05	.46	1.600	0.846	4.53	0.187
219.1	101.6	12.3	16.0	41.2	5500	.06	.46	1.301	0.601	3.35	0.180
219.1	139.7	6.0	17.5	32.0	2630	.03	.64	2.917	2.229	10.18	0.219
219.1	139.7	8.8	17.5	43.0	6000	.04	.64	1.989	1.313	5.82	0.226
219.1	139.7	12.3	17.5	40.0	9000	.06	.64	1.423	0.814	3.57	0.228
298.5	193.7	7.3	7.1	30.2	5450	.02	.65	0.973	1.038	4.24	0.245
298.5	193.7	10.0	7.1	30.0	8000	.03	.65	0.710	0.702	2.67	0.263
298.5	193.7	10.0	7.1	30.0	8730	.03	.65	0.710	0.644	2.67	0.241
219.1	177.8	5.9	16.0	32.0	4130	.03	.81	2.712	2.342	9.57	0.245
219.1	177.8	8.6	16.0	43.0	10000	.04	.81	1.860	1.300	5.52	0.235
219.1	177.8	12.5	16.0	40.0	16400	.06	.81	1.280	0.737	3.2	0.231
Toprac In-Plane Bending Tests (WRC Bulletin 256-Table 3)											
D	**d**	**T**	**t**	**Sy**	**Mt**				**B_L'**	**CC N-392**	
in.	**in.**	**in.**	**in.**	**ksi**	**in.-lbs.**	**T/D**	**d/D**	**t/T**	**$(S_Y Z_T/ML)$**	**C_L**	**B_L'/C_L**
8.66	8.66	0.279	0.279	41.2	645000	.03	1.00	1.000	0.953	3.61	0.264
8.65	8.65	0.323	0.323	26.3	560000	.04	1.00	1.000	0.796	3.31	0.241
4.51	4.51	0.231	0.231	32.5	136000	.05	1.00	1.000	0.755	2.74	0.276
8.66	8.66	0.279	0.279	41.2	772000	.03	1.00	1.000	0.796	3.61	0.220
8.65	8.65	0.300	0.300	48.2	1070000	.03	1.00	1.000	0.715	3.46	0.207
JSSC In-Plane Bending Tests (WRC Bulletin 256-Table 4)											
D	**d**	**T**	**t**	**Sy**	**Mt**				**B_L'**	**CC N-392**	
mm.	**mm.**	**mm.**	**mm.**	**Kg/mm2**	**Kg/m**	**T/D**	**d/D**	**t/T**	**$(S_Y Z_T/ML)$**	**C_L**	**B_L'/C_L**
164.5	42.7	4.7	3.3	48	215	.03	.26	0.702	0.835	3.64	0.229
166.5	76.3	4.5	2.9	48	640	.03	.46	0.644	0.887	2.87	0.309
316.9	60.5	4.4	4.4	45	340	.01	.19	1.000	1.343	6.40	0.210
316.9	139.8	4.4	4.4	45	1520	.01	.44	1.000	1.819	6.19	0.294
456.0	89.1	4.8	3.0	41	620	.01	.20	0.625	1.118	5.04	0.222
456.0	165.0	4.8	4.7	41	1840	.01	.36	0.979	2.055	7.23	0.284

The next column, labeled C_L, lists the values of the stress indices calculated using Code Case N-392. The last column lists the ratio of B_L'/C_L. The average value is 0.227.

Table 4-2 lists similar data from for out-of-plane bending [25]. The average value of B_L'/C_L is 0.207.

Table 4-2
JSSC Out-of-Plane Bending Tests (WRC Bulletin 256-Table 4)

D	d	T	t	Sy	Mt				B_L'	CC N-392	
mm.	mm.	mm.	mm.	Kg/mm2	Kg/m	T/D	d/D	t/T	$(S_Y Z_T/ML)$	C_N	B_L'/C_N
164.5	42.7	4.7	3.3	48	185	.0286	.260	0.702	0.970	4.84	0.200
166.5	76.3	4.5	2.9	48	405	.0270	.458	0.644	1.401	7.64	0.183
316.9	60.5	4.4	4.4	45	225	.0139	.191	1.000	2.029	10.36	0.196
316.9	139.8	4.4	4.4	45	675	.0139	.441	1.000	4.095	20.08	0.204
456.0	89.1	4.8	3.0	41	360	.0105	.195	0.625	1.925	9.19	0.209
456.0	165.0	4.8	4.7	41	680	.0105	.362	0.979	5.561	22.29	0.249

The data contains values of t/T, which are greater than the limit of applicability of N-392, which is $t/T \leq 1.0$. The values of B_L'/C_L, where $t/T > 1.0$, tend to be smaller than for $t/T \leq 1.0$.

Analysis of Results

As discuss earlier, the Code Case specifies that the B indices be calculated as 0.5 times the C indices. The experimental data suggests that this is conservative. Tables 4-1 and 4-2 indicate the B indices determined experimentally from Gibstein, Toprac, and *Tubular Joints* are about 0.2 times the value of the C indices calculated using the Code Case [23,24,25]. For in-plane bending, the average value of B_L'/ C_L is 0.227 for all tests. For $t/T \leq 1.0$ the ratio is 0.248; for $t/T > 1.0$, it is 0.199. For out-of-plane bending, the average value is 0.207 ($t/T \leq 1.0$).

5

COMPARISON OF TEST DATA TO CODE CASE RESULTS

Purpose

The purpose of this section is to summarize the test results and compare them to those calculated by using the Code Case.

C Indices

The analysis of the test data developed as a part of this study indicated that the values of the stress indices calculated by the Code Case are conservative. Two methods were used to evaluate this conservatism. The method referred to herein as the "C_L Indices—Markl Approach" yields a value of C_L(Code Case) / C_L(test) = 1.37. For the method referred to as the "C_L Indices—Class 1 Approach," C_L(Code Case) / C_L(test) = 1.55.

B Indices

The tests performed as a part of this study were not specifically focused on the type of testing required to provide data for experimental determination of the B indices. The data was sufficient to demonstrate that the Code Case was conservative.

Additional experimental data was available. Analysis of the data indicated that the present Code Case is conservative. This was for both in-plane and out-of-plane bending of the trunnion. Based on the experimental data, the value of the B indices is about 0.21 times the value of the C index from the Code Case. The present version of the Code Case specifies that the B indices be taken as 0.5 times the C index.

If the C indices are to be reduced by a factor of 1.4, a value of the B index of 0.3 times the new C index would correspond to the test data.

Loadings in Other Directions

The tests performed for this investigation were for in-plane bending of the trunnion. As the indices for other loading conditions, given in the Code Case, were based on the same theoretical approach (finite element analysis), it is reasonable to assume that the same degree of conservatism exists for these indices. This assumption is verified by the analysis of the B indices for out-of-plane and in-plane moments, which indicated the same degree of conservatism.

6

FINITE ELEMENT ANALYSIS (FEA) INVESTIGATION OF FLEXIBILITY OF TRUNNIONS ON STRAIGHT PIPE

General

This section discusses the flexibility of the trunnion-pipe configuration. This is important because trunnion-pipe configurations are often used as anchors in piping systems.

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

$$\phi = 1/EI \int_o^L M\,dx \qquad \text{(Eq. 6-1)}$$

where M is the bending moment. The rotation, ϕ, is in the same direction as the applied moment.

For a torsional moment, the rotation is given by

$$\phi = 1/GJ \int_o^L M\,dx = 1.3/EI \int_o^L M_T\,dx \qquad \text{(Eq. 6-2)}$$

where M_T is the torsional moment.

The flexibility of the trunnion connection will be investigated. For configurations such as branch connections, or trunnions, the flexibility or rotation is due to local deformations in the area of intersection.

There are several possible ways to model the trunnion / pipe connection. Figure 6-1 indicates one possible model. A rigid link is used to connect point A to point B. At point B, a point spring is used to represent the local flexibility of the connection. This is similar to the standard model for branch connections, which includes the local flexibility of the connection. A rigid link is an element with infinite stiffness; the deflections (including rotations) are the same at both ends of the link.

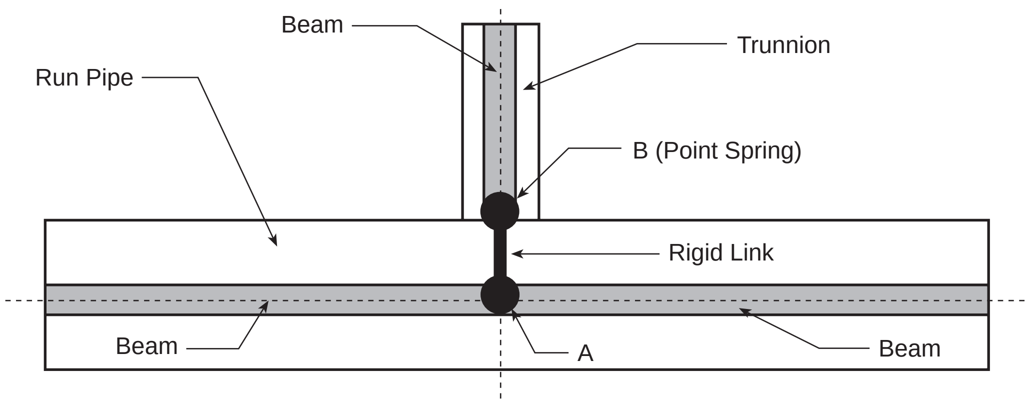

Figure 6-1
Trunnion-Pipe Modeling

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

$$\phi = k\, M\, d_o / EI_t \qquad \text{(Eq. 6-3)}$$

where I_t is the section modulus of the trunnion. Then k is equivalent to the number of trunnion diameters that would be added to represent the local flexibility.

The flexibility factor for the spring will be calculated by

$$k = (\phi_{fea} - \phi_b) / (M d_o / I_t) \qquad \text{(Eq. 6-4)}$$

where ϕ_{fea} is the rotation from the finite element analysis (FEA) and ϕ_b is the rotation from the beam model. This will be discussed in more detail later.

Finite Element Analysis

The general layout for the FEA models is shown in Figure 6-2. Normally, straight sections of pipe (or trunnion) approximately equal to 2 diameters are used in the models. COSMOS / M®[2] version 1.75 from Structural Research and Analysis Corporation was used. Shell elements were used in the models, which usually consisted of approximately 7,000 elements. A typical model is shown in Figure 6-3. The ends of the pipe and trunnion sections are connected to rigid links.

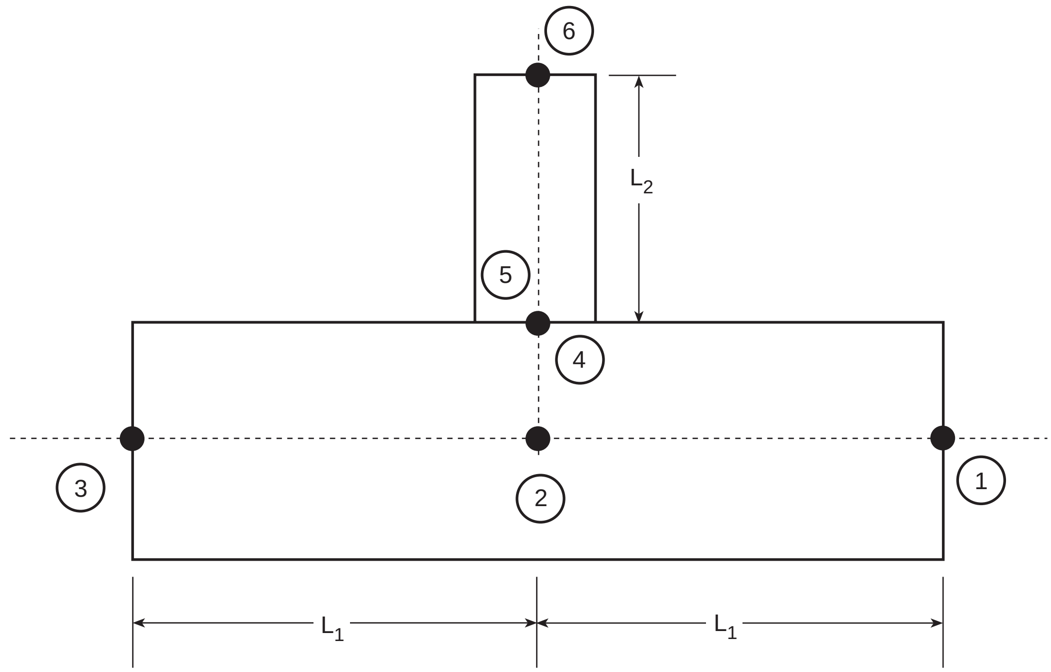

Figure 6-2
FEA Model

[2] COSMOS / M is a registered trademark of Structural Research and Analysis Corporation.

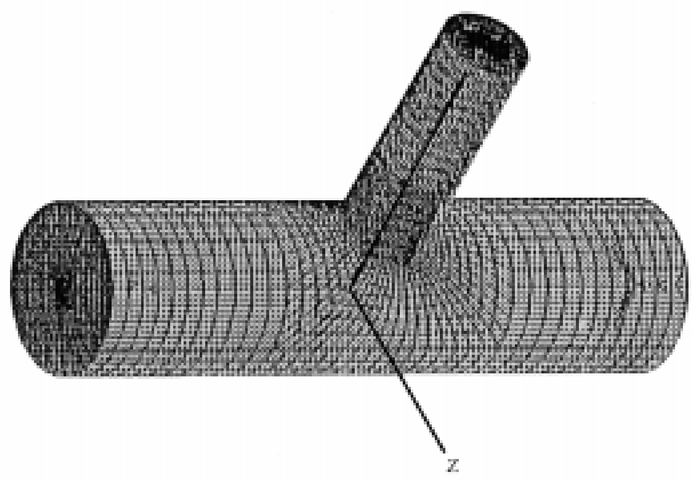

Figure 6-3
Typical FEA Model

The material properties used in the analyses are E = 30E6, G = 12E6, and μ = 0.28.

For evaluation of the flexibility of the configuration, several loading conditions were used. The local rotation at the juncture of the pipe and the trunnion is somewhat dependent on the boundary conditions at the ends of the pipe (points 1 and 3). 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 other 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 straight 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 one end of the model (point 1) was fixed, and the other end (point 3) was free; the loads were applied at the end of the trunnion (point 6) and the free end of the pipe (point 3). In the second case, both ends of the pipe (points 1 and 3) were fixed, and the loads were applied at the end of the trunnion (point 6). The flexibility factors are based on the average of the results. The significance of the boundary conditions will be determined.

The 22 models are listed in Table 6-1, along with the dimensions. Other pertinent data is also included in Table 6-1. The cases listed are representative of actual usage. As an example, it is not expected that a very small trunnion would be used on a large pipe (small d / D). Table 6-1 includes the moments used in the FEA, which are based on a nominal 10 ksi stress in the pipe or trunnion.

Table 6-1
FEA Models

Model	D_o (in.)	T (in.)	d_o (in.)	t (in.)	d_o/D_o	t/T	D_o/T	d_o/t	D (in.)	d (in.)	D/T	d/D	d/t	M_a (in.-lbs.)	M_b (in.-lbs.)	I_p (in^4)	I_t (in^4)	L_1 (in.)	L_2 (in.)
TS1	8.625	0.250	4.50	0.237	0.522	0.948	34.5	19.0	8.375	4.263	33.5	0.51	18.0	33827	137721	57.7	7.2	19.50	15.19
TS2	12.75	0.375	4.50	0.237	0.353	0.632	34.0	19.0	12.375	4.263	33.0	0.34	18.0	33827	451036	279.3	7.2	19.50	13.13
TS3	12.75	0.375	10.75	0.365	0.843	0.973	34.0	29.5	12.375	10.385	33.0	0.84	28.5	309169	451036	279.3	160.7	19.50	13.13
TS4	12.75	0.375	10.75	0.594	0.843	1.584	34.0	18.1	12.375	10.156	33.0	0.82	17.1	481195	451036	279.3	245.2	19.50	13.13
T1	10.00	0.500	5.00	0.250	0.500	0.500	20.0	20.0	9.500	4.750	19.0	0.50	19.0	44301	354411	168.8	10.6	19.50	14.50
T2	10.00	0.500	7.50	0.375	0.750	0.750	20.0	20.0	9.500	7.125	19.0	0.75	19.0	149517	354411	168.8	53.4	19.50	14.50
T3	10.00	0.500	8.50	0.425	0.850	0.850	20.0	20.0	9.500	8.075	19.0	0.85	19.0	217652	354411	168.8	88.1	19.50	14.50
T4	10.00	0.500	5.00	0.500	0.500	1.000	20.0	10.0	9.500	4.500	19.0	0.47	9.0	79521	354411	168.8	18.1	19.50	14.50
T5	10.00	0.500	7.50	0.750	0.750	1.500	20.0	10.0	9.500	6.750	19.0	0.71	9.0	268385	354411	168.8	91.7	19.50	14.50
T6	10.00	0.500	8.50	0.850	0.850	1.700	20.0	10.0	9.500	7.650	19.0	0.81	9.0	390689	354411	168.8	151.3	19.50	14.50
T7	10.00	0.333	5.00	0.167	0.500	0.500	30.0	30.0	9.667	4.833	29.0	0.50	29.0	30580	244637	118.4	7.4	19.50	14.50
T8	10.00	0.333	7.50	0.250	0.750	0.750	30.0	30.0	9.667	7.250	29.0	0.75	29.0	103206	244637	118.4	37.5	19.50	14.50
T9	10.00	0.333	8.50	0.283	0.850	0.850	30.0	30.0	9.667	8.217	29.0	0.85	29.0	150238	244637	118.4	61.8	19.50	14.50
T10	10.00	0.333	5.00	0.333	0.500	1.000	30.0	15.0	9.667	4.667	29.0	0.48	14.0	57014	244637	118.4	13.4	19.50	14.50
T11	10.00	0.333	7.50	0.500	0.750	1.500	30.0	15.0	9.667	7.000	29.0	0.72	14.0	192422	244637	118.4	67.7	19.50	14.50
T12	10.00	0.333	8.50	0.567	0.850	1.700	30.0	15.0	9.667	7.933	29.0	0.82	14.0	280110	244637	118.4	111.7	19.50	14.50
T13	10.00	0.200	5.00	0.100	0.500	0.500	50.0	50.0	9.800	4.900	49.0	0.50	49.0	18857	150859	74.0	4.6	19.50	14.50
T14	10.00	0.200	7.50	0.150	0.750	0.750	50.0	50.0	9.800	7.350	49.0	0.75	49.0	63644	150859	74.0	23.4	19.50	14.50
T15	10.00	0.200	8.50	0.170	0.850	0.850	50.0	50.0	9.800	8.330	49.0	0.85	49.0	92646	150859	74.0	38.6	19.50	14.50
T16	10.00	0.200	5.00	0.200	0.500	1.000	50.0	25.0	9.800	4.800	49.0	0.49	24.0	36191	150859	74.0	8.7	19.50	14.50
T17	10.00	0.200	7.50	0.300	0.750	1.500	50.0	25.0	9.800	7.200	49.0	0.73	24.0	122145	150859	74.0	44.0	19.50	14.50
T18	10.00	0.200	8.50	0.340	0.850	1.700	50.0	25.0	9.800	8.160	49.0	0.83	24.0	177807	150859	74.0	72.7	19.50	14.50

NOTES:

1. See Figure 6-3 for definition of L_1 and L_2.
2. The moments, M_a and M_b, are based on a nominal stress of 10 ksi in the pipe or trunnion, assuming an approximate section modulus of p x mean radius^2 x thickness.
   The values of k are independent of M_a or M_b.

FEA Results

Table 6-2 lists the rotations at the indicated points for the specific load cases. These rotations were taken directly from the FEA output and can be considered the rotation with respect to a fixed point. Table 6-2 and the following tables refer to ϕ_x, ϕ_y, and ϕ_z. These represent, respectively, the rotations around the x-, y-, and z-axes. The x-axis is along the centerline of the trunnion; the y-axis is along the centerline of the pipe, and the z-axis is perpendicular to x and y. The results are discussed in the following sections.

Table 6-2
Summary of Rotations for Point 6—One End of Pipe Fixed

	In-Plane Moment on Trunnion	Out-of-Plane Moment on Trunnion	Torsion Moment on Trunnion	In-Plane Moment on Pipe	Out-of-Plane Moment on Pipe	Torsion Moment on Pipe
Case	**1**	**2**	**3**	**4**	**5**	**6**
Model	f_Z	f_Y	f_X	f_Z	f_X	f_Y
TS1	6.15E-03	1.68E-02	3.99E-03	1.55E-03	1.55E-03	2.03E-03
TS2	4.64E-03	9.25E-03	3.04E-03	1.05E-03	1.05E-03	1.38E-03
TS3	3.44E-03	7.53E-03	2.34E-03	1.04E-03	1.04E-03	1.36E-03
TS4	4.81E-03	1.11E-02	2.96E-03	1.04E-03	1.04E-03	1.36E-03
T1	3.46E-03	5.61E-03	3.11E-03	1.36E-03	1.37E-03	1.79E-03
T2	3.34E-03	6.11E-03	2.78E-03	1.36E-03	1.36E-03	1.78E-03
T3	3.44E-03	5.97E-03	2.89E-03	1.36E-03	1.36E-03	1.77E-03
T4	4.66E-03	8.36E-03	3.54E-03	1.36E-03	1.37E-03	1.79E-03
T5	4.99E-03	9.87E-03	3.57E-03	1.35E-03	1.36E-03	1.78E-03
T6	5.29E-03	9.89E-03	3.91E-03	1.34E-03	1.36E-03	1.77E-03
T7	3.84E-03	8.03E-03	3.08E-03	1.34E-02	1.35E-03	1.76E-03
T8	3.65E-03	8.47E-03	2.77E-03	1.34E-03	1.34E-03	1.76E-03
T9	3.70E-03	7.95E-03	2.88E-03	1.34E-03	1.34E-03	1.75E-03
T10	5.35E-03	1.26E-02	3.47E-03	1.34E-03	1.35E-03	1.76E-03
T11	5.59E-03	1.42E-02	3.57E-03	1.33E-03	1.34E-03	1.75E-03
T12	5.82E-03	1.36E-02	3.93E-03	1.33E-03	1.34E-03	1.74E-03
T13	4.48E-03	1.31E-02	3.06E-03	1.33E-03	1.33E-03	1.74E-03
T14	4.16E-03	1.25E-02	2.76E-03	1.32E-03	1.33E-03	1.74E-03
T15	4.12E-03	1.11E-02	2.87E-03	1.32E-03	1.33E-03	1.73E-03
T16	6.55E-03	2.16E-02	3.44E-03	1.32E-03	1.33E-03	1.74E-03
T17	6.52E-03	2.17E-02	3.59E-03	1.32E-03	1.33E-03	1.73E-03
T18	6.57E-03	1.95E-02	3.96E-03	1.32E-03	1.32E-03	1.73E-03

Notes:
1. Loads on the trunnion were applied at point 6 (Figure 6-2).
2. Loads on the pipe were applied at point 3 (Figure 6-2).

Table 6-2 indicates that the trunnion does not affect the rotations of the pipe for loads applied at the end of the pipe. This is seen by reviewing models T1–T18, where the pipe is the same size and the size of the trunnion is changed.

Figure 6-2 shows the model to be used as the basis of the evaluation of the flexibility of the trunnion. A rigid link is included in the model from the centerline 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 6-2 will be used as the basis of evaluating the FEA results for loads on the trunnion. The rotation at the end of the trunnion (point 6), with respect to the fixed point 1, is given by

$$\phi_6 = \phi_{6\text{-}5} + \phi_{5\text{-}4} + \phi_{4\text{-}2} + \phi_{2\text{-}1} \qquad \text{(Eq. 6-5)}$$

where $\phi_{i\text{-}j}$ is the rotation of point "i" with respect to point "j," and ϕ_6 is the rotation of the end of the trunnion (see Figure 6-2). Note that for in-plane bending:

$$\phi_{6\text{-}5} = ML_2 / (EI_t) \qquad \text{(Eq. 6-6)}$$

$\phi_{5\text{-}4} = k\ Md_o / (EI_t)$ point spring (from Equation 6-3)

$\phi_{4\text{-}2} = 0$ (because this is the rotation over a rigid link)

$$\phi_{2\text{-}1} = ML_1 / (EI_p) \qquad \text{(Eq. 6-7)}$$

Replacing ϕ_6 with ϕ_{fea}, and rearranging yields:

$$k = 1 / (Md_o / (EI_t))\ [\phi_{fea} - \phi_{6\text{-}5} - \phi_{4\text{-}2} - \phi_{2\text{-}1}] \qquad \text{(Eq. 6-8)}$$

For torsion of the trunnion, Equation 6-6 is replaced by:

$$\phi_{6\text{-}5} = 1.3\ ML_2 / (EI_t) \qquad \text{(Eq. 6-9)}$$

For out-of-plane bending of the trunnion because the segment of the beam model from point 1 to point 2 is in torsion, Equation 6-7 is replaced by

$$\phi_{2\text{-}1} = 1.3\ ML_1 / (EI_p) \qquad \text{(Eq. 6-10)}$$

As discussed earlier, the FEA was performed with two sets of boundary conditions, fixed at one pipe end (point 1) and fixed at both ends (points 1 and 3). When fixed at both of the pipe ends, for in-plane moments or torsion on the trunnion, Equation 6-7 is replaced by:

$$\phi_{2\text{-}1} = ML_1 / (8EI_p) \qquad \text{(Eq. 6-11)}$$

For out-of-plane moments, Equation 6-7 is replaced by:

$$\phi_{2\text{-}1} = 1.3\ ML_1 / (2EI_p) \qquad \text{(Eq. 6-12)}$$

Table 6-3 lists the values of k for in-plane bending, out-of-plane bending, and torsion for the case with only one end fixed. For in-plane bending, the values of k range from 1.79 to 6.09. For out-of-plane bending, the values are larger with a maximum of about 27. For torsion, the values are smaller with a range of 0.43 to 1.24.

Table 6-3
Bending of the Trunnion—One Pipe End Fixed

				In-Plane Moment on Trunnion		Out-of-Plane Moment on Trunnion		Torsion Moment on Trunnion	
Model	**D/T**	**d/D**	**d/t**	ϕ_Z	**k**	ϕ_Y	**k**	ϕ_X	**k**
TS1	33.5	0.509	18.0	6.15E-03	4.85	1.68E-02	19.79	3.99E-03	0.761
TS2	33.0	0.344	18.0	4.64E-03	3.58	9.25E-03	10.12	3.04E-03	0.429
TS3	33.0	0.839	28.5	3.44E-03	2.72	7.53E-03	8.34	2.34E-03	0.764
TS4	33.0	0.821	17.1	4.81E-03	4.03	1.11E-02	12.52	2.96E-03	1.032
T1	19.0	0.500	19.0	3.46E-03	1.79	5.61E-03	4.80	3.11E-03	0.435
T2	19.0	0.750	19.0	3.34E-03	2.02	6.11E-03	5.73	2.78E-03	0.636
T3	19.0	0.850	19.0	3.44E-03	2.01	5.97E-03	5.26	2.89E-03	0.712
T4	19.0	0.474	9.0	4.66E-03	3.04	8.36E-03	7.98	3.54E-03	0.650
T5	19.0	0.711	9.0	4.99E-03	3.47	9.87E-03	9.72	3.57E-03	0.957
T6	19.0	0.805	9.0	5.29E-03	3.46	9.89E-03	9.13	3.91E-03	1.066
T7	29.0	0.500	29.0	3.84E-03	2.43	8.03E-03	8.45	3.08E-03	0.453
T8	29.0	0.750	29.0	3.65E-03	2.55	8.47E-03	9.29	2.77E-03	0.678
T9	29.0	0.850	29.0	3.70E-03	2.47	7.95E-03	8.28	2.88E-03	0.760
T10	29.0	0.483	14.0	5.35E-03	4.19	1.26E-02	14.30	3.47E-03	0.678
T11	29.0	0.724	14.0	5.59E-03	4.44	1.42E-02	16.10	3.57E-03	1.029
T12	29.0	0.821	14.0	5.82E-03	4.32	1.36E-02	14.67	3.93E-03	1.154
T13	49.0	0.500	49.0	4.48E-03	3.44	1.31E-02	16.00	3.06E-03	0.482
T14	49.0	0.750	49.0	4.16E-03	3.36	1.25E-02	15.39	2.76E-03	0.720
T15	49.0	0.850	49.0	4.12E-03	3.15	1.11E-02	13.00	2.87E-03	0.807
T16	49.0	0.490	24.0	6.55E-03	6.09	2.16E-02	27.68	3.44E-03	0.739
T17	49.0	0.735	24.0	6.52E-03	5.92	2.17E-02	27.30	3.59E-03	1.109
T18	49.0	0.833	24.0	6.57E-03	5.52	1.95E-02	23.48	3.96E-03	1.236

Table 6-4 lists the values of k for the condition with both ends fixed. The values are very close to the condition with only one end of the pipe fixed. Tables 6-5 through 6-7 include a comparison of the results for the two sets of boundary conditions. The variations are within the analysis methodology tolerance.

Table 6-4
Bending of the Trunnion—Both Ends Fixed

				In-Plane Moment on Trunnion		Out-of-Plane Moment on Trunnion		Torsion Moment on Trunnion	
Model	**D/T**	**d/D**	**d/t**	ϕ_Z	**k**	ϕ_Y	**k**	ϕ_X	**k**
TS1	33.5	0.509	18.0	5.53E-03	4.43	1.50E-02	17.67	3.62E-03	0.71
TS2	33.0	0.344	18.0	4.56E-03	3.57	9.20E-03	10.12	2.98E-03	0.43
TS3	33.0	0.839	28.5	2.78E-03	2.68	7.05E-03	8.33	1.72E-03	0.77
TS4	33.0	0.821	17.1	3.80E-03	3.98	1.04E-02	12.50	1.99E-03	1.05
T1	19.0	0.500	19.0	3.30E-03	1.78	5.50E-03	4.79	2.97E-03	0.44
T2	19.0	0.750	19.0	2.82E-03	1.99	5.73E-03	5.72	2.28E-03	0.65
T3	19.0	0.850	19.0	2.69E-03	1.98	5.42E-03	5.26	2.17E-03	0.73
T4	19.0	0.474	9.0	4.38E-03	3.03	8.16E-03	7.98	3.28E-03	0.65
T5	19.0	0.711	9.0	4.06E-03	3.44	9.19E-03	9.70	2.68E-03	0.98
T6	19.0	0.805	9.0	3.95E-03	3.44	8.90E-03	9.13	2.62E-03	1.10
T7	29.0	0.500	29.0	3.68E-03	2.42	7.92E-03	8.44	2.93E-03	0.46
T8	29.0	0.750	29.0	3.14E-03	2.52	8.10E-03	9.29	2.28E-03	0.69
T9	29.0	0.850	29.0	2.96E-03	2.45	7.41E-03	8.27	2.17E-03	0.78
T10	29.0	0.483	14.0	5.07E-03	4.18	1.24E-02	14.29	3.20E-03	0.68
T11	29.0	0.724	14.0	4.65E-03	4.42	1.35E-02	16.08	2.66E-03	1.05
T12	29.0	0.821	14.0	4.45E-03	4.29	1.35E-02	15.94	2.61E-03	1.19
T13	49.0	0.500	49.0	4.33E-03	3.43	1.30E-02	16.00	2.92E-03	0.49
T14	49.0	0.750	49.0	3.66E-03	3.34	1.21E-02	15.39	2.28E-03	0.73
T15	49.0	0.850	49.0	3.38E-03	3.12	1.05E-02	12.99	2.17E-03	0.82
T16	49.0	0.490	24.0	6.26E-03	6.08	2.14E-02	27.67	3.17E-03	0.75
T17	49.0	0.735	24.0	5.56E-03	5.89	2.09E-02	27.27	2.66E-03	1.13
T18	49.0	0.833	24.0	5.22E-03	5.54	1.86E-02	23.67	2.62E-03	1.28

Table 6-5
In-Plane Bending of the Trunnion—Average of Boundary Conditions

Model	D/T	d/D	d/t	1 End Fixed k Note (1)	2 Ends Fixed k Note (1)	% Diff	Average k Note (1)	R EQ Note (2)	% Diff
TS1	33.5	0.509	18.0	4.85	4.43	-8.5	4.64	4.16	-10.3
TS2	33.0	0.344	18.0	3.58	3.57	-0.2	3.58	3.99	11.5
TS3	33.0	0.839	28.5	2.72	2.68	-1.6	2.70	2.96	9.8
TS4	33.0	0.821	17.1	4.03	3.98	-1.1	4.01	4.36	8.8
T1	19.0	0.500	19.0	1.79	1.78	-0.5	1.79	1.86	3.8
T2	19.0	0.750	19.0	2.02	1.99	-1.1	2.01	1.90	-5.3
T3	19.0	0.850	19.0	2.01	1.98	-1.3	2.00	1.91	-4.1
T4	19.0	0.474	9.0	3.04	3.03	-0.4	3.04	3.26	7.4
T5	19.0	0.711	9.0	3.47	3.44	-0.7	3.46	3.34	-3.3
T6	19.0	0.805	9.0	3.46	3.44	-0.6	3.45	3.37	-2.5
T7	29.0	0.500	29.0	2.43	2.42	-0.4	2.42	2.38	-1.7
T8	29.0	0.750	29.0	2.55	2.52	-0.9	2.54	2.44	-3.8
T9	29.0	0.850	29.0	2.47	2.45	-1.1	2.46	2.46	-0.2
T10	29.0	0.483	14.0	4.19	4.18	-0.3	4.18	4.13	-1.2
T11	29.0	0.724	14.0	4.44	4.42	-0.6	4.43	4.23	-4.5
T12	29.0	0.821	14.0	4.32	4.29	-0.6	4.30	4.26	-1.0
T13	49.0	0.500	49.0	3.44	3.43	-0.3	3.44	3.25	-5.6
T14	49.0	0.750	49.0	3.36	3.34	-0.7	3.35	3.32	-0.9
T15	49.0	0.850	49.0	3.15	3.12	-0.9	3.14	3.35	6.7
T16	49.0	0.490	24.0	6.09	6.08	-0.2	6.08	5.58	-8.4
T17	49.0	0.735	24.0	5.92	5.89	-0.4	5.91	5.71	-3.4
T18	49.0	0.833	24.0	5.52	5.54	0.4	5.53	5.75	4.0
					Average =	-1.0		Average =	-0.2
					Maximum =	0.4		Maximum =	11.5
					Minimum =	-8.5		Minimum =	-10.3
Notes:					STD=	1.73		STD=	6.00

Notes:
1. k based on finite element analysis (FEA)
2. k based on regression Equation 6-13

Table 6-6
Out-of-Plane Bending of the Trunnion—Average of Boundary Conditions

Model	D/T	d/D	d/t	1 End Fixed k Note (1)	2 Ends Fixed k Note (1)	% Diff	Average k Note (1)	w/o factor R EQ Note (2)	% Diff	w/ factor R EQ Note(3)	% Diff
TS1	33.5	0.509	18.0	19.79	17.67	-10.7	18.73	14.99	-19.9	15.4	-17.5
TS2	33.0	0.344	18.0	10.12	10.12	0.0	10.12	14.08	39.1	12.3	21.8
TS3	33.0	0.839	28.5	8.34	8.33	-0.1	8.34	10.82	29.8	10.4	24.6
TS4	33.0	0.821	17.1	12.52	12.50	-0.1	12.51	15.81	26.4	15.5	23.6
T1	19.0	0.500	19.0	4.80	4.79	-0.1	4.80	5.03	4.9	5.1	7.0
T2	19.0	0.750	19.0	5.73	5.72	-0.1	5.73	5.22	-8.9	5.3	-6.8
T3	19.0	0.850	19.0	5.26	5.26	-0.1	5.26	5.28	0.4	5.0	-5.2
T4	19.0	0.474	9.0	7.98	7.98	-0.1	7.98	8.77	9.9	8.8	10.2
T5	19.0	0.711	9.0	9.72	9.70	-0.1	9.71	9.10	-6.3	9.5	-2.4
T6	19.0	0.805	9.0	9.13	9.13	-0.1	9.13	9.20	0.8	9.1	-0.7
T7	29.0	0.500	29.0	8.45	8.44	0.0	8.44	8.01	-5.1	8.2	-2.9
T8	29.0	0.750	29.0	9.29	9.29	-0.1	9.29	8.31	-10.5	8.5	-8.1
T9	29.0	0.850	29.0	8.28	8.27	-0.1	8.27	8.40	1.6	8.0	-3.6
T10	29.0	0.483	14.0	14.30	14.29	-0.1	14.29	13.79	-3.5	14.0	-2.3
T11	29.0	0.724	14.0	16.10	16.08	-0.1	16.09	14.30	-11.1	14.9	-7.5
T12	29.0	0.821	14.0	14.67	15.94	8.6	15.31	14.47	-5.5	14.1	-7.7
T13	49.0	0.500	49.0	16.00	16.00	0.0	16.00	14.27	-10.8	14.7	-8.3
T14	49.0	0.750	49.0	15.39	15.39	-0.1	15.39	14.80	-3.8	15.3	-0.7
T15	49.0	0.850	49.0	13.00	12.99	-0.1	12.99	14.97	15.2	14.3	9.8
T16	49.0	0.490	24.0	27.68	27.67	0.0	27.67	24.32	-12.1	24.9	-10.1
T17	49.0	0.735	24.0	27.30	27.27	-0.1	27.28	25.23	-7.5	26.3	-3.7
T18	49.0	0.833	24.0	23.48	23.67	0.8	23.58	25.51	8.2	24.8	5.0
					Average =	-0.1		Average =	1.4	Average =	0.6
					Maximum =	8.6		Maximum =	39.1	laximum =	24.6
					Minimum =	-10.7		Minimum =	-19.9	linimum =	-17.5
Notes:					STD=	3.01		STD=	14.87	STD=	11.30
1. k based on FEA											
2. k based on regression Equation 6-14											
3. k based on regression Equation 6-15											

Table 6-7
Torsion of the Trunnion—Average of Boundary Conditions

Model	D/T	d/D	d/t	1 End Fixed k Note (1)	2 Ends Fixed k Note (1)	% Diff	Average k Note (1)	R EQ Note (2)	% Diff
TS1	33.5	0.509	18.0	0.76	0.71	-6.7	0.74	0.68	-7.3
TS2	33.0	0.344	18.0	0.43	0.43	1.3	0.43	0.46	5.7
TS3	33.0	0.839	28.5	0.76	0.77	0.9	0.77	0.84	9.4
TS4	33.0	0.821	17.1	1.03	1.05	1.6	1.04	1.12	7.6
T1	19.0	0.500	19.0	0.43	0.44	0.7	0.44	0.42	-2.9
T2	19.0	0.750	19.0	0.64	0.65	1.5	0.64	0.63	-1.0
T3	19.0	0.850	19.0	0.71	0.73	2.3	0.72	0.72	-0.1
T4	19.0	0.474	9.0	0.65	0.65	0.8	0.65	0.63	-3.0
T5	19.0	0.711	9.0	0.96	0.98	2.0	0.97	0.95	-1.9
T6	19.0	0.805	9.0	1.07	1.10	3.2	1.08	1.07	-0.8
T7	29.0	0.500	29.0	0.45	0.46	0.6	0.45	0.45	-1.2
T8	29.0	0.750	29.0	0.68	0.69	1.5	0.68	0.67	-1.4
T9	29.0	0.850	29.0	0.76	0.78	2.1	0.77	0.76	-0.6
T10	29.0	0.483	14.0	0.68	0.68	0.8	0.68	0.68	-0.6
T11	29.0	0.724	14.0	1.03	1.05	2.0	1.04	1.01	-2.5
T12	29.0	0.821	14.0	1.15	1.19	2.8	1.17	1.15	-1.8
T13	49.0	0.500	49.0	0.48	0.49	0.9	0.48	0.48	-0.1
T14	49.0	0.750	49.0	0.72	0.73	1.3	0.72	0.72	0.0
T15	49.0	0.850	49.0	0.81	0.82	1.7	0.81	0.82	0.9
T16	49.0	0.490	24.0	0.74	0.75	0.8	0.74	0.73	-1.4
T17	49.0	0.735	24.0	1.11	1.13	2.1	1.12	1.10	-2.1
T18	49.0	0.833	24.0	1.24	1.28	3.7	1.26	1.24	-1.2
					Average =	1.3		Average =	-0.3
					Maximum =	3.7		Maximum =	9.4
					Minimum =	-6.7		Minimum =	-7.3
Notes:					STD=	1.96		STD=	3.63
1. k based on FEA									
2. k based on regression Equation 6-16									

It is assumed that the average of the two conditions is representative of actual applications. Tables 6-5 through 6-7 list the average values of k and also provide a comparison to equations developed from regression analysis for the specific loading conditions on the trunnion:

In-plane bending:

$$k = 0.34\,(D/T)^{1.351}\,(d/D)^{0.058}\,(d/t)^{-0.76} \qquad (r^2 = 0.97) \qquad \text{(Eq. 6-13)}$$

The average difference between Equation 6-13 and the FEA results is 0.2% with the maximum abut 11.5%. The standard deviation of the percentage difference was 6.0%.

The parameter r^2 is a standard statistical measure of "goodness of fit." The closer to 1.0, the more accurate the curve fit is.

Out-of-plane bending:

$$k = 0.21\,(D/T)^{1.85}\,(d/D)^{0.09}\,(d/t)^{-0.75} \qquad (r^2 = 0.92) \qquad \text{(Eq. 6-14)}$$

The average difference between Equation 6-14 and the FEA results is 1.4%, with the maximum about 39.1%. The standard deviation of the percentage difference was 14.9%.

In order to reduce the difference between the correlation equation and the FEA results, a factor was added to account for the effects of d / D for out-of-plane bending. This resulted in the following expression for out-of-plane bending:

$$k = 0.321\,(1.47(d/D)-(d/D)^{2.45})\,(D/T)^{1.86}\,(d/D)^{-0.14}\,(d/t)^{-0.75} \qquad (r^2 = 0.95) \qquad \text{(Eq. 6-15)}$$

The average difference between Equation 6-15 and the FEA results is 0.6%, with the maximum about 24.6%. The standard deviation of the percentage difference was 11.3%.

This represents a slight improvement over Equation 6-14.

Torsion:

$$k = 0.56\,(D/T)^{0.75}\,(d/D)^{0.998}\,(d/t)^{-0.61} \qquad (r^2 = 0.99) \qquad \text{(Eq. 6-16)}$$

The average difference between Equation 6-16 and the FEA results is 0.2%, with the maximum abut 9.4%. The standard deviation of the percentage difference was 3.6%.

In the FEA, the range of the parameters used to develop Equations 6-13 through 6-16 were: D / T from 19 to 49, d / D from 0.34 to 0.85, and d / t from 9 to 49. It is not possible to analyze all possible combinations of these parameters. In order to determine the applicability of the various equations over the various ranges of parameters, trial calculations were performed to determine the reasonableness of the results. The calculations yielded reasonable results; hence, these parameter ranges will be used as limits in the applicability of the equations.

Comparison to Test Data

While the tests discussed in Chapter 3 were not specifically for determining flexibility factors, they can be used to evaluate one of the equations derived above. Loads and deflections at the load point for in-plane bending were recorded and are included in Appendix C. The average deflection of the four tests at a load of 1,000 lbs. was 0.54 inches. Using an average trunnion length of 46 inches and other dimensions from Figure 3-1 and Equation 6-13 (for in-plane bending), the calculated deflection was 0.46 inches. Considering that the calculation does not include the flexibility of the testing frame or bolted connections—and also that Equation 6-13 is based on the average of the two cases with different conditions—this is considered as verification of the methodology.

7

CONCLUSIONS

The conclusions arrived at from the analyses and tests discussed in this report are enumerated below:

1. The basic approach used by Code Cases N-391 and N-392 can be used in the design and qualification of trunnions on pipe.

2. A more accurate evaluation of trunnions or hollow circular cross section welded on pipe can be made if the tables in Code Cases N-392 and N-392 are modified such that the present values of A_o are reduced by a factor of 1.4.

3. The values of the B indices (B_W, B_L, B_N, and B_T) are defined as 0.3 times the corresponding C index (C_W, C_L, C_N, and C_T) but not less than 1.0.

4. For Code Case N-391, the lower limit on $\gamma = R_o / T$ can be taken as 4.0 instead of 8.33.

5. The flexibility model should be based on Figure 6-1, in which it is assumed that there is a rigid link from the centerline of the pipe to its outer surface where the trunnion is connected. At this location, it is assumed that a point spring exists. The flexibility factors of the point spring are given by:

In-plane bending:

$$k = 0.34\,(D/T)^{1.351}\,(d/D)^{0.058}\,(d/t)^{-0.76} \qquad \text{(Eq. 6-13)}$$

Out-of-plane bending:

$$k = 0.321\,(1.47(d/D)-(d/D)^{2.45})\,(D/T)^{1.86}\,(d/D)^{-0.14}\,(d/t)^{-0.75} \qquad \text{(Eq. 6-15)}$$

Torsion:

$$k = 0.56\,(D/T)^{0.75}\,(d/D)^{0.998}\,(d/t)^{-0.61} \qquad \text{(Eq. 6-16)}$$

For through-run moments, the flexibility is the same as for the run pipe without a trunnion.

The applicability of these equations is limited to the following range of parameters:

D / T: from 19.0 to 49.0
d / D: from 0.34 to 0.85
d / t: from 9.0 to 49.0

The approach suggested should allow for a more accurate evaluation of trunnions on straight pipe.

8

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A

CASE N-391-2, PROCEDURE FOR EVALUATION OF THE DESIGN OF HOLLOW CIRCULAR CROSS SECTION WELDED ATTACHMENTS ON CLASS 1 PIPING, SECTION III, DIVISION 1, AMERICAN SOCIETY OF MECHANICAL ENGINEERS, NEW YORK.

Case N-391-2, Procedure for Evaluation of the design of Hollow Circular Cross Section Welded Attachments on Class 1 Piping, Section III, Division 1, American Society of Mechanical Engineers, New York.

CASE

N-391-2

CASES OF ASME BOILER AND PRESSURE VESSEL CODE

Approval Date: August 24, 1995

See Numerical Index for expiration and any reaffirmation dates.

Case N-391-2
Procedure for Evaluation of the Design of Hollow Circular Cross Section Welded Attachments on Class 1 Piping
Section III, Division 1

Inquiry: What procedure may be used to evaluate the design of hollow circular cross section welded attachments on Class 1 pipe under Section III, Division 1?

Reply: It is the opinion of the Committee that the procedures listed below may be used to evaluate the design of hollow circular cross section welded attachments on Class 1 pipe under Section III, Division 1.

1.0 LIMITATIONS OF APPLICABILITY

1.1 The attachment shall be welded to the pipe by a full penetration weld (see Fig. 1).

1.2 The attachment material and pipe material shall have essentially the same moduli of elasticity and coefficients of thermal expansion.

1.3 The constants, defined in Section 2.0, fall within the following ranges:

(a) $4.0 \leq \gamma \leq 50.0$
(b) $0.2 \leq \tau \leq 1.0$
(c) $0.3 \leq \beta \leq 1.0$, and
(d) the axis of the attachment is perpendicular to the axis of the run pipe.

1.4 The attachment shall be made on straight pipe with the nearest edge of the attachment weld located at a minimum distance of $\sqrt{\underline{R}T}$ from any other weld or discontinuity (see Section 2.0 for definitions of $\underline{R}$ and T). For multiple attachments located at a distance less than $\sqrt{\underline{R}T}$ to each other, the stress effects for each individual attachment shall be superimposed.

2.0 NOMENCLATURE AND DEFINITIONS (See Fig. 2)

R_o = run pipe outside radius, in.
r_o = attachment outside radius, in.
r_i = attachment inside radius, in.
T = run pipe wall thickness, in.
t = attachment wall thickness, in.
D_o = outside diameter of the run pipe, in.
d_o = outside diameter of the attachment, in.
$\underline{R}$ = mean radius of run pipe, in.
$A_T = \pi\,(r_o^2 - r_i^2)$
$Z_T = I_T/r_o$
$I_T = \frac{\pi}{4}(r_o^4 - r_i^4)$
$\underline{A} = \frac{\pi}{2}(r_o^2 - r_i^2)$
$\underline{J}$ = lesser of $\pi r_o^2 T$ or Z_T
$\gamma = R_o/T$
$\tau = t/T$
$\beta = d_o/D_o$
$C = A_o\,(2\gamma)^{n_1}\beta^{n_2}\tau^{n_3}$ but not less than 1.0

The equation for C shall be used to determine C_W, C_L, and C_N, based on the following table. Select the maximum value of the pipe and the attachment equations.

Index	Part	β range	A_o	n_1	n_2	n_3
C_W	Pipe	0.3–1.0	1.40	0.81	(a)	1.33
	attachment	0.3–1.0	4.00	0.55	(b)	1.00
C_L	Pipe	0.3–1.0	0.46	0.60	−0.04	0.86
	attachment	0.3–1.0	1.10	0.23	−0.38	0.38
C_N	Pipe	0.3–0.55	0.51	1.01	0.79	0.89
	attachment	0.3–0.55	0.84	0.85	0.80	0.54
	Pipe	>0.55–1.0	0.23	1.01	−0.62	0.89
	attachment	>0.55–1.0	0.44	0.85	−0.28	0.54

NOTES:
(a) Replace β^{n_2} with $e^{-1.2\beta^3}$.
(b) Replace β^{n_2} with $e^{-1.35\beta^3}$.

C_T = 1.0 for $\beta \leq 0.55$
$C_T = C_N$ for $\beta = 1.0$, but not less than 1.0; C_T should be linearly interpolated for $0.55 < \beta < 1.0$, but not less than 1.0
$B_W = 0.5\,(C_W)$, but not less than 1.0
$B_L = 0.5\,(C_L)$, but not less than 1.0
$B_N = 0.5\,(C_N)$, but not less than 1.0
$B_T = 0.5\,(C_T)$, but not less than 1.0
K_T = 1.8 for full penetration welds
S_m = allowable design stress intensity, psi (lesser of attachment or pipe material)

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S_Y = yield stress at temperature, psi (lesser of attachment or pipe material)

M_L = bending moment applied to the attachment as shown in Fig. 2, in.-lb

M_N = bending moment applied to the attachment as shown in Fig. 2, in.-lb

M_T = bending moment applied to the attachment as shown in Fig. 2, in.-lb

Q_1 = shear load applied to the attachment as shown in Fig. 2, lb

Q_2 = shear load applied to the attachment as shown in Fig. 2, lb

W = thrust load applied to the attachment as shown in Fig. 2, lb

M_L, M_N, M_T, Q_1, Q_2, and W are determined at the surface of the pipe.

$M_L{}^{**}$, $M_N{}^{**}$, $M_T{}^{**}$, $Q_1{}^{**}$, $Q_2{}^{**}$, and W^{**} are absolute values of maximum loads occurring simultaneously under all service loading conditions.

T_T = average temperature of that portion of the attachment within a distance of $2t$ from the surface of the pipe, °F

T_W = average temperature of the portion of the pipe under the attachment and within a distance of $\sqrt{RT}$ from the edge of the attachment, °F

$E\alpha$ = modulus of elasticity, E, times the mean coefficient of thermal expansion, α, both at room temperature, psi/°F

3.0 EVALUATION PROCEDURE

The loads on the attachment cause stresses in the pipe wall. Equations are provided in 3.1(a) to determine these stresses. The attachment stresses are then added to the piping system stresses at the attachment. The piping system stresses are determined by NB-3652 Eq. (9), NB-3653.1 Eq. (11) NB-3653.2 Eq. (11), and NB-3653.6 Eqs. (12), (13), and (14). The Code equations including the attachment stress terms are given in 3.1(b). The attachment stresses S_{MT}, S_{MP}, and S_{PT} are to be calculated for the loading conditions corresponding to NB-3652 Eq. (9), NB-3653.1 Eq. (10), NB-3653.2 Eq. (11), and NB-3653.6 Eqs. (12), (13), and (14). For example, in calculating S_{MT} for use in NB-3652 Eq. (9) for design conditions, W, M_L, M_N, Q_1, Q_2, and M_T are the loads on the attachment due to design mechanical loads.

There are additional equations given in 3.1(c) that also must be checked for attachment stresses. These are based on the absolute values of maximum loads occurring simultaneously under all service loading conditions.

3.1 Analysis of Attachments

(a) Calculate the stresses S_{MT}, S_{NT}, S_{PT}, and $S_{NT}{}^{**}$:

$$S_{MT} = \frac{B_W W}{A_T} + \frac{B_N M_N}{Z_T} + \frac{B_L M_L}{Z_T} + \frac{Q_1}{A} + \frac{Q_2}{A} + \frac{B_T M_T}{J} \quad (1)$$

$$S_{NT} = \frac{C_W W}{A_T} + \frac{C_N M_N}{Z_T} + \frac{C_L M_L}{Z_T} + \frac{Q_1}{A} + \frac{Q_2}{A} + \frac{C_T M_T}{J} + 1.7E\alpha|T_T - T_W| \quad (2)^1$$

$$S_{PT} = K_T(S_{NT}) \quad (3)$$

$$S_{NT}{}^{**} = \frac{C_W W^{**}}{A_T} + \frac{C_N M_N{}^{**}}{Z_T} + \frac{C_L M_L{}^{**}}{Z_T} + \frac{Q_1{}^{**}}{A} + \frac{Q_2{}^{**}}{A} + \frac{C_T M_T{}^{**}}{J} \quad (4)$$

(b) The following modified Code equations shall be satisfied.

(1) NB-3652 Eq. (9) becomes:

$$B_1 \frac{PD_o}{2t} + B_2 \frac{D_o}{2I} M_i + S_{MT}$$

$\leq 1.5S_m$	for Design and Service Level A loadings
$\leq 1.8S_m$	but not greater than $1.5S_y$ for Level B loadings
$\leq 2.25S_m$	but not greater than $1.8S_y$ for Level C loadings
$\leq 3.0S_m$	but not greater than $2.0S_y$ for Level D loadings

(NB-9)

where $B_1 = 0.5$ and $B_2 = 1.0$ for straight pipe.

(2) NB-3653.1 Eq. (10) becomes:

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[1] For thermal transients with fluid temperature changes greater than 100°F (37.8°C) and rate of change greater than 10°F/min. $|T_T - T_W|$ may be conservatively taken as one-half of the difference between the initial metal temperature and the transient fluid temperature during a temperature transient.

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$$S_n = C_1 \frac{P_o D_o}{2t} + C_2 \frac{D_o}{2I} M_i + S_{NT} \leq 3S_m \quad \text{(NB-10)}$$

where $C_1 = C_2 = 1.0$ for straight pipe.

If S_n, as calculated by Eq. (NB-10), exceeds $3S_m$, NB-3653.6 Eqs. (12) and (13) and the thermal stress ratchet check of NB-3653.7 must be satisfied; S_{NT} need not be included in these checks. However, the value of K_e shall be determined from S_n, including S_{NT}.

(3) NB-3653.2 Eq. (11) becomes:

$$S_p = K_1 C_1 \frac{P_o D_o}{2t} + K_2 C_2 \frac{D_o}{2I} M_i + \frac{1}{2(1-\nu)} K_3 E\alpha|\Delta T_1| + \frac{1}{1-\nu} E\alpha|\Delta T_2| + S_{PT} \quad \text{(NB-11)}$$

where $K_1 = K_2 = K_3 = 1.0$ for straight pipe.

(4) NB-3653.6 Eq. (14) becomes:

$$S_{ALT} = K_e \frac{S_p}{2} \quad \text{(NB-14)}$$

where S_n and S_p are as calculated by Eqs. (NB-10) and (NB-11) of this Case.

All terms except attachment stresses, or where otherwise noted, are defined in NB-3652 and NB-3653.

(c) In addition to the Code equations, the following equations shall also be satisfied:

$$S_{NT}^{**} \leq 2S_y \quad (5)$$

$$\frac{Q_1^{**}}{A} + \frac{Q_2^{**}}{A} + \frac{M_T^{**}}{J} \leq S_y \quad (6)$$

3.2 Analysis

Analysis complying with this Case shall be included in the Design Report for the piping system.

4.0 IDENTIFICATION

This Case number shall be shown on the Data Report Form.

Case N-391-2, Procedure for Evaluation of the design of Hollow Circular Cross Section Welded Attachments on Class 1 Piping, Section III, Division 1, American Society of Mechanical Engineers, New York.

CASE (continued)

N-392-3

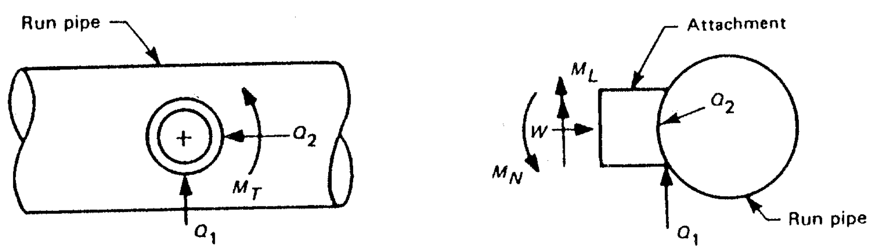

FIG. 1 NOMENCLATURE

B

CASE N-392-3, PROCEDURE FOR EVALUATION OF THE DESIGN OF HOLLOW CIRCULAR CROSS SECTION WELDED ATTACHMENTS ON CLASSES 2 AND 3 PIPING, SECTION III, DIVISION 1, AMERICAN SOCIETY OF MECHANICAL ENGINEERS, NEW YORK

Case N-392-3, Procedure for Evaluation of the design of Hollow Circular Cross Section Welded Attachments on Classes 2 and 3 Piping, Section III, Division 1, American Society of Mechanical Engineers, New York

CASE

N-392-3

CASES OF ASME BOILER AND PRESSURE VESSEL CODE

Approval Date: December 12, 1994

See Numerical Index for expiration and any reaffirmation dates.

Case N-392-3
Procedure for Evaluation of the Design of Hollow Circular Cross Section Welded Attachments on Classes 2 and 3 Piping
Section III, Division 1

Inquiry: What procedure may be used to evaluate the design of hollow circular cross section welded attachments on Classes 2 and 3 pipe under Section III, Division 1?

Reply: It is the opinion of the Committee that the procedures listed below may be used to evaluate the design of hollow circular cross section welded attachments on Classes 2 and 3 pipe under Section III, Division 1.

1.0 LIMITATIONS OF APPLICABILITY

1.1 The attachment shall be welded to the pipe along the entire circumference by either a full penetration weld, a fillet weld or a partial penetration weld.

1.2 The attachment material and pipe material shall have essentially the same moduli of elasticity and coefficients of thermal expansion.

1.3 The constants, defined in Section 2.0, fall within the following ranges:

(*a*) $4.0 \leq \gamma \leq 50.0$
(*b*) $0.2 \leq \tau \leq 1.0$
(*c*) $0.3 \leq \beta \leq 1.0$, and
(*d*) the axis of the attachment is perpendicular to the axis of the run pipe.

1.4 The attachment shall be made on straight pipe with the nearest edge of the attachment weld located at a minimum distance of $\sqrt{\overline{R}T}$ from any other weld or discontinuity (see Section 2.0 for definitions of $\overline{R}$ and T). For multiple attachments located at a distance less than $\sqrt{\overline{R}T}$ to each other, the stress effects for each individual attachment shall be superimposed.

2.0 NOMENCLATURE AND DEFINITIONS (See Fig. 2)

R_o = run pipe outside radius, in.
r_o = attachment outside radius, in.
r_i = attachment inside radius, in.
T = nominal run pipe wall thickness, in.
t = nominal attachment wall thickness, in.
D_o = outside diameter of the run pipe, in.
d_o = outside diameter of the attachment, in.
$\overline{R}$ = mean radius of run pipe, in.
$A_T = \pi (r_o^2 - r_i^2)$
$Z_T = I_T / r_o$

$$I_T = \frac{\pi}{4}(r_o^4 - r_i^4)$$

$$\overline{A} = \frac{\pi}{2}(r_o^2 - r_i^2)$$

$\overline{J}$ = lesser of $\pi r_o^2 T$ or Z_T
$\gamma = R_o/T$
$\tau = t/T$
$\beta = d_o/D_o$
$C = A_o (2\gamma)^{n_1} \beta^{n_2} \tau^{n_3}$, but not less than 1.0

The equation for C shall be used to determine C_W, C_L, and C_N, based on the following table. Select the maximum value of the pipe and the attachment equations.

Index	Part	β Range	A_o	n_1	n_2	n_3
C_W	Pipe	0.3–1.0	1.40	0.81	(a)	1.33
	attachment	0.3–1.0	4.00	0.55	(b)	1.00
C_L	Pipe	0.3–1.0	0.46	0.60	−0.04	0.86
	attachment	0.3–1.0	1.10	0.23	−0.38	0.38
C_N	Pipe	0.3–0.55	0.51	1.01	0.79	0.89
	attachment	0.3–0.55	0.84	0.85	0.80	0.54
	Pipe	>0.55–1.0	0.23	1.01	−0.62	0.89
	attachment	>0.55–1.0	0.44	0.85	−0.28	0.54

NOTES:
(a) Replace β^{n_2} with $e^{-1.2\beta^3}$.
(b) Replace β^{n_2} with $e^{-1.35\beta^3}$.

C_T = 1.0 for $\beta \leqslant 0.55$
$C_T = C_N$ for $\beta = 1.0$, but not less than 1.0; C_T should be linearly interpolated for $0.55 < \beta < 1.0$, but not less than 1.0
B_W = 0.5 (C_W), but not less than 1.0
B_L = 0.5 (C_L), but not less than 1.0
B_N = 0.5 (C_N), but not less than 1.0
B_T = 0.5 (C_T), but not less than 1.0
K_T = 2.0 for fillet or partial penetration welds
= 1.8 for full penetration welds
S_h = basic material allowable stress at maximum (hot) temperature, psi (lesser of attachment or pipe material allowable)
S_c = basic material allowable stress at ambient temperature, psi (lesser of attachment or pipe material allowable)
$S_A = f\,(1.25S_c + 0.25S_h)$, psi, as defined in NC/ND-3611.2 (lesser of attachment or pipe material allowable)
S_Y = yield stress at temperature, psi (lesser of attachment or pipe material yield stress)
Z_{wn} = section modulus of fillet weld or partial penetration weld about the neutral axis of bending parallel to run pipe center line, in.[3]
Z_{wl} = section modulus of fillet weld or partial penetration weld about the neutral axis normal to the run pipe center line, in.[3]
Z_{wt} = torsional section modulus of fillet weld or partial penetration weld for torsional loading, in.[3]
A_w = fillet weld or partial penetration weld throat area, in.[2]
M_L = bending moment applied to the attachment as shown in Fig. 1, in.-lb
M_N = bending moment applied to the attachment as shown in Fig. 1, in.-lb
M_T = torsional moment applied to the attachment as shown in Fig. 1, in.-lb
Q_1 = shear load applied to the attachment as shown in Fig. 1, lb
Q_2 = shear load applied to the attachment as shown in Fig. 1, lb
W = thrust load applied to the attachment as shown in Fig. 1, lb

M_L, M_N, M_T, Q_1, Q_2, and W are determined at the surface of the pipe. The values of attachment loads used in the stress evaluation (Section 3.0) are based on the loads used in the different Code equations. M_L^{**}, M_N^{**}, M_T^{**}, Q_1^{**}, Q_2^{**}, and W^{**} are absolute values of maximum loads occurring simultaneously under all service loading conditions.

3.0 EVALUATION PROCEDURE

The loads on the attachment cause stresses in the pipe wall. Equations are provided in 3.1(a) to determine these stresses. The attachment stresses are then added to the piping system stresses at the attachment. The piping system stresses are determined by NC-3652 Eq. (8), NC-3653.1 Eq. (9), and NC-3653.2 Eqs. (10), (10a), and (11) for straight pipe. The Code equations, including the attachment stress terms are given in 3.1(b). The attachment stresses S_{MT}, S_{NT}, and S_{PT} are to be calculated for the loading conditions corresponding to NC-3652 Eq. (8), NC-3653.1 Eq. (9), and NC-3653.2 Eqs. (10), (10a), and (11). For example, in calculating S_{MT} for use in NC-3652 Eq. (8), W, M_L, M_N, Q_1, Q_2, and M_T are the loads on the attachment due to weight and other sustained loads.

There are additional equations given in 3.1(c) and 3.2(b), for fillet welded or partial penetration weld atttachments, that also must be checked for attachment stresses. These are based on the absolute values of maximum loads occurring simultaneously under all service loading conditions.

3.1 Analysis of Attachment Welded to Pipe with a Full Penetration Weld

(a) Calculate the stresses S_{MT}, S_{NT}, S_{PT}, and S_{NT}^{**}:

$$S_{MT} = \frac{B_W W}{A_T} + \frac{B_N M_N}{Z_T} + \frac{B_L M_L}{Z_T} + \frac{Q_1}{A} + \frac{Q_2}{A} + \frac{B_T M_T}{J} \quad (1)$$

$$S_{NT} = \frac{C_W W}{A_T} + \frac{C_N M_N}{Z_T} + \frac{C_L M_L}{Z_T} + \frac{Q_1}{A} + \frac{Q_2}{A} + \frac{C_T M_T}{J} \quad (2)$$

$$S_{PT} = K_T(S_{NT}) \quad (3)$$

$$S_{NT}^{**} = \frac{C_W W^{**}}{A_T} + \frac{C_N M_N^{**}}{Z_T} + \frac{C_L M_L^{**}}{Z_T} + \frac{Q_1^{**}}{A} + \frac{Q_2^{**}}{A} + \frac{C_T M_T^{**}}{J} \quad (4)$$

(b) The following modified Code equations shall be satisfied.

(1) NC-3652 Eq. (8) becomes:

$$S_{SL} = B_1 \frac{PD_o}{2t_n} + B_2 \frac{M_A}{Z} + S_{MT} \leqslant 1.5S_h \quad \text{(NB-8)}$$

where B_1 = 0.5 and B_2 = 1.0 for straight pipe.

(2) NC-3653.1 Eq. (9) becomes:

$$S_{OL} = B_1 \frac{P_{max.} D_o}{2t_n} + B_2 \frac{M_A + M_B}{Z} + S_{MT}$$

$\leq 1.8 S_h$	but not greater than $1.5 S_y$ for Level A and B loadings
$\leq 2.25 S_h$	but not greater than $1.8 S_y$ for Level C loadings
$\leq 3.0 S_h$	but not greater than $2.0 S_y$ for Level D loadings

(3) NC-3653.2 Eq. (10) becomes:

$$S_E = \frac{iM_C}{Z} + \frac{S_{PT}}{2} \leq S_A \qquad \text{(NC-10)}$$

(4) NC-3653.2 Eq. (10a) becomes:

$$\frac{iM_D}{Z} + \frac{S_{PT}}{2} \leq 3.0\, S_c \qquad \text{(NC-10a)}$$

(5) NC-3653.2 Eq. (11) becomes:

$$S_{TE} = \frac{PD_o}{4t_n} + 0.75i\left(\frac{M_A}{Z}\right) + i\left(\frac{M_c}{Z}\right) + S_{MT} + \frac{S_{PT}}{2} \leq (S_h + S_A) \qquad \text{(NC-11)}$$

where all terms except attachment stresses are defined in NC-3652. In Eq. (NC-11), S_{MT} is the same as used in Eq. (NC-8), and S_{PT} is the same as used in Eq. (NC-10).

(c) In addition to the Code equations, the following equations shall also be satisfied:

$$S_{NT}^{**} \leq 2S_y \qquad (5)$$

$$\frac{Q_1^{**}}{\bar{A}} + \frac{Q_2^{**}}{\bar{A}} + \frac{M_T^{**}}{\bar{J}} \leq S_y \qquad (6)$$

3.2 Analysis of Attachment Welded to Pipe With Fillet Welds or Partial Penetration Welds

(a) The requirements of 3.1 shall be met.

(b) The following additional requirements shall be met:

$$\frac{W^{**}}{A_w} + \frac{M_L^{**}}{Z_{wl}} + \frac{M_N^{**}}{Z_{wn}} + \frac{[(Q_1^{**})^2 + (Q_2^{**})^2]^{1/2}}{A_w} + \frac{M_T^{**}}{Z_{wt}} \leq 2S_y \qquad (7)$$

$$\left\{\left(\frac{W^{**}}{A_w}\right)^2 + 4\left[\left(\frac{Q_1^{**} + Q_2^{**}}{A_w}\right) + \frac{M_T^{**}}{Z_{wt}}\right]^2\right\}^{1/2} \leq S_y \qquad (8)$$

E

3.3 Analysis

Analysis complying with this Case shall be included in the Design Report for the piping system.

4.0 IDENTIFICATION

This Case number shall be shown on the Data Report Form.

NOTE: The potential for increased stress at the attachment welds, which may occur as a result of differential metal temperatures between the attachment and the run, should be considered in the design evaluation.

Case N-392-3, Procedure for Evaluation of the design of Hollow Circular Cross Section Welded Attachments on Classes 2 and 3 Piping, Section III, Division 1, American Society of Mechanical Engineers, New York

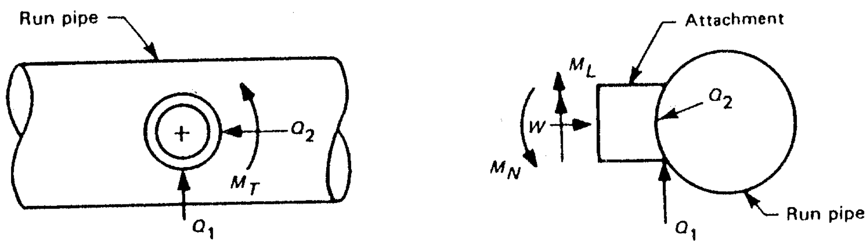

FIG. 1 NOMENCLATURE

C

TEST DATA AND RESULTS

INTRODUCTION

The description of the testing is contained in Section 3. Table 3-1 contains a summary of the results. This Appendix contains more details regarding the test data. For each of the 4 tests (A, B, C, D) the following is provided:

1. Standard sheets containing load-displacement data.

Data sheets are provided for the two loading directions: "Positive Loading" and "Negative Loading", (e.g. up and down). Both the "Loading" and "Unloading" conditions for each of the directons are included for a total of four data sheets. The sheets are used to determine the linear slopes of the load-deflection curves for the four loading conditions.

The data includes loads, deflections etc. The columns identified as "Modified" are for the case where adjustments are required to the data, such as resetting a dial gauge, etc. No modifications were required for these tests.

2. Summary Load Deflection Sheet.

This sheet contains a plot of the load deflection curve and the four straight lines determined from the load-displacement data (item 1 above). This plot indicates the reasonableness of the slope of the load deflection curves.

3. Fatigue Test Data Analysis.

This sheet contains the displacements and number of cycles at each displacement (if more than one displacement is used). The calculations of the SIF are included. The stiffness used in the calculation is the average value of the four loading conditions (in item 1). Equivalent cycles are also calculated.

TEST DATA

SPECIMEN: TRUNNION ON PIPE

TEST IDENTIFICATION: A

TEST #: TRUNNION-PIPE-A

TYPE: FATIGUE - LOAD DEFLECTION CURVE

POSITIVE LOAD - LOADING CONDITION

$F = Fo + m\,\delta$ "m" TO BE BASED ON N DATA POINTS, N = 6

THE VALUE OF "m" = 1836 0

NOMINAL STRESS = M/Z KSI, M=F x L. L(IN) = 46.0625 $Z(IN^3)$ = 3.215

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	0.000	0	0.000	0	N/A	0	
2	0.100	199.4	0.100	199	1,994	184	2.6
3	0.248	507	0.248	507	2,047	455	6.5
4	0.374	748	0.374	748	2,010	687	9.8
5	0.508	990	0.508	990	1,960	932	13.4
6	0.822	1503	0.822	1503	1,836	1509	21.6
7	0.998	1759	0.998	1759	1,764	1832	26.2
8	1.200	2001	1.200	2001	1,682	2203	31.6
9	1.450	2250	1.450	2250	1,580	2662	38.1
10	1.753	2491	1.753	2491	1,459	3218	46.1
11	1.752	2469.9	1.752	2470	1,405	3216	46.1
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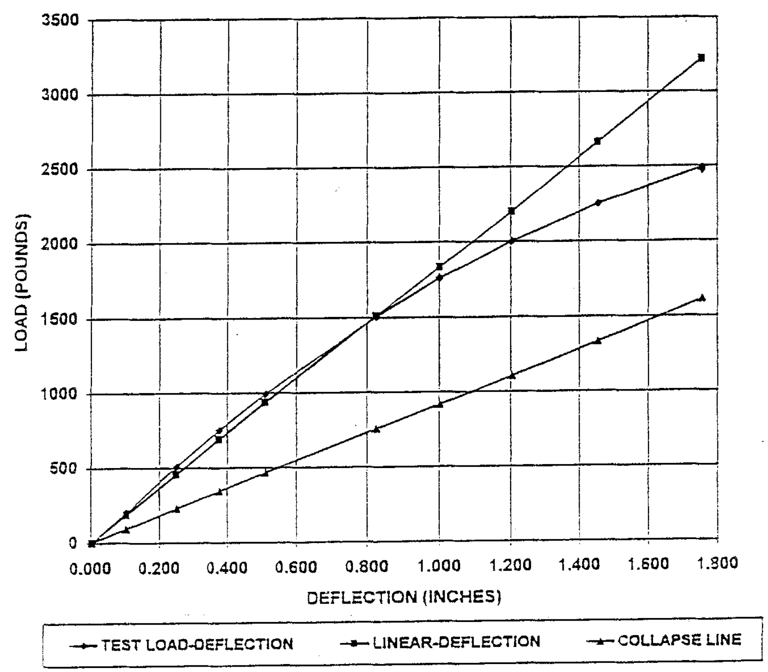

NOTES:
Loading is in a downward direction.

TEST #: TRUNNION-PIPE-A **TYPE:** FATIGUE - LOAD DEFLECTION CURVE

$F = Fo + m\,\delta$ "m" TO BE BASED ON N DATA POINTS, N = 5
THE VALUE OF "m" = 1914 o (LBS) = 2

NOMINAL STRESS = M/Z KSI, M=F x L, L(IN) = 46.0625 $Z(IN^3)$ = 3.215

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	1.752	2469.9	1.752	2470	1,987	2402	34.4
2	1.718	2396	1.718	2396	1,975	2337	33.5
3	1.530	2001	1.530	2001	1,955	1977	28.3
4	1.413	1759	1.413	1759	1,938	1753	25.1
5	1.287	1503	1.287	1503	1,914	1512	21.7
6	1.039	998	1.039	998	1,849	1037	14.9
7	0.785	499	0.785	499	1,731	551	7.9
8	0.644	243	0.644	243	1,651	281	4.0
9	0.498	2	0.498	2	N/A	2	0.0
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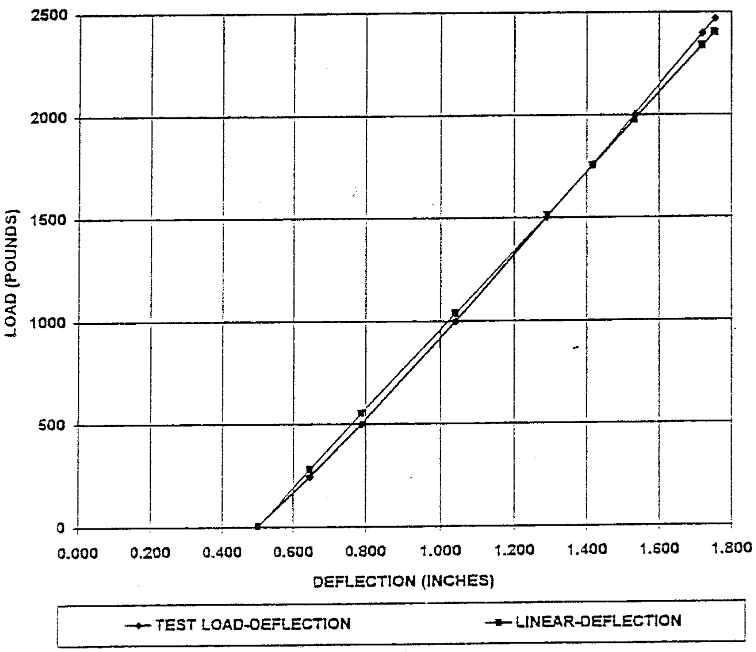
NOTES:

POSITIVE LOAD - UNLOADING CONDITION



TEST #: TRUNNION-PIPE-A

TYPE: FATIGUE - LOAD DEFLECTION CURVE

NEGATIVE LOAD - LOADING CONDITION

$F = F_o + m\,\delta$

"m" TO BE BASED ON N DATA POINTS, N = 7
THE VALUE OF "m" = 1566

F_o (LBS) = 0

NOMINAL STRESS = M/Z KSI, M=F x L, L(IN) = 46.0625 Z(IN³) = 3.215

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	0.498	2	0.498	2	N/A	0	0.0
2	0.331	-247	0.331	-247	1,491	-261	-3.7
3	0.174	-511	0.174	-511	1,582	-507	-7.3
4	0.019	-760	0.019	-760	1,599	-750	-10.7
5	-0.004	-797	-0.004	-797	1,603	-786	-11.3
6	-0.138	-1001	-0.138	-1001	1,593	-996	-14.3
7	-0.312	-1251	-0.312	-1251	1,566	-1268	-18.2
8	-0.505	-1514	-0.505	-1514	1,528	-1570	-22.5
9	-0.739	-1800	-0.739	-1800	1,475	-1937	-27.7
10	-0.826	-1903	-0.826	-1903	1,444	-2073	-29.7
11	-0.931	-2005	-0.931	-2005	1,413	-2238	-32.1
12	-1.189	-2254	-1.189	-2254	1,361	-2641	-37.8
13	-1.489	-2503	-1.489	-2503	1,292	-3111	-44.6
14	-1.726	-2650	-1.726	-2650	1,222	-3482	-49.9
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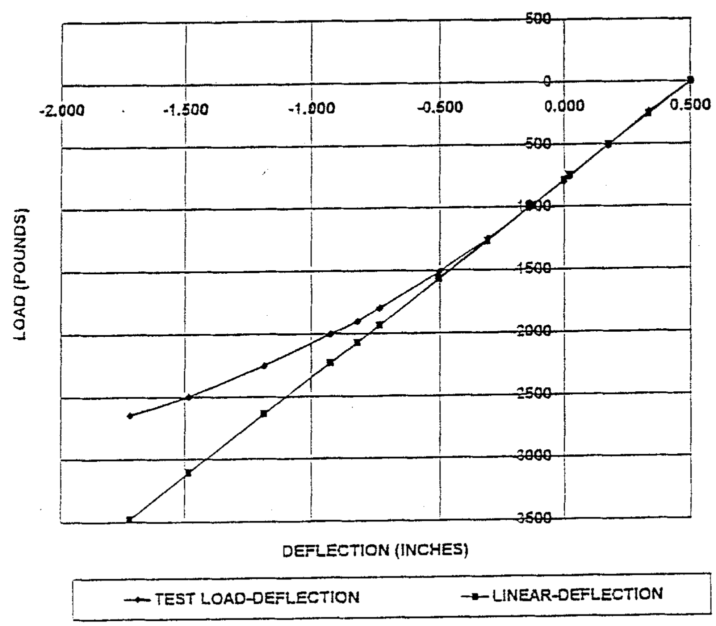

NOTES:

TEST #: TRUNNION-PIPE-A

TYPE: FATIGUE - LOAD DEFLECTION CURVE

NEGATIVE LOAD - UNLOADING CONDITION

$F = F_0 + m\,\delta$

"m" TO BE BASED ON N DATA POINTS, N = 6
THE VALUE OF "m" = 1650 F_0 (LBS) = 2

NOMINAL STRESS = M/Z KSI, M=F x L, L(IN) = 46.0625 $Z(IN^3)$ = 3.215

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	-1.726	-2650	-1.726	-2650	1826	-2407	-34.5
2	-1.557	-2300	-1.557	-2300	1794	-2128	-30.5
3	-1.412	-1998	-1.412	-1998	1763	-1889	-27.1
4	-1.283	-1749	-1.283	-1749	1736	-1676	-24.0
5	-1.097	-1397	-1.097	-1397	1697	-1369	-19.6
6	-0.874	-994	-0.874	-994	1650	-1001	-14.3
7	-0.738	-753	-0.738	-753	1608	-777	-11.1
8	-0.600	-518	-0.600	-518	1552	-549	-7.9
9	-0.449	-255	-0.449	-255	1404	-300	-4.3
10	-0.266	2	-0.266	2	N/A	2	0.0
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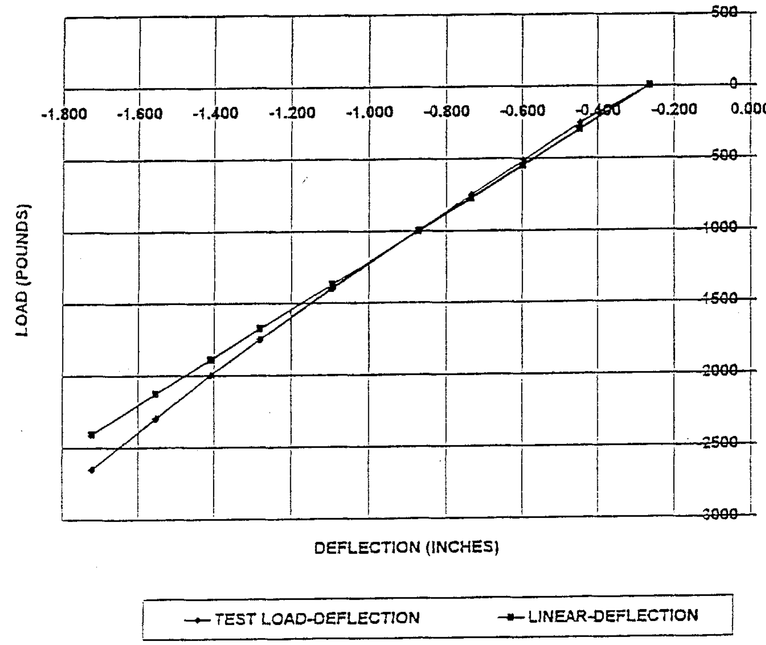
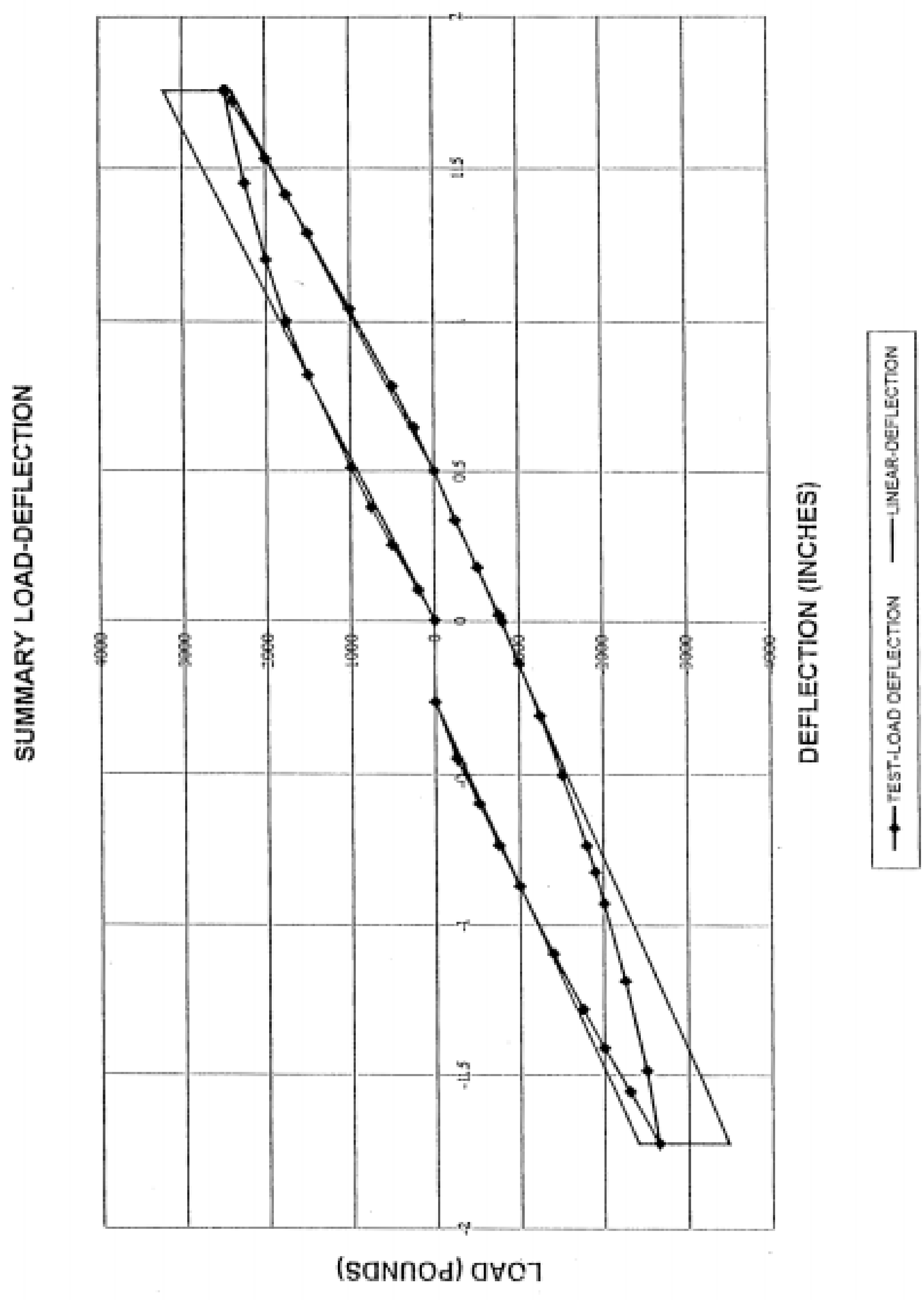


NOTES:
Deflection is in an upward direction.


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

FATIGUE TEST DATA ANALYSIS

TEST #: **TRUNNION-PIPE-A**

COMPONENT: TRUNNION ON PIPE

STIFFNESS (lbs/in) = 1741 MOMENT ARM (in)= 46.0625

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

TEST DISPLACEMENT/CYCLE DATA:

CONDITION #	DISPLACEMENT AMPLITUDE (+/-) (in.) d_i	EFFECTIVE APPLIED LOAD (lbs)	NOMINAL STRESS (+/-) (psi) S	NUMBER OF TEST CYCLES N_i
1	1.05	1828	26,193	500
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:	500

THE EQUIVALENT NO OF CYCLES, BASED ON A DISPLACEMENT OF d_{max} = 1.05

IS: $N_{eq} = SUM(d_i/d_{max})^5 * N_i$ = 500

FOR MEASURED DIMENSIONS: $i = 245{,}000 * N_{eq}^{(-0.2)}/S$ = 2.70

FOR NOMINAL DIMENSIONS: Z(IN^3) = 3.215 i = 2.70

COMMENTS:

1. HT # 0950276C (PIPE), #64022A (TRUNNION)
2. Load cell data indicated loads initially about +/- 2000 lbs.
3. Failure occured at toe of weld on pipe at bottom of trunnion.
4. Crack grew around bottom of weld, approximately 1/2 around trunnion.

TEST DATA

SPECIMEN: TRUNNION ON PIPE

TEST IDENTIFICATION: B

TEST #: TRUNNION-PIPE-B

TYPE: FATIGUE - LOAD DEFLECTION CURVE

$F = Fo + m\,\delta$

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

THE VALUE OF "m" = 1797 0

NOMINAL STRESS = M/Z KSI, M=F x L. L(IN) = 45.5 $Z(IN^3)$ = 3.215

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	-0.28	-514.5	-0.280	-514	1,979	-487	(6.6)
3	-0.533	-1005	-0.533	-1005	1,885	-958	(13.6)
4	-0.855	-1540	-0.855	-1540	1,797	-1537	(21.7)
5	-1.115	-1913	-1.115	-1913	1,716	-2004	(28.4)
6	-1.47	-2360	-1.470	-2360	1,610	-2642	(37.4)
7	-1.584	-2477	-1.584	-2477	1,564	-2847	(40.3)
8	-1.85	-2726	-1.850	-2726	1,479	-3325	(47.0)
9	-2.116	-2902	-2.116	-2902	1,388	-3803	(53.8)
10	-2.346	-3063	-2.346	-3063	1,308	-4216	(59.7)
11	-2.49	-3144	-2.490	-3144	1,247	-4475	(63.3)
12	-2.576	-3181	-2.576	-3181	1,202	-4630	(65.5)
13	-2.576	-3188	-2.576	-3188	1,174	-4630	(65.5)
14	-2.576	-3195	-2.576	-3195	1,156	-4630	(65.5)
15	-2.576	-3195	-2.576	-3195	1,143	-4630	(65.5)
16	-2.576	-3202	-2.576	-3202	1,134	-4630	(65.5)
17	-2.576	-3210	-2.576	-3210	1,127	-4630	(65.5)
18	-2.576	-3217	-2.576	-3217	1,122	-4630	(65.5)
19	-2.576	-3224	-2.576	-3224	1,118	-4630	(65.5)
20							
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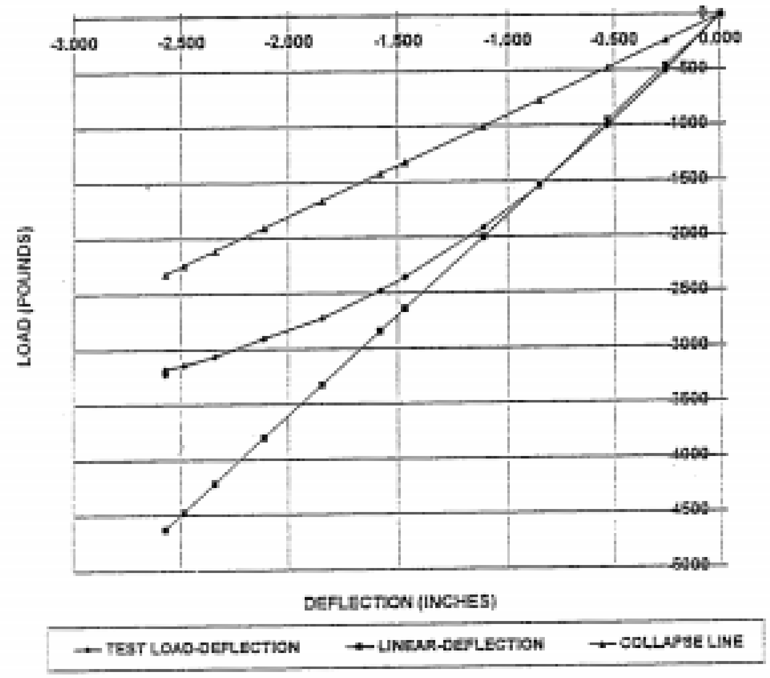
25							

POSITIVE LOAD - LOADING CONDITION



NOTES:
Loading is in an upward direction. For purposes of the evaluation of the stiffness calculation, the directions of loading (e.g. positive load-loading condition) will remain the same. The sign of the deflection will indicate the load direction.

TEST #: TRUNNION-PIPE-B **TYPE:** FATIGUE - LOAD DEFLECTION CURVE

F = Fo + m δ "m" TO BE BASED ON N DATA POINTS, N = 5
THE VALUE OF "m" = 1755 Fo (LBS) = 64

NOMINAL STRESS = M/Z KSI, M=F x L, L(IN) = 45.5 Z(IN³) = 3.215

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	-2.576	-3224	-2.576	-3224	1,979	-2814	-39.8
2	-2.576	-3232	-2.576	-3232	1,931	-2814	-39.8
3	-2.576	-2997	-2.576	-2997	1,855	-2814	-39.8
4	-2.486	-2712	-2.486	-2712	1,800	-2656	-37.6
5	-2.349	-2411	-2.349	-2411	1,755	-2416	-34.2
6	-2.209	-2104	-2.209	-2104	1,705	-2170	-30.7
7	-2.063	-1796	-2.063	-1796	1,652	-1914	-27.1
8	-1.877	-1430	-1.877	-1430	1,595	-1588	-22.5
9	-1.698	-1108	-1.698	-1108	1,547	-1273	-18.0
10	-1.513	-800.1	-1.513	-800	1,501	-949	-13.4
11	-1.335	-507.2	-1.335	-507	1,431	-636	-9.0
12	-1.141	-206.9	-1.141	-207	1,322	-296	-4.2
13	-0.936	64	-0.936	64	N/A	64	0.9
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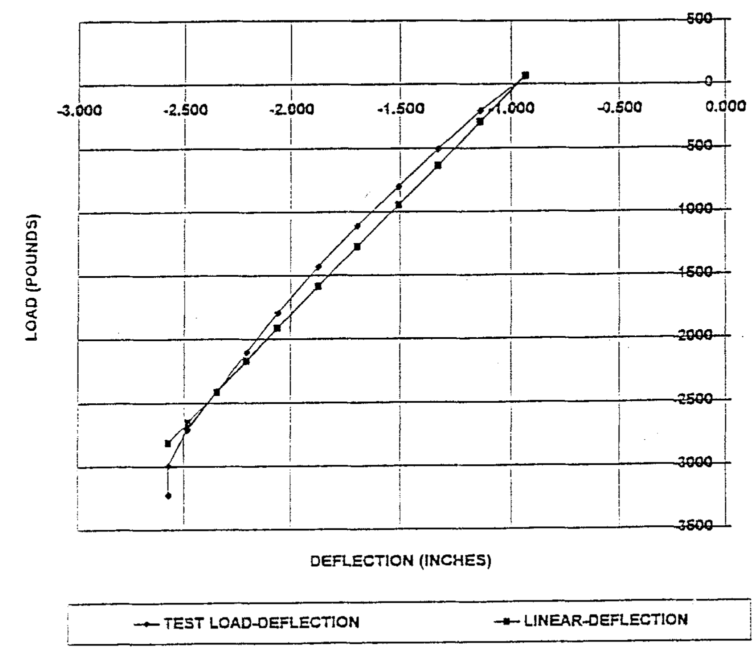
NOTES:

POSITIVE LOAD - UNLOADING CONDITION



TEST #: TRUNNION-PIPE-B

TYPE: FATIGUE - LOAD DEFLECTION CURVE

NEGATIVE LOAD - LOADING CONDITION

$F = Fo + m\,\delta$

"m" TO BE BASED ON N DATA POINTS, N = 5
THE VALUE OF "m" = 1495

Fo (LBS) = 64.119

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

L(IN) = 45.5

$Z(IN^3)$ = 3.215

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	-0.936	64.119	-0.936	64	N/A	64	0.9
2	-0.782	291.17	-0.782	291	1,474	294	4.2
3	-0.573	606.111	-0.573	606	1,494	607	8.6
4	-0.38	899.08	-0.380	899	1,503	895	12.7
5	-0.174	1199.373	-0.174	1199	1,495	1203	17.0
6	0.052	1499.666	0.052	1500	1,464	1541	21.8
7	0.259	1748.689	0.259	1749	1,425	1850	26.2
8	0.331	1799.959	0.331	1800	1,391	1958	27.7
9	0.463	1961.092	0.463	1961	1,365	2155	30.5
10	0.555	2063.631	0.555	2064	1,345	2292	32.4
11	0.636	2144.197	0.636	2144	1,326	2414	34.2
12	0.688	2195.467	0.688	2195	1,311	2491	35.3
13	0.734	2224.763	0.734	2225	1,295	2560	36.2
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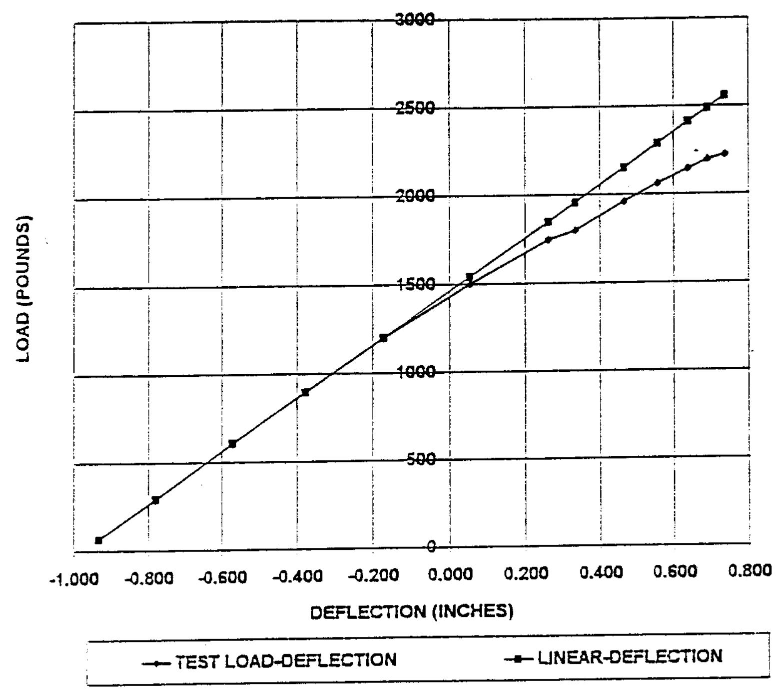

NOTES:

TEST #: TRUNNION-PIPE-B

TYPE: FATIGUE - LOAD DEFLECTION CURVE

NEGATIVE LOAD - UNLOADING CONDITION

$F = F_o + m\,\delta$

"m" TO BE BASED ON N DATA POINTS, N = 3

THE VALUE OF "m" = 1881

Fo (LBS) = -9.123

NOMINAL STRESS = M/Z KSI, M=F x L, L(IN) = 45.5 Z(IN³) = 3.215

DATA POINT	MEASURED DEFLECTION	MEASURED LOAD	MODIFIED DEFLECTION	MODIFIED LOAD	SLOPE FOR START TO DATA POINT	F BASED ON "m"	NOMINAL STRESS
#	δ (INCHES)	F (LBS)	δ (INCHES)	F (LBS)	(LBS/INCH)	(LBS)	(KSI)
1	0.734	2224.763	0.734	2225	1953	2127	30.1
2	0.597	1917.146	0.597	1917	1917	1870	26.5
3	0.457	1616.853	0.457	1617	1881	1606	22.7
4	0.311	1316.56	0.311	1317	1839	1332	18.8
5	0.168	1016.267	0.168	1016	1782	1063	15.0
6	0.016	715.974	0.016	716	1718	777	11.0
7	-0.141	415.681	-0.141	416	1626	482	6.8
8	-0.332	100.74	-0.332	101	1557	123	1.7
9	-0.394	5.525	-0.394	6	1831	6	0.1
10	-0.402	-9.123	-0.402	-9	N/A	-9	-0.1
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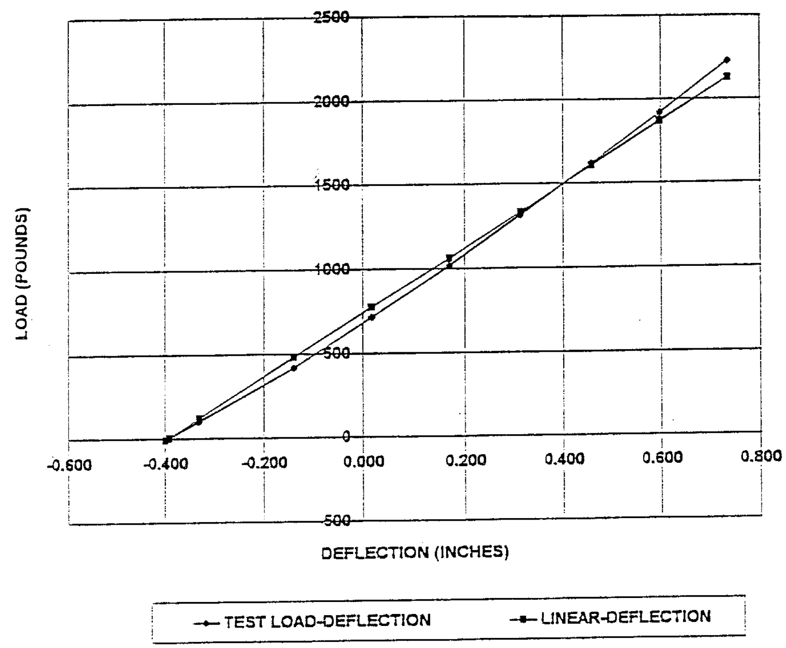
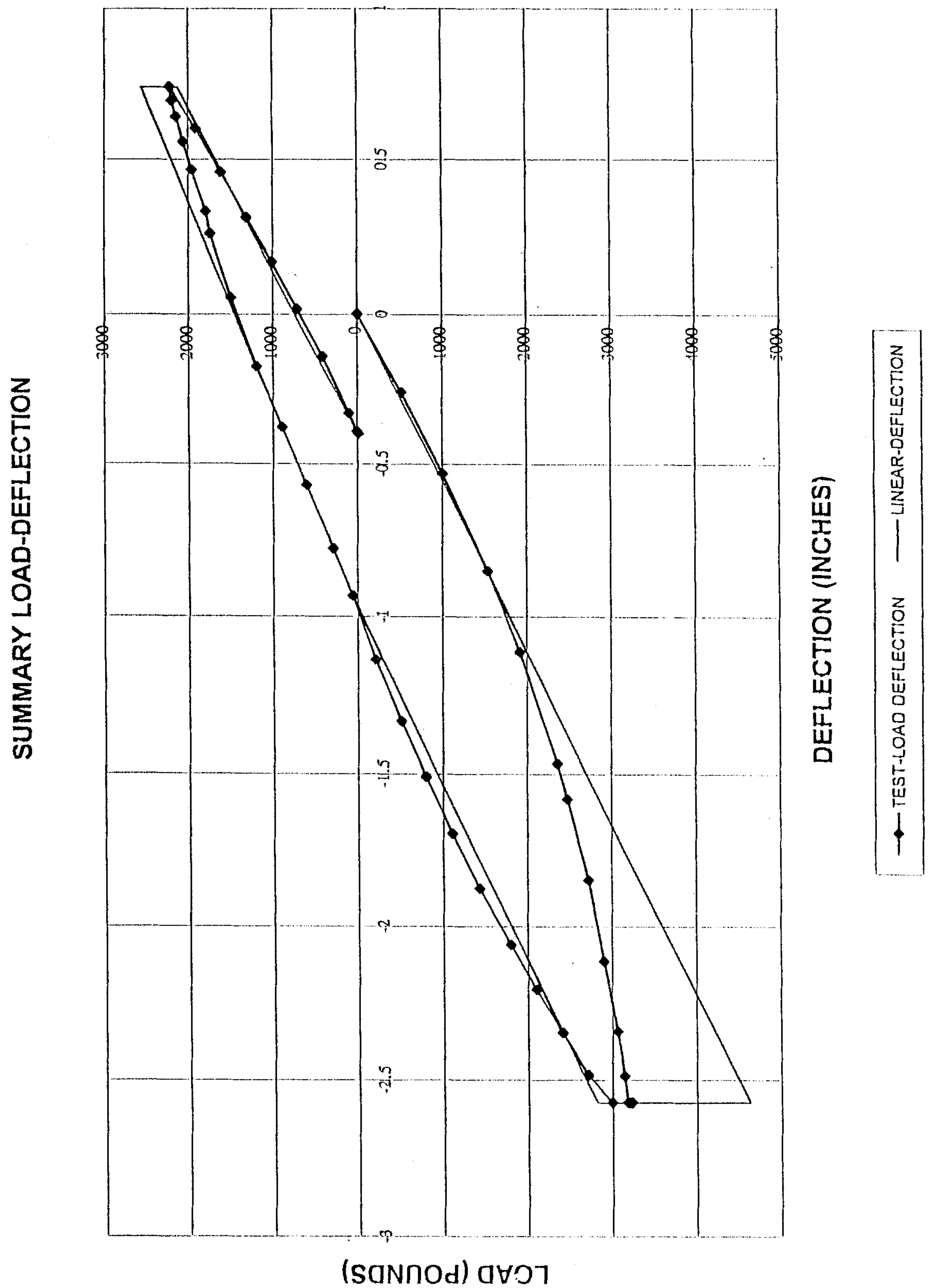
NOTES:
Deflection is in an upward direction.




SUMMARY LOAD-DEFLECTION
DEFLECTION (INCHES)
LOAD (POUNDS)
-3000
-2000
-1000
0
1000
2000
3000
4000
5000
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
TEST-LOAD DEFLECTION
LINEAR-DEFLECTION

FATIGUE TEST DATA ANALYSIS

TEST #: **TRUNNION-PIPE-B**

COMPONENT: TRUNNION ON PIPE

STIFFNESS (lbs/in) = 1732 MOMENT ARM (in)= 45.5

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

TEST DISPLACEMENT/CYCLE DATA:

CONDITION #	DISPLACEMENT AMPLITUDE (+/-) (in.) d_i	EFFECTIVE APPLIED LOAD (lbs)	NOMINAL STRESS (+/-) (psi) S	NUMBER OF TEST CYCLES N_i
1	0.90	1559	22,057	1,280
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:	1,280

THE EQUIVALENT NUMBER OF CYCLES, BASED ON A DISPLACEMENT O $d_{max}=$ 0.9

IS: $N_{eq} = SUM(d_i/d_{max})^5 * N_i =$ 1,280

FOR MEASURED DIMENSIONS: $i = 245{,}000 * N_{eq}^{(-0.2)}/S =$ **2.656**

FOR NOMINAL DIMENSIONS: Z(IN^3) = 3.215 i = **2.656**

COMMENTS:

1. HT # 0950276C (PIPE), #64022A (TRUNNION)
2. Load initially in up direction.

TEST DATA

SPECIMEN: TRUNNION ON PIPE

TEST IDENTIFICATION: C

TEST #: TRUNNION-PIPE-C

TYPE: FATIGUE - LOAD DEFLECTION CURVE

$F = Fo + m\,\delta$

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

THE VALUE OF "m" = 1752 0

NOMINAL STRESS = M/Z KSI, M=F x L, L(IN) = 46.125 $Z(IN^3)$ = 3.215

DA POI #	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	0.137	248	0.137	248	1,810	240	3.4
3	0.281	505	0.281	505	1,797	492	7.1
4	0.431	754	0.431	754	1,752	755	10.8
5	0.592	1003	0.592	1003	1,698	1037	14.9
6	0.752	1252	0.752	1252	1,661	1318	18.9
7	0.919	1501	0.919	1501	1,629	1610	23.1
8	1.106	1757	1.106	1757	1,589	1938	27.8
9	1.299	1984	1.299	1984	1,537	2276	32.7
10	1.3	1984	1.300	1984	1,514	2278	32.7
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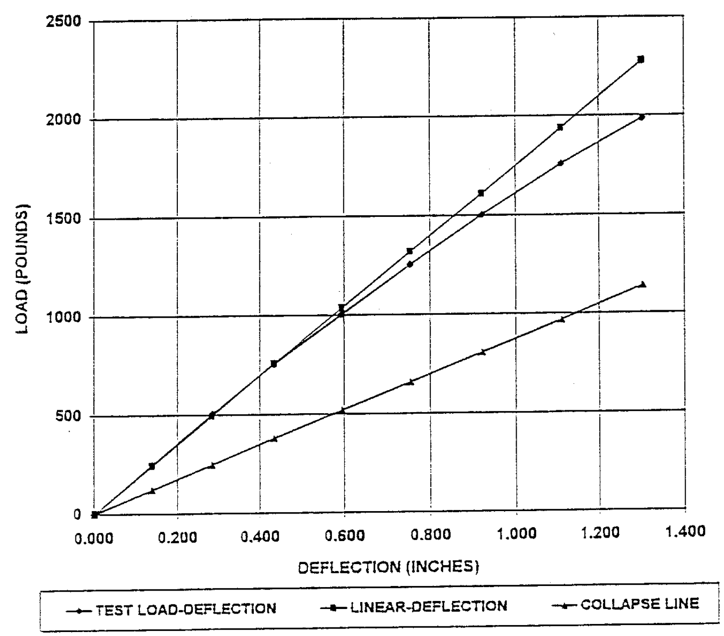
NOTES:
L LOAD IS IN DOWN DIRECTION.

POSITIVE LOAD - LOADING CONDITION



TEST #: TRUNNION-PIPE-C

TYPE: FATIGUE - LOAD DEFLECTION CURVE

$F = Fo + m\,\delta$ "m" TO BE BASED ON N DATA POINTS, N = 3

THE VALUE OF "m" = 1877 Fo (LBS) = 0

NOMINAL STRESS = M/Z KSI, M=F x L, L(IN) = 46.125 Z(IN^3) = 3.215

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	1.3	1984	1.300	1984	1,966	1883	27.0
2	1.196	1706	1.196	1706	1,910	1688	24.2
3	1.099	1501	1.099	1501	1,877	1506	21.6
4	0.953	1200	0.953	1200	1,833	1231	17.7
5	0.856	1003	0.856	1003	1,794	1049	15.1
6	0.757	805	0.757	805	1,749	864	12.4
7	0.649	600	0.649	600	1,701	661	9.5
8	0.541	402	0.541	402	1,647	458	6.6
9	0.424	205	0.424	205	1,614	238	3.4
10	0.297	0	0.297	0	N/A	0	0.0
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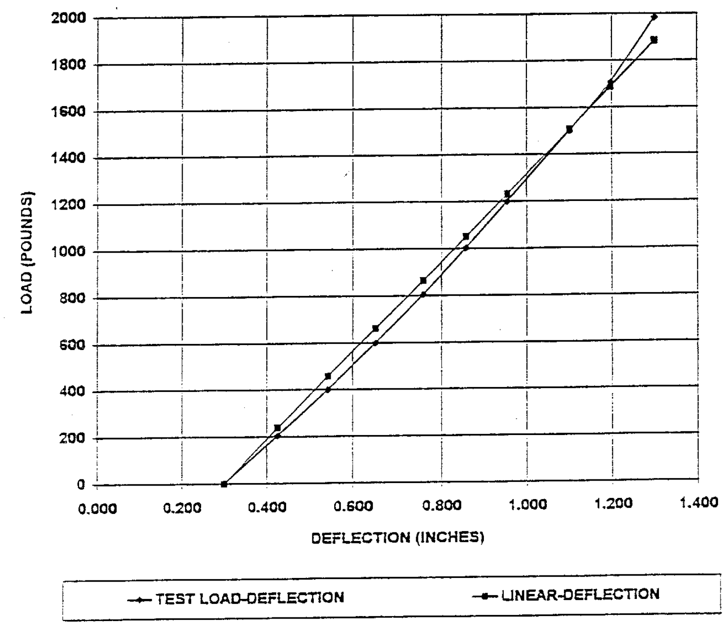
NOTES:

POSITIVE LOAD - UNLOADING CONDITION



TEST #: TRUNNION-PIPE-C

TYPE: FATIGUE - LOAD DEFLECTION CURVE

NEGATIVE LOAD - LOADING CONDITION

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

THE VALUE OF "m" = 1473 Fo (LBS) = 0

NOMINAL STRESS = M/Z KSI, M=F x L, L(IN) = 46.125 Z(IN^3) = 3.215

DATA POINT	MEASURED		MODIFIED		SLOPE FOR START TO DATA POINT	F BASED ON "m"	NOMINAL STRESS
#	DEFLECTION δ (INCHES)	LOAD F (LBS)	DEFLECTION δ (INCHES)	LOAD F (LBS)	(LBS/INCH)	(LBS)	(KSI)
1	0.297	0	0.297	0	N/A	0	0.0
2	0.143	-205	0.143	-205	1,331	-227	-3.3
3	0.01	-403	0.010	-403	1,402	-423	-6.1
4	-0.12	-601	-0.120	-601	1,444	-614	-8.8
5	-0.247	-798	-0.247	-798	1,473	-801	-11.5
6	-0.38	-1003	-0.380	-1003	1,491	-997	-14.3
7	-0.516	-1201	-0.516	-1201	1,494	-1197	-17.2
8	-0.668	-1406	-0.668	-1406	1,481	-1421	-20.4
9	-0.829	-1605	-0.829	-1605	1,456	-1658	-23.8
10	-0.992	-1802	-0.992	-1802	1,427	-1898	-27.2
11	-1.18	-2007	-1.180	-2007	1,390	-2175	-31.2
12	-1.287	-2117	-1.287	-2117	1,361	-2333	-33.5
13	-1.292	-2117	-1.292	-2117	1,344	-2340	-33.6
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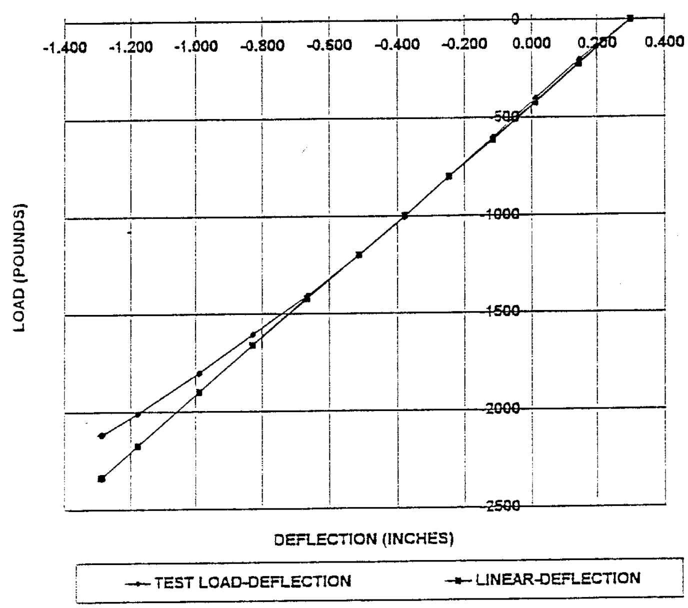

NOTES:

TEST #: TRUNNION-PIPE-C

TYPE: FATIGUE - LOAD DEFLECTION CURVE

F = Fo + m δ

"m" TO BE BASED ON N DATA POINTS, N = 3

THE VALUE OF "m" = 1707 Fo (LBS) = -15

NOMINAL STRESS = M/Z KSI, M=F x L, L(IN) = 46.125 Z(IN³) = 3.215

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	-1.292	-2117	-1.292	-2117	1805	-2004	-28.7
2	-1.21	-1904	-1.210	-1904	1753	-1864	-26.7
3	-1.117	-1699	-1.117	-1699	1707	-1705	-24.5
4	-1.025	-1509	-1.025	-1509	1660	-1548	-22.2
5	-0.929	-1304	-0.929	-1304	1605	-1384	-19.9
6	-0.831	-1106	-0.831	-1106	1551	-1217	-17.5
7	-0.66	-806	-0.660	-806	1490	-925	-13.3
8	-0.53	-601	-0.530	-601	1452	-703	-10.1
9	-0.341	-301	-0.341	-301	1336	-380	-5.5
10	-0.127	-15	-0.127	-15	N/A	-15	-0.2
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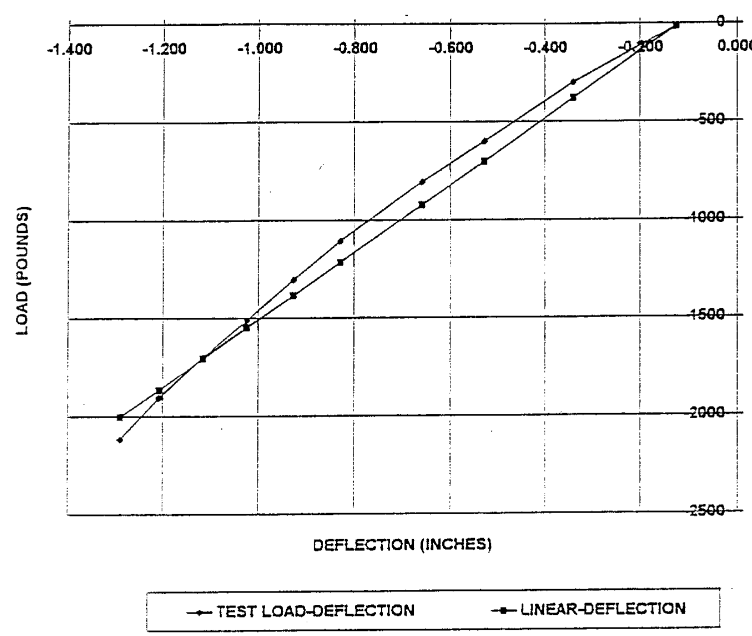
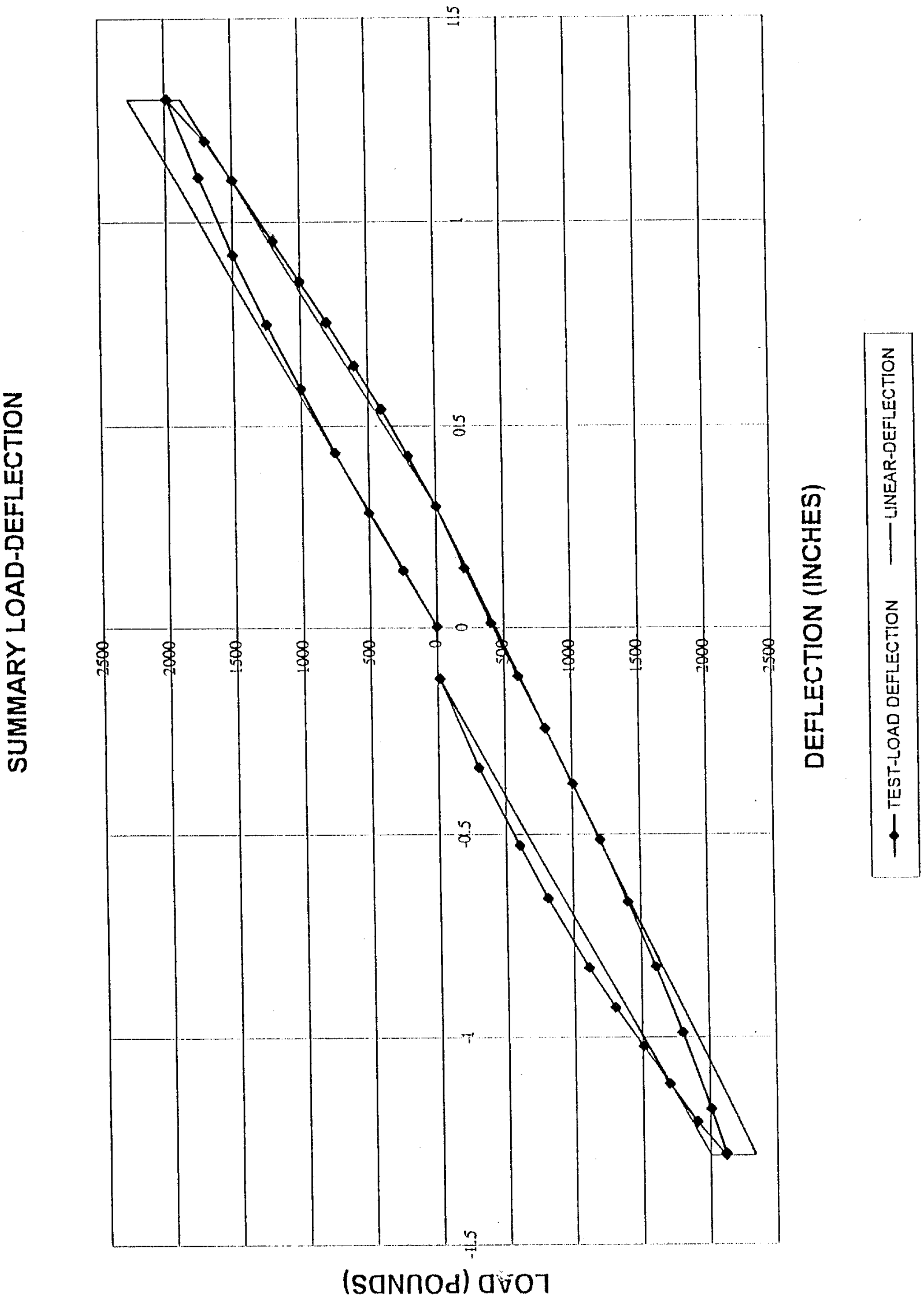
NEGATIVE LOAD - UNLOADING CONDITION



NOTES:

Deflection is in an upward direction.


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

FATIGUE TEST DATA ANALYSIS

TEST #: **TRUNNION-PIPE-C**

COMPONENT: TRUNNION ON PIPE

STIFFNESS (lbs/in) = 1702 MOMENT ARM (in)= 46.125

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

TEST DISPLACEMENT/CYCLE DATA:

CONDITION #	DISPLACEMENT AMPLITUDE (+/-) (in.) d_i	EFFECTIVE APPLIED LOAD (lbs)	NOMINAL STRESS (+/-) (psi) S	NUMBER OF TEST CYCLES N_i
1	0.90	1532	21,978	934
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:	934

THE EQUIVALENT NUMBER OF CYCLES, BASED ON A DISPLACEMENT O $d_{max} =$ 0.9

IS: $N_{eq} = SUM(d_i/d_{max})^5 * N_i =$ 934

FOR MEASURED DIMENSIONS: $i = 245{,}000 * N_{eq}^{(-0.2)}/S =$ **2.839**

FOR NOMINAL DIMENSIONS: $Z(IN^3) =$ 3.215 $i =$ **2.839**

COMMENTS:

1. HT # 0950276C (PIPE), #64022A (TRUNNION)
2. Load initially in up direction.

TEST DATA

SPECIMEN: TRUNNION ON PIPE

TEST IDENTIFICATION: D

TEST #: TRUNNION-PIPE-D

TYPE: FATIGUE - LOAD DEFLECTION CURVE

POSITIVE LOAD - LOADING CONDITION

$F = F_o + m\,\delta$ "m" TO BE BASED ON N DATA POINTS, N = 6

THE VALUE OF "m" = 1890 0

NOMINAL STRESS = M/Z KSI, M=F x L, L(IN) = 45.5 Z(IN³) = 3.215

DATA POINT	MEASURED		MODIFIED		SLOPE FOR START TO DATA POINT	F BASED ON "m"	NOMINAL STRESS
	DEFLECTION δ	LOAD F	DEFLECTION δ	LOAD F			
#	(INCHES)	(LBS)	(INCHES)	(LBS)	(LBS/INCH)	(LBS)	(KSI)
1	0	0	0.000	0	N/A	0	
2	0.098	205	0.098	205	2,092	185	2.6
3	0.204	402	0.204	402	1,969	386	5.5
4	0.304	600	0.304	600	1,961	575	8.1
5	0.419	805	0.419	805	1,919	792	11.2
6	0.529	1003	0.529	1003	1,890	1000	14.1
7	0.646	1201	0.646	1201	1,856	1221	17.3
8	0.768	1406	0.768	1406	1,826	1452	20.5
9	0.892	1604	0.892	1604	1,795	1686	23.9
10	1.027	1801	1.027	1801	1,757	1941	27.5
11	1.176	2000	1.176	2000	1,711	2223	31.5
12	1.21	2028	1.210	2028	1,679	2287	32.4
13	1.248	2065	1.248	2065	1,652	2359	33.4
14	1.335	2182	1.335	2182	1,628	2523	35.7
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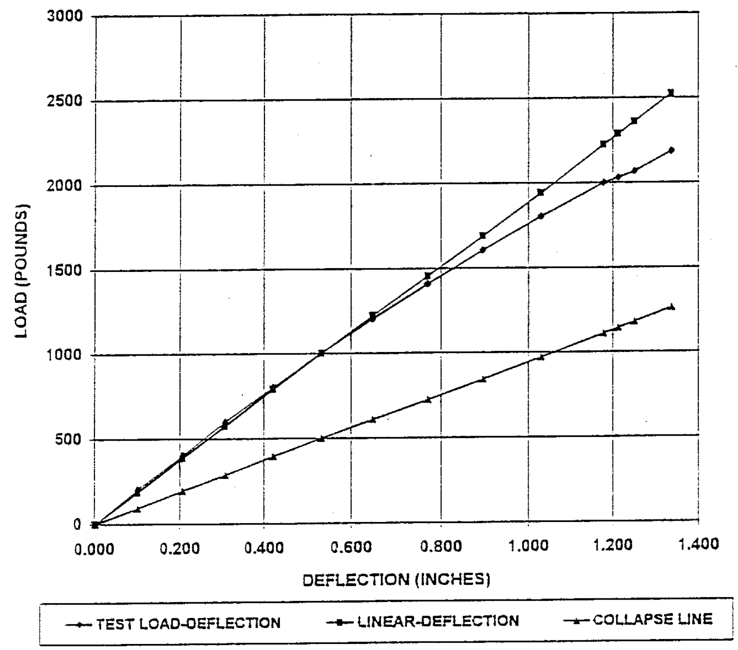

NOTES:

Loading is in an upward direction. For purposes of the evaluation of the stiffness calculation, the directions of loading (e.g. positive load-loading condition) will remain the same. The sign of the deflection will indicate the load direction.

TEST #: TRUNNION-PIPE-D

TYPE: FATIGUE - LOAD DEFLECTION CURVE

$F = F_o + m\,\delta$

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

THE VALUE OF "m" = 1903

F_o (LBS) = 0

NOMINAL STRESS = M/Z KSI, M=F x L, L(IN) = 45.5 Z(IN³) = 3.215

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	1.335	2182	1.335	2182	2,003	2082	29.5
2	1.254	2000	1.254	2000	1,985	1928	27.3
3	1.112	1699	1.112	1699	1,963	1658	23.5
4	0.969	1406	0.969	1406	1,939	1385	19.6
5	0.82	1098	0.820	1098	1,903	1102	15.6
6	0.671	798	0.671	798	1,855	818	11.6
7	0.525	505	0.525	505	1,775	540	7.6
8	0.408	285	0.408	285	1,707	318	4.5
9	0.326	146	0.326	146	1,718	162	2.3
10	0.241	0	0.241	0	N/A	0	0.0
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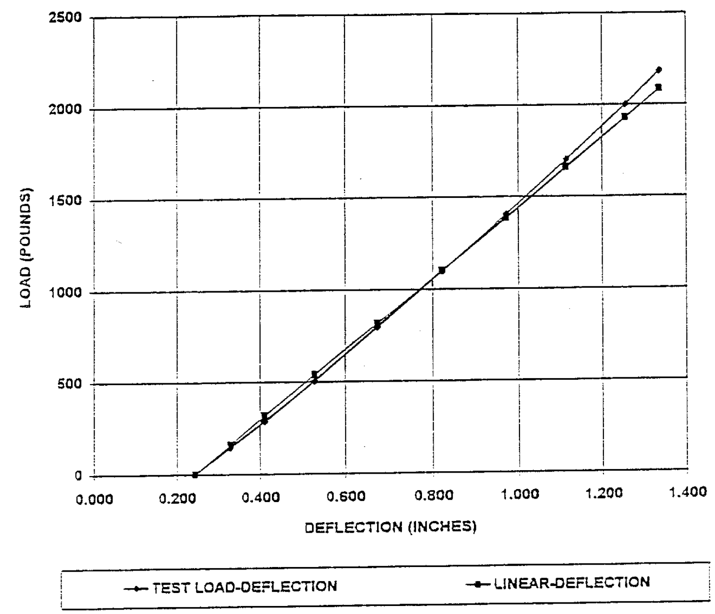
NOTES:

POSITIVE LOAD - UNLOADING CONDITION



TEST #: TRUNNION-PIPE-D

TYPE: FATIGUE - LOAD DEFLECTION CURVE

NEGATIVE LOAD - LOADING CONDITION

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

THE VALUE OF "m" = 1766 Fo (LBS) = 0

NOMINAL STRESS = M/Z KSI, M=F x L, L(IN) = 45.5 Z(IN^3) = 3.215

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	0.241	0	0.241	0	N/A	0	0.0
2	0.136	-175	0.136	-175	1,667	-185	-2.6
3	0	-425	0.000	-425	1,767	-426	-6.0
4	-0.124	-644	-0.124	-644	1,774	-644	-9.1
5	-0.238	-857	-0.238	-857	1,793	-846	-12.0
6	-0.354	-1054	-0.354	-1054	1,786	-1051	-14.9
7	-0.508	-1310	-0.508	-1310	1,766	-1323	-18.7
8	-0.704	-1611	-0.704	-1611	1,726	-1669	-23.6
9	-0.983	-2000	-0.983	-2000	1,660	-2161	-30.6
10	-1.143	-2197	-1.143	-2197	1,608	-2444	-34.6
11	-1.291	-2350	-1.291	-2350	1,558	-2705	-38.3
12	-1.361	-2409	-1.361	-2409	1,521	-2829	-40.0
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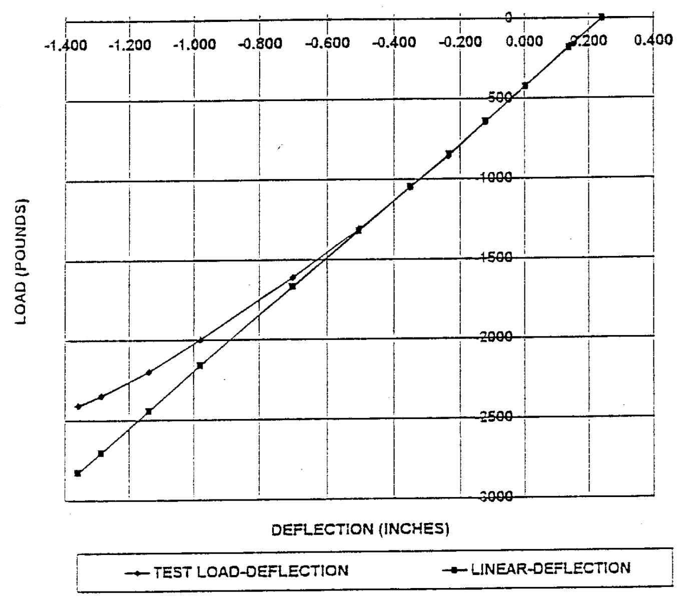

NOTES:

TEST #: TRUNNION-PIPE-D

TYPE: FATIGUE - LOAD DEFLECTION CURVE

$F = Fo + m\delta$

"m" TO BE BASED ON N DATA POINTS, N = 3

THE VALUE OF "m" = 1806

Fo (LBS) = 0

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

L(IN) = 45.5

Z(IN³) = 3.215

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	-1.361	-2409	-1.361	-2409	1944	-2179	-30.8
2	-1.25	-2072	-1.250	-2072	1867	-1978	-28.0
3	-1.072	-1669	-1.072	-1669	1806	-1657	-23.4
4	-0.909	-1332	-0.909	-1332	1760	-1362	-19.3
5	-0.677	-900	-0.677	-900	1721	-943	-13.3
6	-0.558	-688	-0.558	-688	1708	-728	-10.3
7	-0.424	-461	-0.424	-461	1705	-486	-6.9
8	-0.338	-307	-0.338	-307	1677	-331	-4.7
9	-0.244	-153	-0.244	-153	1719	-161	-2.3
10	-0.155	0	-0.155	0	N/A	0	0.0
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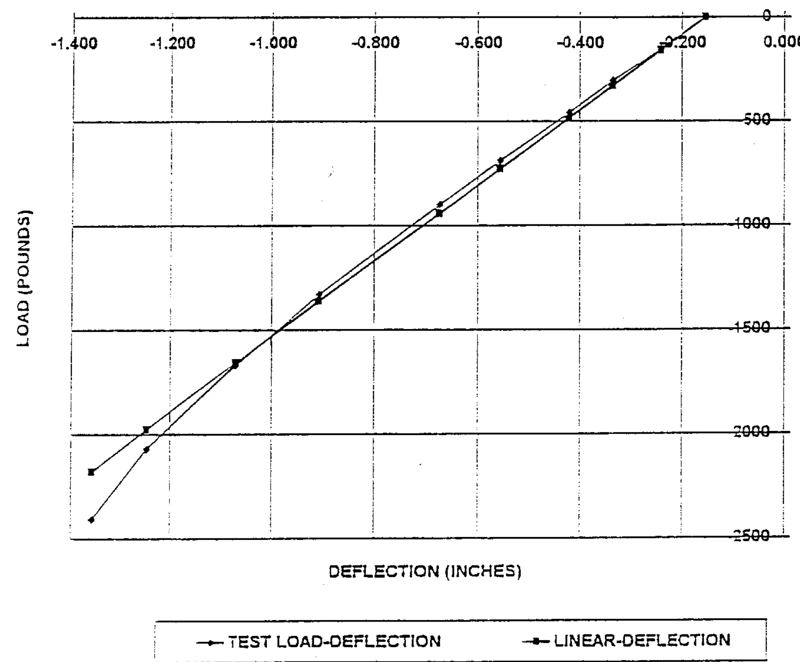
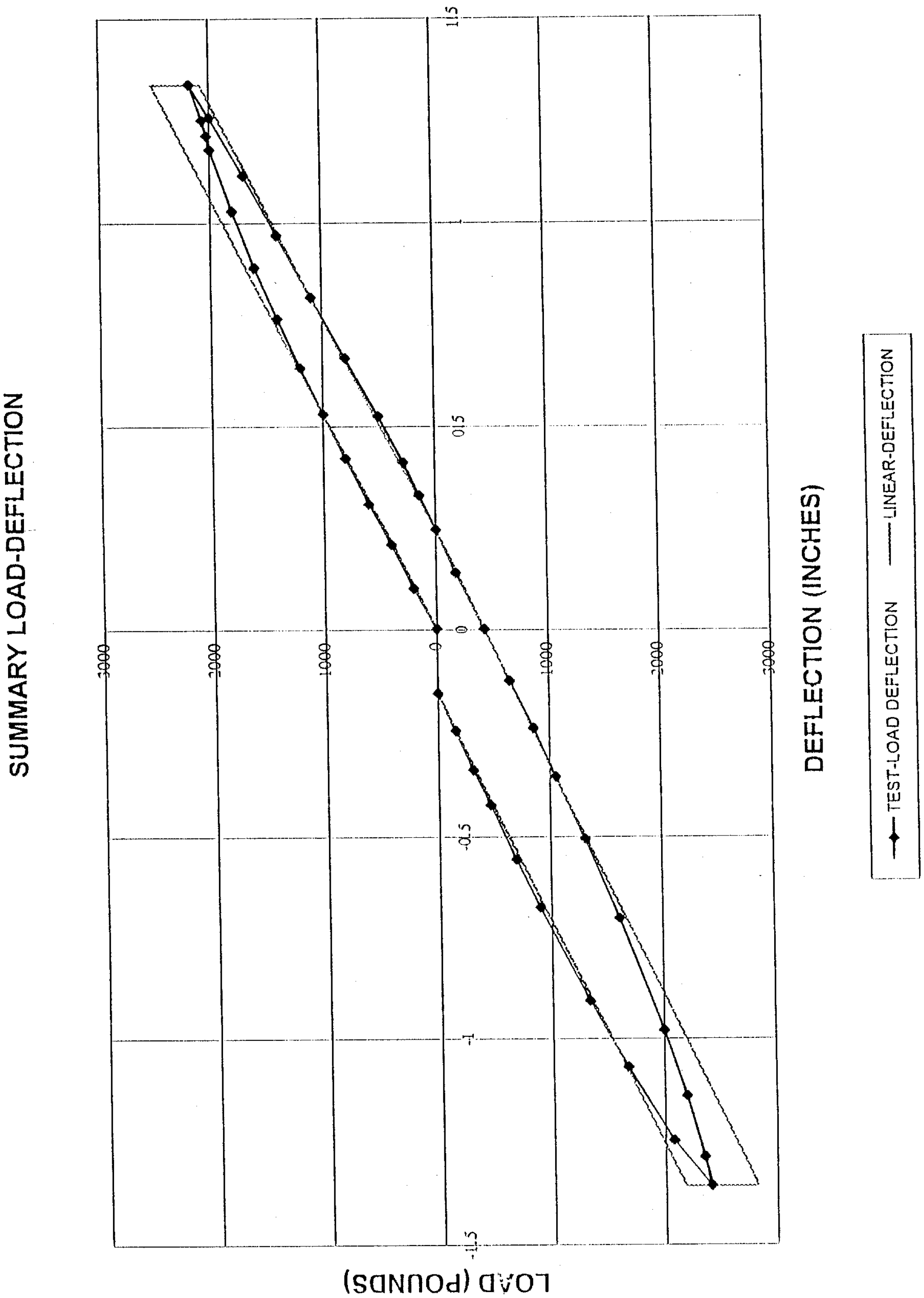
NOTES:
Deflection is in an upward direction.

NEGATIVE LOAD - UNLOADING CONDITION




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

FATIGUE TEST DATA ANALYSIS

TEST #: **TRUNNION-PIPE-D**

COMPONENT: TRUNNION ON PIPE

STIFFNESS (lbs/in) = 1841

MOMENT ARM (in)= 45.5

D (in) = 4.5

t (in) = 0.237

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

TEST DISPLACEMENT/CYCLE DATA:

CONDITION #	DISPLACEMENT AMPLITUDE (+/-) (in.) d_I	EFFECTIVE APPLIED LOAD (lbs)	NOMINAL STRESS (+/-) (psi) S	NUMBER OF TEST CYCLES N_I
1	0.80	1473	20,845	1,866
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:	1,866

THE EQUIVALENT NUMBER OF CYCLES, BASED ON A DISPLACEMENT O d_{max} = 0.8

IS: $N_{eq} = SUM(d_I/d_{max})^5 * N_I$ = 1,866

FOR MEASURED DIMENSIONS: $i = 245,000 * N_{eq}^{(-0.2)}/S$ = **2.606**

FOR NOMINAL DIMENSIONS: $Z(IN^3)$ = 3.215 i = **2.606**

COMMENTS:

1. HT # 0950276C (PIPE), #64022A (TRUNNION)
2. Load initiallly in up direction.

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