Stress Indices for Circumferential Fillet Welded and Socket Welded Joints

This report describes research sponsored by EPRI and the U.S. Department of Energy under the Nuclear Energy Plant Optimization (NEPO) Program.

Technical Report

Stress Indices for Circumferential Fillet Welded and Socket Welded Joints

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EPRI Project Manager
R. Carter

EPRI • 3412 Hillview Avenue, Palo Alto, California 94304 • PO Box 10412, Palo Alto, California 94303 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com

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CITATIONS

This report was prepared by

Wais and Associates, Inc.
2475 Spalding Drive
Atlanta, Georgia 30350
waisassoc@aol.com

Principal Investigators
E. A. Wais
E. C. Rodabaugh

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REPORT SUMMARY

Design and engineering for fatigue are major concerns in piping systems. Stress indices are used in the design of piping systems that must meet the requirements of ASME Section III for Class 1 systems. This report reviews the basis for the existing values of certain stress indices for circumferential and socket welded joints and develops new values based on more recent data.

Background

The ASME Section III Code uses factors such as C_2 and K_2 indices to account for the fatigue effects produced by reversing loads. For piping systems designed to the Class 1 requirements of ASME Section III, stress indices are used to evaluate specific stress limits. In addition, a fatigue analysis that uses these indices is performed. For piping systems designed to the Class 2 or 3 requirements of Section III, stress intensification factors (SIFs) are used. The SIFs are “fatigue correlation factors” that compare the fatigue life of piping components (for example, tees and branch connections) to that of circumferential butt welds in straight pipe subjected to bending moments. Recently, Section III approved Code Case N-646 that modified the SIFs for circumferential fillet welded or socket welded joints. The technical basis for the modification was EPRI TR-106415, *Evaluation of Stress Intensification Factors for Circumferential Fillet Welded or Socket Welded Joints.*

This report reviews TR-106415 and other data and recommends changes to the stress indices used in a Class 1 analysis.

Objectives

- To develop more accurate values of the B_1, B_2, and C_2 stress indices for circumferential fillet welded and socket welded joints
- To establish the limits of applicability of the stress indices

Approach

A review of the present approach for the evaluation of circumferential fillet welded and socket welded stress indices in accordance with the ASME Code provided information on the current methodology for determining the various indices. Available data on studies, experiments, and testing were collected and reviewed. Fatigue evaluations were performed to estimate the values of the C_2 stress index.

Results

Test data for undersized and small welds were used to conservatively estimate B_2 indices. The C_2 indices were evaluated by two methods: 1) using the relationship between SIFs and the stress indices ($i = C_2K_2/2$) and 2) performing fatigue evaluations of test data on small welds.

The following are the specific results of this study:

- The value of the stress index associated with primary stresses due to moments, B_2, can be changed from $B_2 = 1.5\ (t_n/C_x) \geq 1.0$ to $B_2 = 1.0$.
- The value of the stress index associated with the primary plus secondary stresses due to moments, C_2, can be changed from $C_2 = 2.1\ (t_n/C_x) \geq 1.3$ to $C_2 = 1.3$.
- The value of the stress index associated with primary stresses due to pressure, B_1, can be limited to a maximum of 0.75.

These recommendations are applicable for configurations where $(C_x / t_n) \geq 0.75$.

EPRI Perspective

Design for fatigue is a significant concern for any power or process facility. Accurate methods of engineering for fatigue are important to ensure cost-effective design, determine root cause failures, and evaluate remaining fatigue life of plant designs. This work continues to establish the technical justification to allow for reductions in current ASME Code stress indices. These and associated reductions in design stresses can provide a basis for reducing the scope of ongoing 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.

Keywords

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

ABSTRACT

Stress indices are used in the design of piping systems that must meet the requirements of ASME Section III for Class 1 systems. This report reviews the basis for the existing values of certain stress indices for circumferential fillet welded and socket welded joints and develops new values based on more recent data. The values presented in this report significantly improve the evaluation of circumferential fillet welded and socket welded joints.

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INTRODUCTION

1.1 Background

For piping systems designed to the Class 1 requirements of ASME Section III [1], stress indices are used to evaluate specific stress limits. In addition, a fatigue analysis that uses these indices is performed. For piping systems designed to the Class 2 or 3 requirements of Section III, stress intensification factors (SIFs) are used. The SIFs are "fatigue correlation factors" that compare the fatigue life of piping components (for example, tees and branch connections) to that of welds in straight pipe subjected to bending moments. Recently, Section III approved a Code Case [2] that modified the SIFs for circumferential fillet welded or socket welded joints. The basis for the modification was the EPRI study on SIFs for these joints [3]. This report reviews EPRI TR-106415 [3] and other data and recommends changes to the stress indices used in Class 1 analysis.

1.2 Nomenclature

B_2 = stress index related to primary stress intensity

B_2' = stress index related to primary stress intensity based on test data

C = constant in Markl's equation: 245,000 for carbon steel

C_2 = stress index related to secondary stress intensity

C_x = dimension associated with socket welds (see Figure 1-1)

δ_i = deflection of i^{th} loading condition, in.

δ_{max} = maximum test deflection, in.

D_o = outside diameter of the pipe, in.

i = stress intensification factor

K_2 = stress index related to peak stress intensity

K_e = plasticity factor used in fatigue analysis from NB-3653.6 [1]

L = length from load point to failure point, in.

M = bending moment, in-lb.

M_{LIMIT} = limit bending moment, in-lb.

m = material parameter from Table NB-3228.5(b)-1 [1]

n = material parameter from Table NB-3228.5(b)-1 [1]

N = number of cycles to failure

S = nominal stress range, psi

S_{alt} = alternating stress, psi (see Equation 3-1)

S_m = design stress intensity [1]

S_{nom} = nominal bending stress from tests

S_n = primary plus secondary stress intensity range, psi [1]

S_p = peak stress intensity range, psi [1]

S_{alt} = alternating stress intensity amplitude ($S_{alt} = K_e S_p/2$), psi [1]

S_y = yield stress, psi

t_n = nominal thickness of the pipe

Z = section modulus of the pipe, in^3

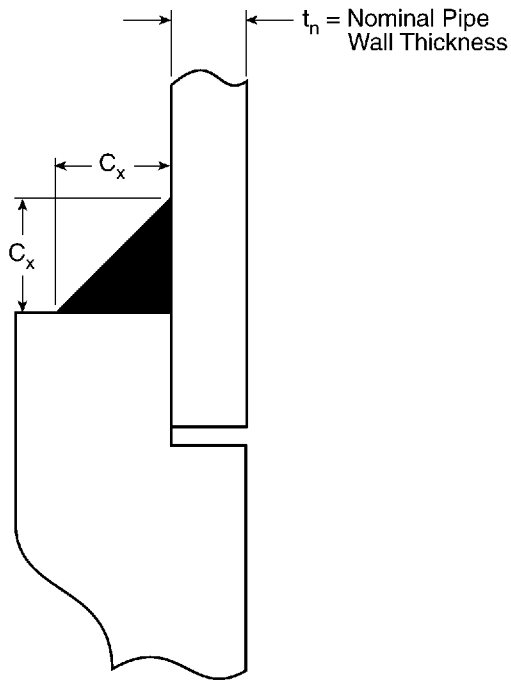


Figure 1-1
Socket Weld Configuration

1.3 Code Indices

This study is focused on the three indices associated with bending moments and the associated stresses: B_2 (primary bending stress), C_2 (secondary bending stress), and K_2 (peak stress). Over the years, these indices have changed. In B31.7 [4], which was published in the late 1960s and was the precursor to Section III for piping, the indices were:

$B_2 = 1.0$

$C_2 = 1.5$

$K_2 = 2.0$

These were the same values contained in early 1970s versions of ASME Section III.

In the mid 1970s, the indices were changed to:

$B_2 = 1.0$

$C_2 = 2.1$

$K_2 = 2.0$

The change in C_2 was parallel to the corresponding change in the SIF from 1.3 to 2.1 This change in C_2 uses the relationship: $i = C_2K_2/2$, which is discussed in Section 3 of this report.

The history of this change is discussed in detail in “Evaluation of Stress Intensification Factors for Circumferential Fillet welded or Socket welded Joints” [5] and is summarized here.

The basis of the change is the evaluation of the test data from Markl [6] and a recognition that certain dimensional requirements would not always be satisfied. Originally, Markl suggested a value of 1.3 for the SIF applicable to “single hub welded slip-on or socket welded flanges.” It was based on the average value of test data, which ranged from approximately 1.05 to 1.66 for normal sized welds.

The defining dimension for socket welds is C_x, which corresponds to the length of the “leg” of the weld (see Figure 1-1). The basis for C_x needs some explanation. For circumferential fillet welds on flanges (which correspond to socket welds), there is no physical limit (within reason) on C_x because of the size of the flange face. It was desired to make the weld so that it had the same pressure capacity as the pipe. This was achieved by making the thickness of the weld throat equal to the nominal thickness of the pipe, t_n. Because $(1.4\ t_n)(\sin 45^o) = t_n$, the minimum value of C_x was specified to be 1.4 t_n.

Many socket welded fittings do not permit the same amount of “face” as flanges. For B19.11 fittings, the amount of the material available for the weld was only 1-1/4 t_n. Consequently, the lower limit of C_x was reduced to 1-1/4 t_n.

By 1974, it was recognized that 1-1/4t_n was not always obtainable because of manufacturing tolerance. The lower limit was then changed to $C_x = 1.09\ t_n$. The tolerance corresponds to the tolerance on the pipe wall: ±12.5%. (Note that 1.25 x 0.875 = 1.09.)

B16.11 [7] specifies certain dimensions for fittings of various pressure classes and the corresponding pipe. Included is a “C” dimension that corresponds to C_x and provides both average and minimum dimensions. In general, the minimum “C” value is 87.5% of the average value. Except for 1/8-inch (3.175-mm) pipe, the value of C_x/t_n is 1.25 for the average value of C_x and 1.09 for the minimum value (1.25 x 0.875 = 1.09). In recognition of this, the minimum value of C_x was changed to 1.09 t_n.

Because the desired value of C_x was not always obtainable, it was decided that i (the SIF), which was based on “reasonable sized welds,” also should be changed. In addition to the baseline tests, Markl’s [6] tests included “supplementary tests” with special welds that were described as having a “bead-like, unfinished appearance” or “small and poorly contoured.” These supplementary tests had i factors that, on the average, were higher than those for the "main series" tests. Based on a review of these data, the value of $i = 2.1$ was adopted.

This change in the SIF led to a change in the stress index C_2. The relationship $i = C_2K_2/2$ modified to $C_2 = 2i/K_2$, and the assumption that $K_2 = 2.0$ led to the change of C_2 to 2.1 (for example, $C_2 = 2*2.1/2 = 2.1$). This is the value of C_2 that was adopted by the ASME Code.

It was later recognized that this was too conservative for the SIFs, and a heuristically derived "correction factor" was added to account for larger welds:

$$i = 2.1\,(t_n/C_x), \text{ but not less than } 1.3 \qquad \textbf{Eq. 1-1}$$

Corresponding to the change in the SIF, the stress indices were also changed:

$$B_2 = 1.5(t_n/C_x) \geq 1.0 \qquad \textbf{Eq. 1-2}$$

$$C_2 = 2.1(t_n/C_x) \geq 1.3 \qquad \textbf{Eq. 1-3}$$

$$K_2 = 2.0 \qquad \textbf{Eq. 1-4}$$

where C_x and t_n are defined in Figure 1-1. In Figure 1-1, C_x is the minimum weld length. The requirement is that $C_x \geq 0.75t_n$. For unequal lengths, the smaller length is to be used for C_x.

The expression for B_2 was also changed at the same time. Because the factor (t_n/C_x) was used for C indices, it was also deemed appropriate for the B_2 indices.

2
EXPERIMENTAL DATA

2.1 Introduction

This investigation is focused on test data. This section discusses test data that are specifically applicable to this study of stress indices.

EPRI TR-106415 [3] identified the results of 183 tests that were deemed directly applicable or could serve as the basis of extrapolation to be used in that study. EPRI TR-106415 [3] was focused on SIFs. This information was used in justification of the recent Code Case N-646 [2], which revised the SIF from $2.1(t_n/C_x)$ to 1.3. This Code Case maintains the basic limit of the size of the weld: $C_x/t_n \geq 1.09$.

Additional test data support this change in SIF. “Investigation of Stress Intensification Factors for Circumferential Fillet Welds” [8] describes the results of new test data that were developed specifically for intentionally small welds. This paper [8] concludes: “a SIF of 1.3 may be used for the evaluation of circumferential fillet welds to socket welded fittings for values of $C_x/t_n \geq 0.75$.”

This paper [8] also contains the results of 12 tests of small welds. Six of these tests had welds where either the minimum or average value of $C_x = 0.75\ t_n$ was exceeded. These tests formed the basis of the conclusion.

Based on this experimental study, a proposal is under consideration by Section III to change the limit on the weld size requirement from $C_x/t_n \geq 1.09$ to $C_x/t_n \geq 0.75$.

2.2 B_2 Indices from Test Data

The ASME Code uses limits on the primary stress intensity to limit gross plastic deformation of piping and/or components. The Code has specific limits that apply to stresses calculated using B indices. The B indices are associated with the limit load for the component. For bending moments, the stress, S, is calculated from $S = B_2M/Z$. For a limit load condition, using S_y (yield stress) as the allowable stress and solving for the load (the limit moment) yields:

$$M = M_{LIMIT} = S_yZ/B_2 \qquad \textbf{Eq. 2-1}$$

Rearranging yields:

$$B_2 = S_yZ/M_{LIMIT} \qquad \textbf{Eq. 2-2}$$

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

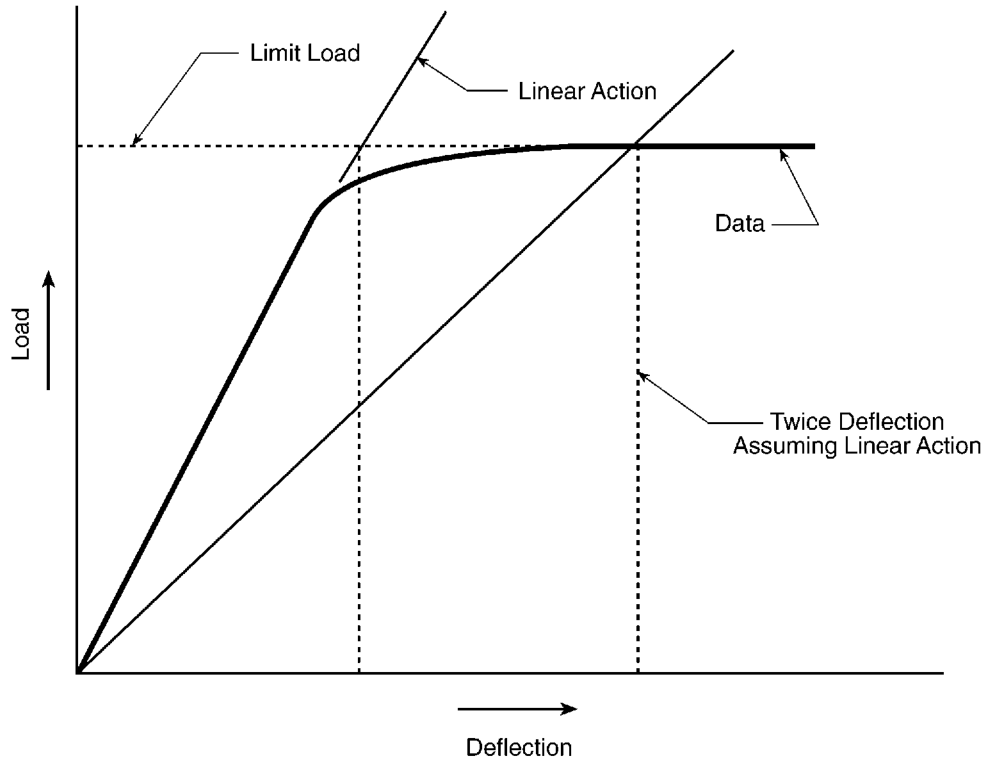


Figure 2-1
Limit Load Definition

After the limit load is obtained from the experimental data, the test B_2 index can be obtained from Equation 2-2, where M_{LIMIT} is the moment associated with the limit load.

In experimental determination of SIFs, one of the first activities is to determine the stiffness of the test specimen and the test fixture. Typically during the test, the loading method is deflection controlled and is loaded in both positive and negative directions. A load deflection curve is experimentally determined. Typically, the specimen is loaded in one direction, unloaded, loaded in the opposite direction, and then unloaded.

Typically, the maximum loads are such that the resultant stresses are slightly into the plastic region. Consequently, the maximum loading condition can be used to investigate the value of B_2. Because the force is less than the limit load, assuming that the load is the limit load would result in an over-prediction of the values of B_2. However, it is possible to use these data to obtain an idea about the magnitude or lower bound of B_2.

In order to investigate the value of B_2 for socket welds, the test data for the 12 tests discussed in “Investigation of Stress Intensification Factors for Circumferential Fillet Welds” [8] were studied. These tests were specifically for intentionally small size welds on 2-inch (50.8-mm) schedule 160 A53-B pipe with a socket weld flange welded to the pipe. The average values of C_x/t_n for a test specimen ranged from 0.65 to 1.14 versus the present requirement of 1.25. Because of the values of C_x/t_n, these tests should provide a conservative basis of the values of B_2.

Table 2-1 summarizes the test results and also conservatively estimates the B_2 indices. The calculated indices are referred to as B_2' because they are the test results. For reference, the minimum and average values of C_x/t_n are listed. The original purpose of these tests was to evaluate the SIFs, not to provide a basis for development or verification of the B_2 indices. Consequently, the maximum loading is less than the limit load as defined in Figure 2-1. As indicated in Table 2-1, typically the maximum load was 1300 lbs (589.7 kg).

Figures 2-1 and 2-2 show the load deflection curves for test specimens G and H. These two curves were obtained from the original data (taken from "Investigation of Stress Intensification Factors for Circumferential Fillet Welds" [8]) and are typical of all of the tests. Clearly the maximum load is less than the limit load. The maximum deflection of all of the tests was for Test F and was equal to 1.91 inches (48.51 mm).

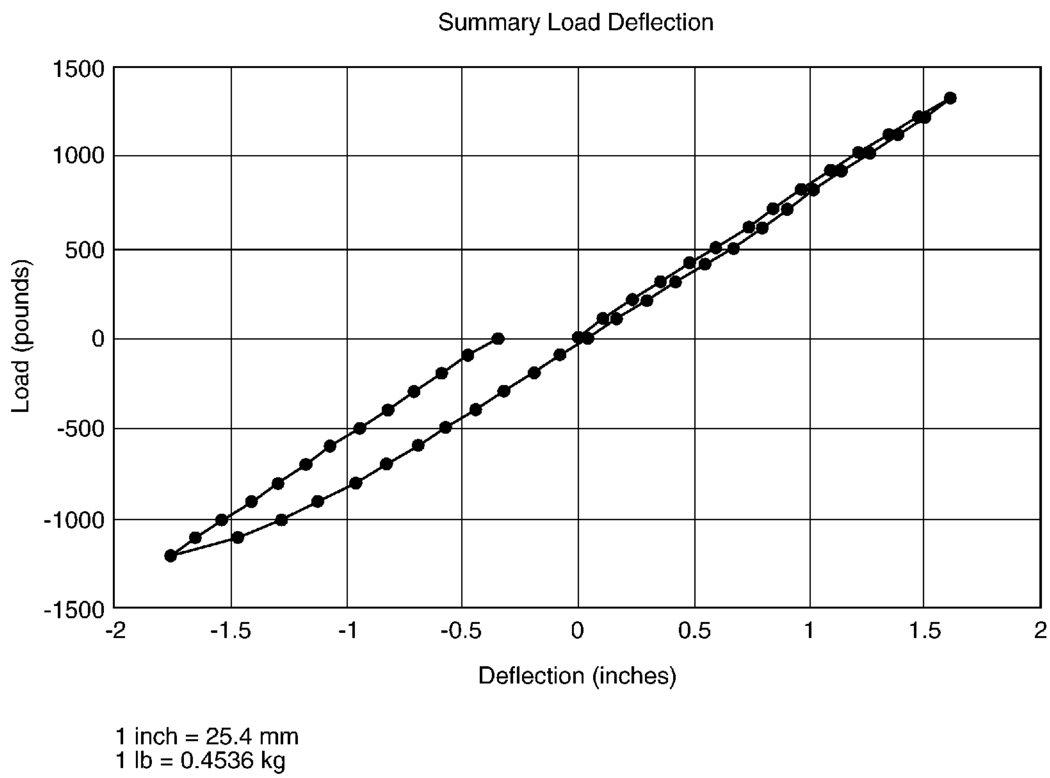
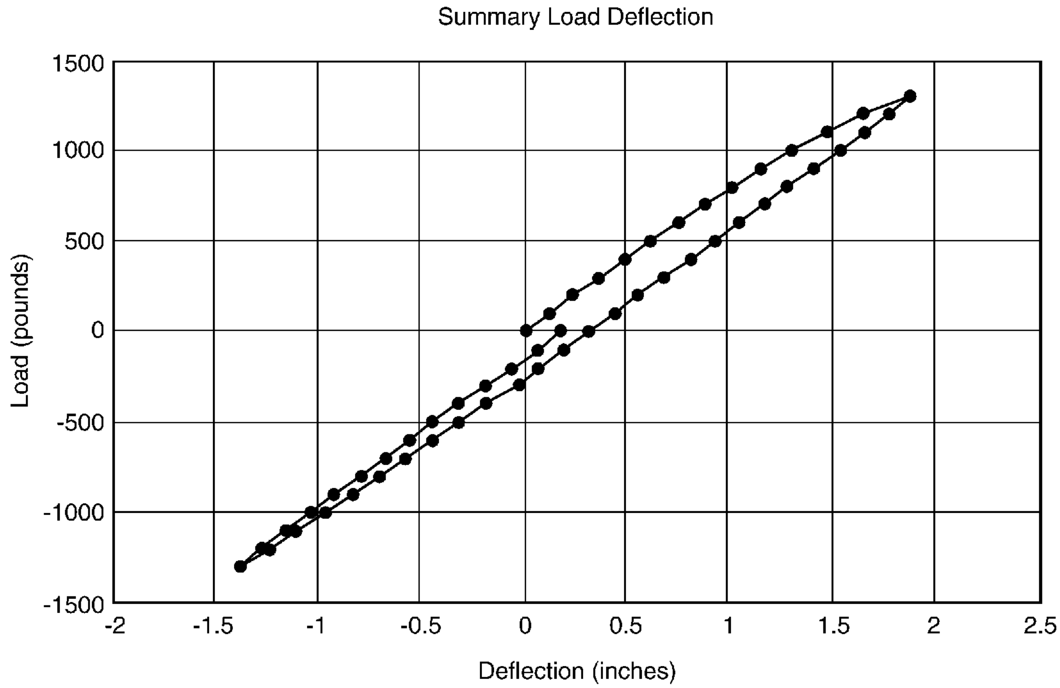


Figure 2-2
Load Deflection for Test G



1 inch = 25.4 mm
1 lb = 0.4536 kg

Figure 2-3
Load Deflection for Test H

Based on all of the data (including tests with very small welds) and this approach, the average value of B_2' is 0.875. For the specimens with $C_x/t_n \geq 0.75$, the average value of B_2' is 0.842.

Another approach is to compare the maximum applied moment to the limit moment of the pipe, given by:

$$M = (r_o^3 - r_i^3)\ (4/3)\ S_y \qquad \textbf{Eq. 2-3}$$

where r_o and r_i are the outside and inside radii of the pipe. For S_y = 51.7 ksi (356.5 MPa), this yields a moment of 73,900 in-lbs (8350 N-m). The maximum applied test load was 1300 lbs (589.7 kg), yielding a moment of 60,100 in-lbs (6790 N-m), or 0.81 times the limit moment of the specific pipe (S_y = 51.7 ksi [356.5 MPa]) used in the tests.

For a pipe at room temperature, the Code [1] -specified yield strength is 35.0 ksi (241.3 MPa). If the Code limit were:

$$B_2 M/Z \leq S_y \qquad \textbf{Eq. 2-4}$$

then the maximum permissible moment (for B_2 = 1.00) would be 34,265 in-lbs (3871 N-m). Then the maximum applied moment was 1.75 times the moment permitted by Equation 2-4 (with no failures).

These data suggest that, for $C_x/t_n \geq 0.75$, the value of B_2 can be conservatively taken as 1.0.

Table 2-1
B_2 Evaluation

Test	Minimum C_x/t_n	Average C_x/t_n	Maximum Load F (lbs)	$B_2' = S_y$ *Z/L*F
A	0.52	0.65	1300	0.842
B	0.52	0.64	1200	0.912
C	0.52	0.65	1200	0.912
D	0.58	0.60	1300	0.842
E	0.61	0.73	1000	1.094
F	0.64	0.71	1300	0.842
G	0.81	0.92	1300	0.842
H	0.76	0.86	1300	0.842
I	0.90	1.11	1300	0.842
J	0.87	1.09	1300	0.842
K	0.81	0.95	1300	0.842
L	0.90	1.14	1300	0.842
				Average = 0.875

1 lbf = 0.4536 kg

Notes:

$Z = 0.979\ in^3$ ($16.05\ cm^3$) for 2-inch (50.8-mm) schedule 160 pipe
L = 46.25 in. (1.17 m)
S_y = 51,700 psi for the pipe (356.5 MPa)

3
COMPARISON OF INDICES TO SIFS AND FATIGUE ANALYSIS

3.1 Comparison of Indices to SIFs Using Code-Defined Relationship

It is generally recognized that a relationship exists between the SIFs (which are used for Section III, Class 2 piping) and the stress indices C_2 and K_2 (which are used for Section III, Class 1 piping). EPRI TR-106415 [3] presents information on the history of SIFs for socket welds as well as the results of 183 tests. After adjustments to consider variations in material, weld sizes, etc., the average value was 1.07. Following standard approaches to determining SIFs, a value of 1.07 can be justified. However, based on the history of the SIF for socket welds, the conclusion of EPRI TR-106415 [3] was that “a constant value of 1.3 provides a reasonable, conservative value.”

Based on this information, the value of the SIF for ASME Section III (via a Code Case [2]) was modified to be equal to 1.3.

Analytical determination of stress intensification factor (i) is based on the empirical relationship contained in paragraph NC-3673.2(h) of Section III, which defines a relationship between Class 1 indices (C_2 and K_2) and the SIFs:

$$i = C_2K_2/2, \text{ but not less than } 1.0$$

where C_2 and K_2 are stress indices for Class 1 piping.

Additional guidance is also provided regarding the development of SIFs and stress indices.

This expression can be used in evaluating stress indices when SIFs are known. Using $i = 1.3$, $C_2K_2 = 2.6$. Further, using $K_2 = 2.0$ (as presently defined by Section III [1]), $C_2 = 1.3$.

Note that the test data [3] could justify a SIF of 1.07, which—following the same logic—would yield a smaller value of C_2. The implication is that the use of $K_2 = 2.0$ and $C_2 = 1.3$ would be conservative.

As discussed in Section 2, “Investigation of Stress Intensification Factors for Circumferential Fillet Welds” [8] presents the results of additional tests that were focused on intentionally small size welds. These 12 test specimens included configurations with values of t_n/C_x that were as low as 0.52. The average SIF of all 12 tests was 1.61. However, the average of the six tests with weld sizes of $C_x \geq 0.75\ t_n$ was $i = 1.27$. This supports the use of $i = 1.3$ for $C_x/t_n \geq 0.75$ and, in turn, $C_2 = 1.3$ for $C_x/t_n \geq 0.75$.

3.2 Development of Indices from Fatigue Evaluation

The data from these tests can be used to estimate the values of K_2 and C_2 by performing fatigue analyses. Several methodologies can be used to evaluate the test data; Tables 3-1 and 3-2 are used in this evaluation. Both of these tables contain the results of fatigue analysis of the test conditions using slightly different approaches.

Table 3-1
Usage Factor Evaluation Based on Equivalent Number of Load Cycles

Case	**S_{nom}= ±M/Z (Amplitude)**	**S_n=2 C_2 M/Z (Range)**	**K_e**	**S_p = K_2C_2M/Z (Range)**	**S_{alt}=K_eS_p/2**	**$N_{allowable}$**	**N_{test}**	**CUF**
	(ksi)	(ksi)		(ksi)	(ksi)			
A	34.8	78.0	1.60	155.9	125	7,082	765	0.108
B	31.8	71.2	1.37	142.5	98	12,909	836	0.065
C	29.6	66.3	1.21	132.6	80	21,866	1,214	0.056
D	28.1	62.9	1.10	125.9	69	33,304	270	0.008
E	49.9	111.8	3.73	223.6	305	937	241	0.257
F	42.7	95.6	2.19	191.3	209	2,132	1,726	0.810
G	43.9	98.3	2.28	196.7	224	1,833	1,309	0.714
H	42.5	95.2	2.17	190.4	207	2,187	1,095	0.501
I	41.0	91.8	2.06	183.7	189	2,670	1,792	0.671
J	44.7	100.1	2.34	200.3	234	1,664	2,983	1.793
K	45.2	101.2	2.37	202.5	240	1,568	2,040	1.302
L	44.7	100.1	2.34	200.3	234	1,664	1,697	1.020
					Average of all tests		**=**	**0.609**
Constants								
C_2 =	**1.12**	S_m (ksi) =	20	**Average of tests G to L**			**=**	**1.000**
K_2 =	**2.00**	m =	3.0					
		n =	0.2					

1 ksi = 6.855 MPa

Table 3-2
Usage Factor Evaluation

Case	S_{nom}= ±M/Z (Amplitude)	S_n= 2 C_2 M/Z (Range)	K_e	S_p = K_2C_2M/Z (Range)	S_{alt}= K_eS_p/2	$N_{allowable}$	N_{test}	UF	CUF
	(ksi)	(ksi)		(ksi)	(ksi)				
A	34.8	78.3	1.61	157	126	6,878	765	0.111	0.111
B	31.8	71.6	1.39	143	99.1	12,499	836	0.067	0.067
C	29.6	66.9	1.22	133	81.3	21,101	1,214	0.058	0.058
D	28.1	63.2	1.11	126	70.1	32,031	270	0.008	0.008
E	49.9	112	2.74	225	308	915	241	0.263	0.263
F	33.0	74.2	1.47	148	109	9,770	2,044	0.209	
	36.9	83	1.76	166	146	4,831	1,141	0.236	
	42.7	96	2.20	192	212	2,078	615	0.296	0.741
G	39.9	90	1.99	180	179	3,029	1,402	0.463	
	43.9	99	2.29	198	227	1,788	438	0.245	0.708
H	38.6	87	1.90	174	165	3,645	1,422	0.390	
	42.5	96	2.19	191	209	2,129	212	0.100	0.490
I	32.8	74	1.46	147	107	10,197	80	0.008	
	36.9	83	1.76	166	146	4,824	997	0.207	
	41.0	92	2.07	184	191	2,618	1,177	0.450	0.664
J	40.7	91	2.05	183	187	2,729	3,754	1.376	
	44.7	101	2.35	201	237	1,620	652	0.403	1.778
K	45.2	102	2.39	203	243	1,530	2,040	1.333	1.333
L	40.7	92	2.05	183	188	2,708	1,697	0.627	
	44.8	101	2.36	202	238	1,607	643	0.400	1.027
	Constants								
C_2 =	**1.13**	S_m (ksi) =	20			**Average of all tests =**			**0.604**
K_2=	**2.00**	m =	3.0						
		n =	0.2			**Average of tests G to L =**			**1.00**

1 ksi = 6.895 MPa

Notes:

The value of UF is the usage factor associated with the associated Case. The value of CUF is the cumulative usage factor for all load conditions associated with the particular test specimen.

The methods used to evaluate the test data follow the fatigue evaluation approach used for Class 1 analysis (NB-3600) [1]. Table 3-1 lists the test data to be used in this evaluation. The objective is to determine values of K_2 and C_2 that will result in cumulative usage factors (CUFs) that match the test data. For this study, it was assumed that the value of K_2 was 2.0—the value that the Code has always used for these configurations.

In Table 3-1, the nominal stress is equal to ±M/Z for the basic configuration. The moment is that derived from the test data. For the calculation of S_n, the value of C_2 is as indicated in Table 3-1. For S_{alt} in ksi, the value of the allowable cycles is given by:

$$N_{allowable} = (8{,}664/(S_{alt}-21.645))^2 \qquad \textbf{Eq. 3-1}$$

This expression does not include the factors of safety of 2 on stress and 20 on cycles that are part of the Section III, Appendix I, S-N design curves [1]. The value of S_m used in the evaluation was 20 ksi (137.9 MPa) as specified by the Code [1].

Table 3-1 presents the results of fatigue analyses in which the value of C_2 was varied until the average value of the CUF for tests G through L was equal to 1.00. Tests A through F were for very small welds (smaller than what is allowed by the Code or any proposals at this time) and hence will not be used in the evaluation. They are included only for reference.

The corresponding value of C_2 to an average value of the CUF of 1.00 (for tests G through L) is 1.12.

Table 3-1 was based on a calculated equivalent number of load cycles. This is used when the deflection used in a test is changed during the test. The conditions at the maximum deflection are used as the basis of the evaluation. The stress is based on the load determined from maximum deflection multiplied by the elastic stiffness. The equivalent number of cycles used at this deflection (and associated stress) is determined from the expression:

$$N_{eq} = \Sigma\, (\delta_i/\delta_{max})^5 * N_i \qquad \textbf{Eq. 3-2}$$

where δ_{max} corresponds to the condition with the maximum displacement. The term δ_i corresponds to the displacement associated with the i^{th} loading condition. N_i is the associated number of cycles at that loading condition.

As indicated in Table 3-1, a value of C_2 = 1.12 matches the data.

Table 3-2 provides similar data for a fatigue analysis based on actual loading cycles and associated stresses. Tests F, G, H, I, J, and L had more than one loading condition. The CUF approach used in Section III was also used in this evaluation. As indicated in Table 3-2, the results were essentially the same as those given in Table 3-1. The use of C_2 = 1.13 (with K_2 = 2.0) results in an average CUF of 1.0 for tests G through L. Because these tables were produced on a spreadsheet using Excel, the number of significant figures actually used is greater than indicated.

The evaluations indicate that values of C_2 = 1.13 and K_2 = 2.0 will result in fatigue usage factors of 1.0 for these two approaches of fatigue analysis. The definition of failure does not include a factor of 2 on cycles and 20 on stress levels.

Table 3-3 lists the values of C_2 for each case that yields a CUF of 1.00. Table 3-3 is based on the data in Table 3-2 and also includes the values of C_x/t_n from "Investigation of Stress Intensification Factors for Circumferential Fillet Welds" [8]. The maximum value of C_2 for tests where $C_x/t_n \geq 0.75$ is 1.28.

Table 3-3
Values of C_2 That Yield CUF = 1.0 and Size of Weld (C_x/t_n)

Case	Minimum C_x/t_n	Average C_x/t_n	C_2 to yield CUF=1.00
A	0.52	0.65	1.67
B	0.52	0.64	1.80
C	0.52	0.65	1.80
D	0.58	0.60	2.57
E	0.61	0.73	1.48
F	0.64	0.71	1.16
G	0.81	0.92	1.19
H	0.76	0.86	1.28
I	0.90	1.11	1.20
J	0.87	1.09	1.01
K	0.81	0.95	1.07
L	0.90	1.14	1.12

3.3 Recommendations for C_2 and K_2

The recommendations are based on the test results for specimens where $C_x/t_n \geq 0.75$ and the assumption that K_2 = 2.0. As discussed in Section 3.1, the use of the relationship $i = C_2K_2/2$ yields an average value of C_2 = 1.27. The fatigue evaluations presented in Section 3.2 indicate that a value of C_2 = 1.13 yields an average CUF of 1.00 for tests where $C_x/t_n \geq 0.75$. Recognizing the conservatism in the fatigue evaluation approach and the determination of the plasticity factor, K_e, it is deemed reasonable to use C_2 = 1.3 and K_2 = 2.0.

4
OTHER STRESS INDICES

This report describes the C_2, K_2, and B_2 indices. Because indices associated with thermal loadings (for example, C_3, C_3', and K_3) are not included in this study, no changes to Section III of the Code [1] are suggested. Indices associated with pressure are described in Section 4.1.

4.1 Stress Indices for Pressure Loading

Section III [1] provides indices for internal pressure loading, for example, B_1, C_1, and K_1. These indices are:

$$B_1 = 0.75\ (t_n/C_x) \geq 0.5 \qquad \textbf{Eq. 4-1}$$

$$C_1 = 1.8\ (t_n/C_x) \geq 1.4 \qquad \textbf{Eq. 4-2}$$

and

$$K_1 = 3.0 \qquad \textbf{Eq. 4-3}$$

No changes are suggested for C_1 or K_1; however, the B_1 index does warrant discussion. Table 4-1 lists the values as calculated from Equation 4-1 for various values of t_n/C_x.

Table 4-1
B_1 Index for Pressure Loading

t_n/C_x	C_x/t_n	B_1=0.75(t_n/C_x)
1.333	0.75	1.000
1.000	1.00	0.750
0.800	1.25	0.600
0.667	1.50	0.500
0.571	1.75	0.429
0.500	2.00	0.375

Based on a heuristic evaluation, it is believed that it is reasonable to establish upper limits of 0.75 for B_1. This is based on consideration of the nature of the loading and the geometric configuration. No changes are suggested for C_1.

5
CONCLUSIONS

This report reviews the background of the stress indices (B_2, C_2, and K_2) for circumferential fillet welded or socket welded joints. Test data for undersized and small welds were used to conservatively estimate B_2 indices. The C_2 indices were evaluated by two methods: 1) using the relationship between SIFs and the stress indices ($i = C_2K_2/2$) and 2) performing fatigue evaluations of test data on small welds.

The following were concluded from the evaluations described in this report:

- These recommendations are applicable for configurations where $(C_x / t_n) \geq 0.75$.
- The value of the stress index [1] associated with primary stresses due to moments, B_2, can be changed from $B_2 = 1.5\ (t_n/C_x) \geq 1.0$ to $B_2 = 1.0$.
- The value of the stress index [1] associated with the primary plus secondary stresses due to moments, C_2, can be changed from $C_2 = 2.1\ (t_n/C_x) \geq 1.3$ to $C_2 = 1.3$.
- The value of the stress index [1] associated with primary stresses due to pressure, B_1, can be changed from $B_1 = 0.75\ (t_n/C_x) \geq 0.5$ to $B_1 = 0.75\ (t_n/C_x) \geq 0.5$ but not larger than 0.75.
- All other indices should remain as defined in Section III of the Code [1].

These changes should allow for a more accurate evaluation of circumferential fillet welded or socket welded joints.

6
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