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The B_2 Stress Index as a Function of Internal Pressure, Bend Angle, Loading Type and Material

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ABSTRACT

The current ASME Boiler and Pressure Vessel Code equation for the B_2 stress index, which is used in the design equation for primary stresses in piping components, is widely considered to be overly conservative. In recent years, various researchers have investigated the behavior of piping components, primarily elbows, to determine the effect of parameters such as internal pressure, bend angle, location of adjacent flanges, loading type, etc. on the inelastic response of elbows. This paper contains a detailed evaluation of the effects of elbow size and schedule, loading type, internal pressure and material type on the collapse moments of straight pipes and elbows using nonlinear finite element analysis, and then uses these data to construct B_2 stress indices for the various combinations of parameters. Using these results, various equations for the stress index as a function of the pipe bend characteristic parameter, the bend angle, internal pressure and material type are investigated and an optimal form of one of the equations is recommended for use.

KEY WORDS: B_2 stress index, collapse moments, inelastic behavior, nonlinear finite element analysis, carbon steel, stainless steel, internal pressure, elbow bend angle, curvature definition, piping elbow components, piping design, nuclear power plants

INTRODUCTION

The B_2 stress index is used in Equation (9) of the ASME Boiler and Pressure Vessel Code [1] for Class I piping to control gross plastic deformation. For elbows, the Code gives the following equation for this index:

$$B_2 = \frac{1.30}{h^{2/3}} \geq 1.0 \qquad (1)$$

where h is the characteristic pipe bend parameter (See the NOMENCLATURE section for more information.) This equation is independent of variables such as internal pressure, bend angle, temperature, material type, loading type, proximity to flanges or other components, although elbow behavior is known to be dependent on some or all of these variables. In 1991, Touboul and Acker [2] presented an equation, based on one given earlier by Dodge and Moore [3], for the stress index in which internal pressure and bend angle were also parameters. Their equation took the following form (after converting it to the notation used in this paper):

$$B_2 = \frac{1.6}{h^{2/3}}\left(\frac{\alpha}{\pi}\right)^{0.4}\left(1+\frac{0.7Pr_m}{htS_y}\right)^{-1} \qquad (2)$$

In 2002, Matzen and Tan [4] described a new procedure for calculating the B_2 stress index. Their equation took the form:

$$B_2 = \frac{M_{CL_{\text{straight pipe}}}}{M_{CL_{\text{elbow}}}} \qquad (3)$$

where the collapse moments were obtained using nonlinear finite element analysis and were based on the twice-elastic slope method. The straight pipe must have the same geometric and material properties as the component. They considered only 90^o, long radius, butt-welding, stainless steel 304L elbows at room temperature and quasi-static monotonic loading, but any combination of these parameters could presumably be used with this approach. Also, with a proper definition of collapse, the procedure should be applicable to other components, as well. Matzen and Tan suggest that Eq. (3) can be applied either to a specific elbow (using measured data if available) or to one that is generic (using nominal geometric dimensions and Code-defined material properties.) The first case might be useful in a fitness-forservice application or where a particular component response is needed; whereas the second might be used when design code equations are being investigated.

In this paper, we describe a study in which the Matzen and Tan approach is extended to include the effects of various other parameters on elbow behavior. Specifically, we consider the following:

- characteristic pipe bend parameter, h (5 values from h=0.072 (8” schedule 5) to h=0.997 (2” schedule 160))
- internal pressure (p=0, 0.618 and 1, where p is the ratio of internal pressure to the design pressure)
- bend angle (30, 90 and 150°)
- material type (one carbon steel and two stainless steels, one low strength and one high strength)
- loading type (in-plane closing and out-of-plane bending - results from in-plane opening mode and out-of-plane torsion showed that they rarely, if ever, governed.)

Using FEA results (with nominal geometric dimensions), we appraise the validity of Eqs. (1) and (2) and then investigate two other equations – both modifications of the Touboul and Acker equation.

B_2 VALUES FROM FEA

Curvature definition

The FEA procedure used by Matzen and Tan in Eq. (3) requires that the moment-curvature graphs be obtained for both the component and the straight pipe. For the elbow component, the straight pipe segments welded to each end, which are included to remove end effects, should not be included in the curvature calculation. For in-plane loading, either opening or closing, this calculation is trivial if elbow elements are used. If shell elements are used (which was our case), then the situation is somewhat more complicated since plane sections may not remain plane. Our solution to this problem was to compute, at each end of the elbow, the vector from a node at the extrados to one at the intrados. At zero load and pressure, the angle between these two vectors, for a 90° elbow, would be 90°. When the elbow deforms, then the angle between the two vectors does also, and the difference between this angle and the starting angle can be easily calculated. We then define the curvature of an elbow as the change in this angle divided by the centerline length of the elbow.

We applied this same definition to out-of-plane behavior. There are two modes of out-of-plane bending – one pure bending and the other pure torsion, both as defined at the mid-point of the elbow bend angle (although the moments are actually applied at the end of the straight portion of the pipe.) Figure 1 demonstrates these moments. In this case, the vector used in the curvature calculation runs from flank to flank rather than extrados to intrados. In the case of pure bending, we projected these vectors onto a plane that was perpendicular to the pure bending double-headed arrow shown in Fig. 1. The angle change between the vectors at each end of the component was used in the curvature definition. The application to pure torsion was similar.

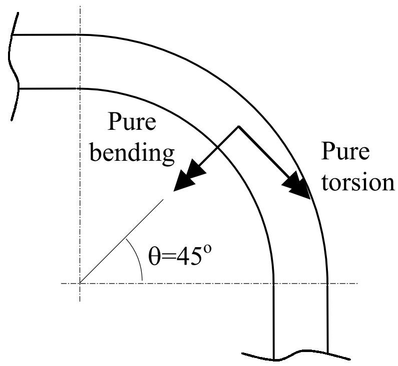

Fig. 1. Out-of-Plane Loading Modes

FEA results

In our FEA analyses, we investigated the five sizes and schedules of elbows shown in Table 1, using nominal geometric data for all dimensions. The internal pressures we considered were relative to the design pressure, $P_a = \frac{2S_m t}{D_o - 2yt}$, where S_m was taken to be $\min(\frac{1}{3}S_y, \frac{2}{3}S_u)$. The pressures were 0, $0.618P_a$, and P_a. The three materials are defined in Table 2. The total number of B_2 values computed then, was 5 values of h * 3 pressures * 3 bend angles * 3 materials * 2 loading conditions for a total of 270. For the two loading conditions, the results were quite similar, but we always used the maximum of the two B_2 values. For zero pressure, in-plane closing always controlled, i.e. it had the highest value of B_2. For the other two pressures, the results were mixed, but the differences between the two values (for given h, bend angle, etc) were small (< 5%). A set of typical results is shown in Fig. 2.

The analyses were performed using ANSYS [5] with SHELL43, considering both geometric and material nonlinearities. Stress-strain curves were generated using a scaling technique described in Matzen and Tan [4].

Table 1 Elbow Sizes and Schedules

Size	Schedule	h
8	5	0.0721
6	10	0.1145
6	40	0.2504
4	80	0.4667
2	160	0.9968

Table 2 Material Properties (ksi)

Designation	S_y	S_u	S_m
Carbon Steel SA-36	36	58	19.3
Stainless Steel – 304L	25	70	16.7
Stainless Steel – High Strength	50	100	33.3

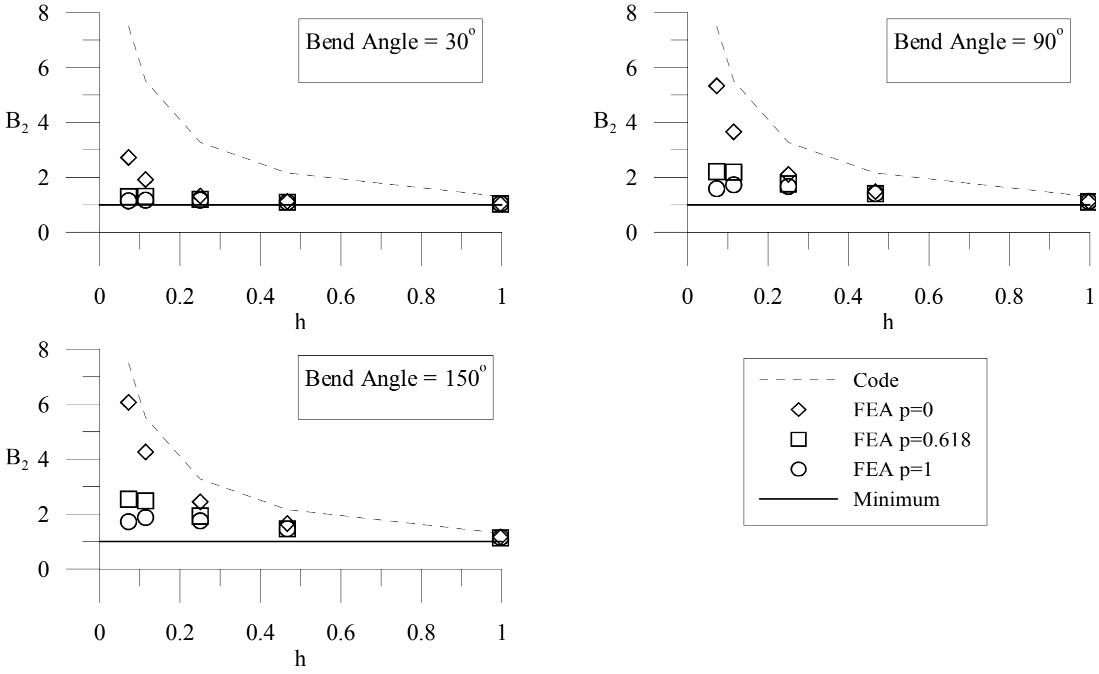

Fig. 2. FEA results for SS 304L, including the Code equation and the minimum value.

DEVELOPMENT OF B_2 EQUATION

As described above, we first investigated the equation given by Touboul and Acker in Ref. [2]. These results for SS 304L are given in Fig. 3. We observe that the values can be less than one, which is the minimum value, and the correlation is not particularly good. We also considered two modifications of their equation. The first was an equation with exactly the same form as Eq. (2), but with the constants left as variables. We then optimized the equation by minimizing the squared difference between this equation and the FEA data. The constants 1.60, 0.70, 2/3 and 0.40 became 1.33, 0.21, 0.59 and 0.38, respectively. These results are shown in Fig. 4 - again, some values are less than one, but the correlation is much improved. To overcome the problem of having values that are less than one, we modified the equation by adding the constant one to it. The resulting equation, with the four open variables designated c_1 and c_2 for the coefficients, and e_1 and e_2 for the exponents, is as follows:

$$B_2 = 1 + \frac{c_1}{h^{e_1}}\left(\frac{\alpha}{\pi}\right)^{e_2}\left(1 + \frac{c_2 P r_m}{h t S_y}\right)^{-1} \qquad (4)$$

Again computing a squared error and minimizing it, we obtained the following values for the four constants: c_1=0.37, c_2=0.45, e_1=1.07 and e_2=0.66. These results for Eqn. (4), referred to as the NCSU equation, are shown in Fig. 5.

All of the above results are for SS 304L. Results for the other two materials (carbon steel and a high strength stainless steel, neither of which is shown) were similar, but the values of the constants were somewhat different. To obtain one “best fit” equation for all three materials, we computed a single squared error by using FEA results and the appropriate value for S_y for each material, but with the same set of constants in Eqn. (4). These results are shown in Fig. 5. They are the light grey lines, and it is a bit difficult to see them since they are quite close to the curves for 304L. Table 3 summarizes the results. The last line of the table is the squared error for each equation.

Table 3. Coefficients and Exponents for B_2 Equations

	Touboul and Acker, Ref. [2]			**Optimized Touboul and Acker**			**NCSU Equation**			
	A	B	C	A	B	C	A	B	C	D
c_1	1.60	1.60	1.60	1.33	1.29	1.31	0.37	0.35	0.37	0.36
c_2	0.70	0.70	0.70	0.21	0.34	0.28	0.45	0.88	0.55	0.60
e_1	0.67	0.67	0.67	0.59	0.65	0.62	1.07	1.14	1.10	1.10
e_2	0.40	0.40	0.40	0.38	0.37	0.39	0.66	0.59	0.64	0.63
Sum Sq Err	22.37	13.95	19.53	2.14	2.44	2.19	1.20	1.10	1.13	5.31

A: Stainless Steel 304L; B: High Strength Stainless Steel; C: Carbon Steel SA-36 D: Combined Stainless Steel 304L, High Strength Stainless, and Carbon Steel SA-36

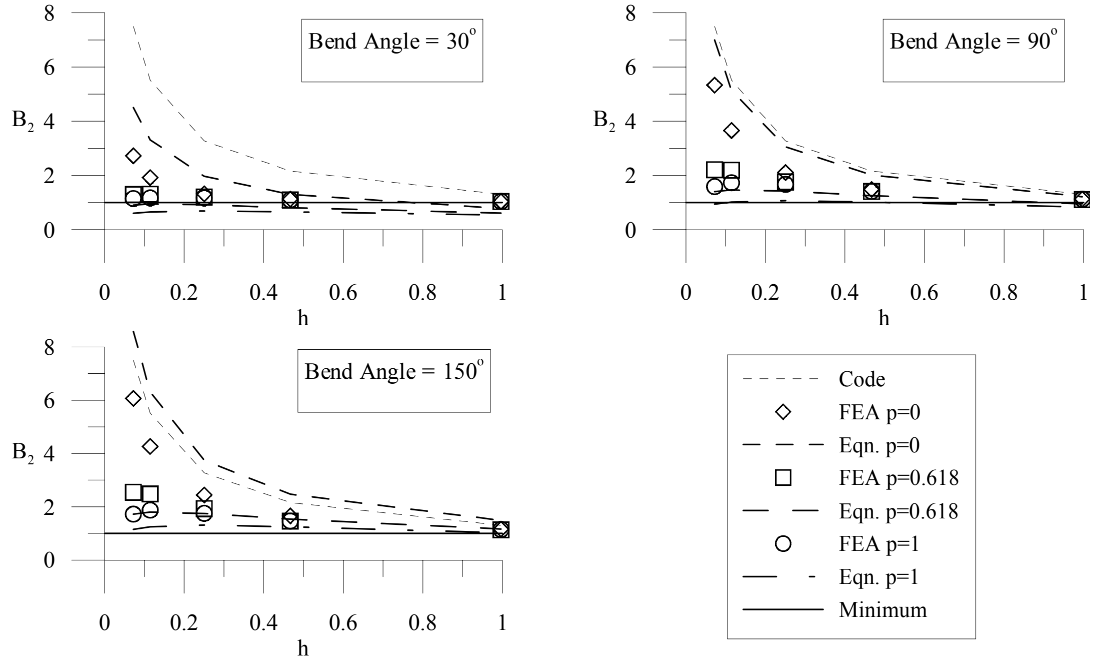

Fig. 3. Touboul and Acker [2] equation for SS 304L

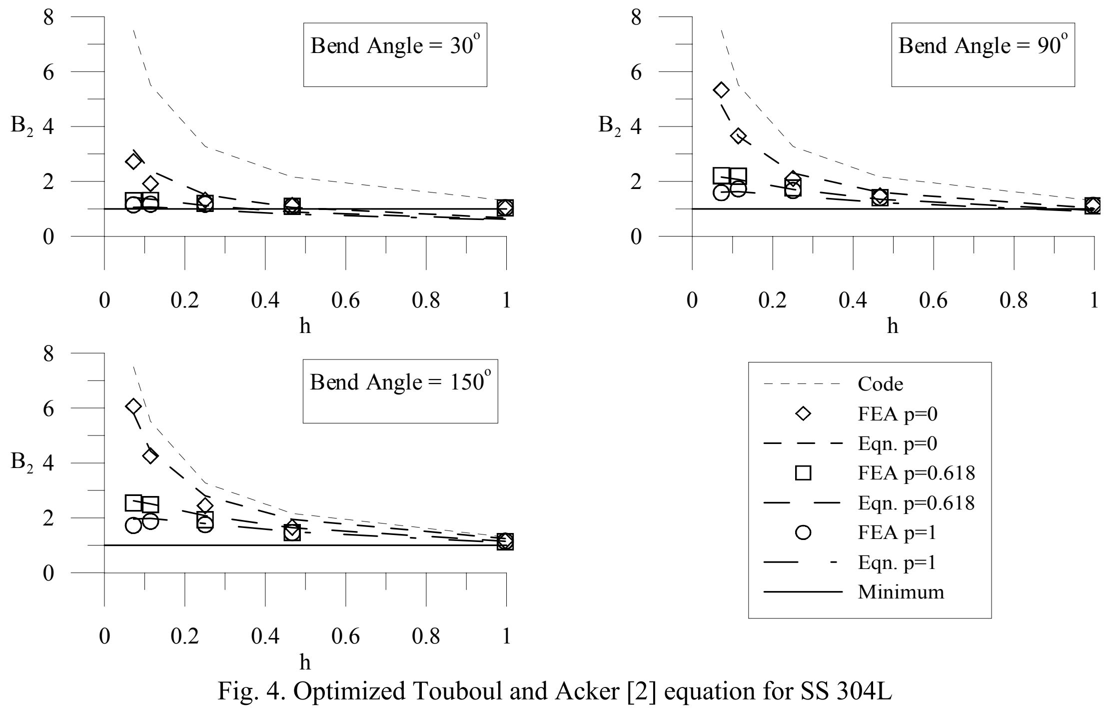

Fig. 4. Optimized Touboul and Acker [2] equation for SS 304L

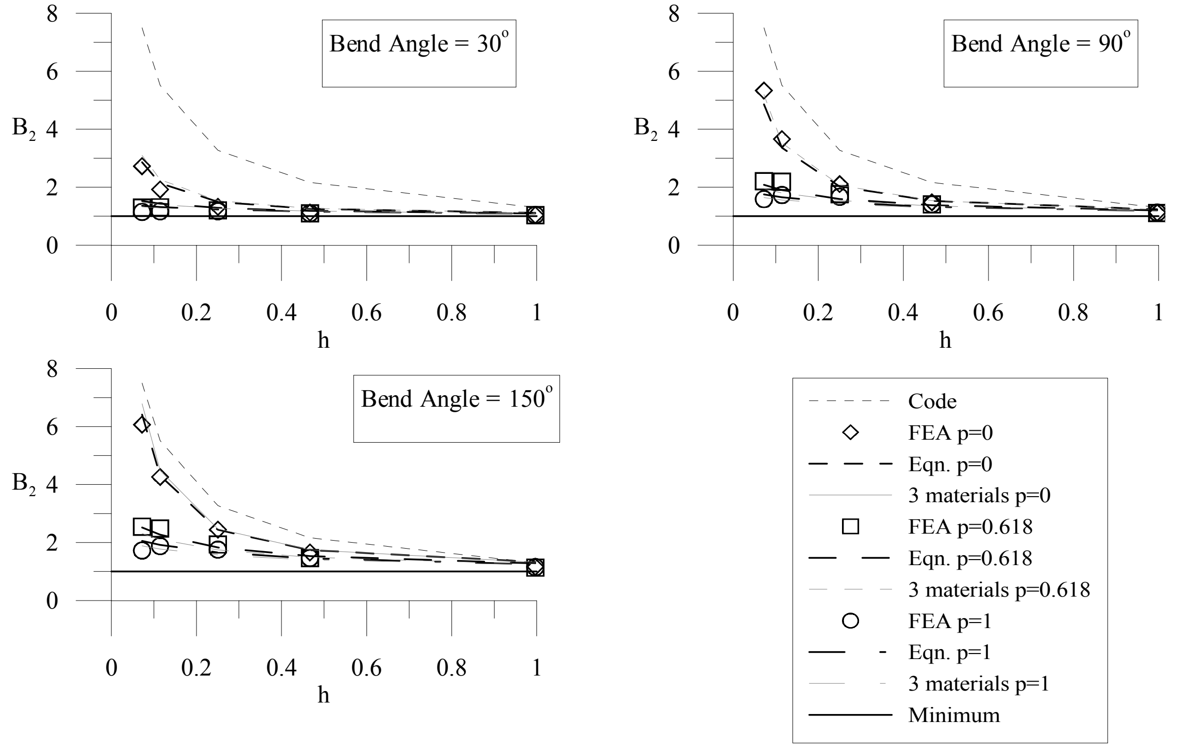

Fig. 5. NCSU equation for SS 304L and the combined set of materials (labeled 3 materials.)

SUMMARY AND CONCLUSION

We used nonlinear FEA to compute B_2 stress indices for 270 combinations of elbow size and schedule, material type, internal pressure, and bend angle using Eq. (3). Only 90 of those results – the ones for SS 304L - are shown here, but the results for high strength stainless steel and carbon steel SA-36 were similar. We then investigated the ability of three different equations plus the current Code equation to simulate these FEA results. Both the Optimized Touboul and Acker equation and the NCSU equation match the FEA data quite well, but the NCSU equation has the advantage of always remaining above the minimum value of one. Thus, we conclude that the most appropriate equation for obtaining the B_2 stress index for any combination of size and schedule, bend angle, internal pressure, material and loading type is the NCSU equation with the constants obtained from the combined sets of material data. This equation is given below.

$$B_2 = 1 + \frac{0.36}{h^{1.10}}\left(\frac{\alpha}{\pi}\right)^{0.63}\left(1 + \frac{0.60 P r_m}{h t S_y}\right)^{-1} \tag{5}$$

NOMENCLATURE

B_2 = primary stress index for bending
c_1, c_2 = coefficients in an equation for B_2
D_o = outside diameter of pipe
e_1, e_2 = exponents in an equation for B_2
h = characteristic bend parameter, tR/r_m^2
$M_{CL_{elbow}}$ = Twice-elastic slope collapse moment for an elbow
$a = a_p$ = Twice-elastic slope collapse moment for a straight pipe
p = normalized pressure, P/P_a
P = internal pressure
P_a = allowable working pressure
R = nominal bend radius of elbow
r_m = mean pipe radius, $(D_o\text{-}t)/2$
S_m = allowable design stress intensity
S_y = yield stress
S_u = ultimate stress
t = nominal wall thickness
y = 0.4
α = bend angle of elbow, in radians

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