Transactions, SMiRT 16, Washington DC, August 2001 *Paper # 2066*

Revised C_2 Stress Index for 90-degree Piping Elbows

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ABSTRACT

The moment stress based on the current C2 stress index from the ASME-Code is the maximum stress anywhere in the piping elbow. Therefore, that moment stress is an upper-bound of the secondary stress to be calculated in the current Equations 10 and 12 of the Piping Code (NB-3600). That moment stress is overly conservative, as NB-3200 defines the secondary stress as the stress associated with the global distortion of the piping component, and not as the maximum stress anywhere in that piping component.

The purpose of this technical paper is to present a methodology that has been used to show that, based on the NB-3200 definitions, the Piping Elbow C2 stress index can be smaller than the C2 stress index currently defined in the ASME-Code. The revised C2 stress index is derived through Finite-Element elasto-plastic calculations. A conservative practical approximation is presented for the calculation of the revised C2 stress index, based on the current ASME-Code equations. This revised C2 stress index leads to a revised Piping-Elbow K2 stress index which is greater than 1.0 and which is required because the maximum stress anywhere in the elbow is greater than the newly calculated secondary stress.

In addition, it is shown that, based on the revised Piping Elbow C2 stress index, the newly calculated Piping Elbow secondary stress leads to Fatigue Penalty Factors (so-called Ke Factors) which are very consistent with those of the straight pipe.

1.) INTRODUCTION

In Class 1 Piping Stress Analyses, one of the most critical load cases to be considered at this time is probably the thermal expansion of the line (in most cases, much more severe than the seismic loadcase). The thermal expansion loadcase has become critical primarily because of the non-negligible temperature differences which have been measured at Nuclear Power Plants (e.g. operating experience has been found in many cases to be more severe than the original design bases, thus causing a need for reanalysis).

As a result, there is a demand for more "accurate" and more "appropriate" analysis techniques. One topic which has received some visibility lately is the topic of the so-called Ke factor. This factor, which is also known as the Fatigue Penalty Factor, is, for a certain loading level, the ratio between the total elasto-plastic strain from the elasto-plastic structural analysis and the purely elastic strain from the purely-elastic structural analysis of the line (again, for the same loading level).

This Technical Paper focuses only on Piping Elbows. We will present a methodology to reduce the primary plus secondary bending stress index C2 (for those Piping Elbows), while, as a side goal, we want to keep the Ke factor as defined in the current ASME-Code. We believe that the reason why the Ke factor should stay as specified now, as far as bending from thermal expansion is concerned, is because this Ke factor can be shown to be "appropriate" for the simple case of the Straight Pipe. This leads us to conclude that the stress analysis of the Class 1 Piping Elbows is not "appropriate" at the present time as specified in the ASME-Code, and that their secondary stress due to bending is really "over-predicted" in the current ASME-Code (Ref. 1).

2.) DEFINITION OF SECONDARY STRESS AND PEAK STRESS FROM THE ASME-CODE

In NB-3600, the Moment terms are as follows in the Stress Equations 10 and 11:

- in Stress Equation 10, for the Primary Plus Secondary Stress Range: $C_2 * \mathit{Moment\ Range} * D_O \,/\, (2 * I)$.
- in Stress Equation 11, for the Total Stress Range: $K_2 * C_2 * \mathit{Moment\ Range} * D_O \,/\, (2 * I)$.

, where $\mathit{Moment\ Range}$ is primarily due to Thermal Expansion of the line.

The ASME-Code Sub-article NB-3600, for Piping Design, does not provide any definition of the different types of Stress, such as Primary Stress, Secondary Stress, Peak Stress, etc… Therefore, in accordance with NB-3611.2, which allows the user to perform Piping Stress Analysis in accordance with the requirements of NB-3200, rather than NB-3600, it is appropriate to use the definitions given in Paragraph NB-3213. In this NB-3213, the definitions of the Secondary and Peak Stresses are as follows:

- From NB-3213.9: a Secondary stress is a normal stress or a shear stress developed by the constraint of adjacent material or by self-constraint of the structure ... as an example of a secondary stress, the Code refers to NB-3213.13(a) General Thermal Stress, where it is clearly stated that this type of stress is "associated with distortion of the structure in which it occurs".
- From NB-3213.11: a Peak stress is that increment of stress which is additive to the primary plus secondary stresses ... The next sentence gives then the most relevant statement for the decoupling of a peak stress from the secondary stress: "The basic characteristic of a peak stress is that it does not cause any noticeable distortion and...". Furthermore, it states that "a stress which is not highly localized" falls into the Peak stress category if it is of a type which "cannot cause noticeable distortion".

In this paper, the sum of the Primary, Secondary and Peak stresses is referred to as the "Total Stress". This is consistent with NB-3213.11, where the Peak stress is defined as that increment of stress which is "additive to the primary plus secondary stresses".

3.) ELASTO-PLASTIC FINITE-ELEMENT ANALYSES / GLOBAL STRUCTURAL BEHAVIOR

Because of the distinction made in Section 2 above between the definitions of the Secondary stress and the Peak stress, it was decided to evaluate the influence of a progressive plasticity of a cross-section and of the structure, in general, on the resulting deformation (or distortion) of the Pipe. To be able to perform that evaluation, an ANSYS Finite-Element Model of the 90-degree Piping Elbow has been built, as well as the corresponding Straight Pipe Finite-Element Model. The Finite Element Model of the 90-degree Piping Elbow is shown in Figure 1. The Piping Elbow Model and the Straight Pipe Model use the same ANSYS Shell Elements (Ref. 2).

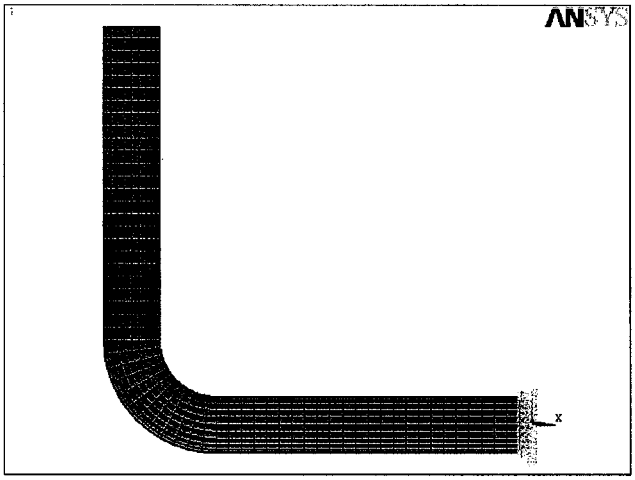

Figure 1: Finite Element Model of the 12" Sch. 140 Piping Elbow

The cross-sectional and material properties used for this example are listed in Table 1, where the two current ASME-Code stress indices B2 and C2 are also calculated.

Table 1: Cross-sectional and Material Properties of the 90-degree Piping Elbow

Cross-sectional Properties for this relatively thick Piping Elbow (4 in. Sch. 120)		
Outside Diameter: Do = 4.5 in. Thickness: T = 0.438 in. Radius of curvature: Rc = 6.0 in. Mid-Radius: Rm = 2.031 in.	$h = \frac{T * Rc}{Rm^2} = \frac{0.438 * 6.0}{2.031^2} = 0.64$ $I = (\pi / 4) * (R_o^4 - R_i^4) = 11.662\, in.^4$	$B_2 = 1.3 / h^{2/3} = 1.76$ $C_2 = 1.95 / h^{2/3} = 2.63$
Material Properties		
For the elastic domain: E = 28,300 Ksi. [Modulus of Elasticity]	**For the elasto-plastic domain:** Perfectly Plastic Material Yield Strength Sy = 30 Ksi. 1.5 Sm = 30 Ksi. The choice of a Perfectly Plastic Material has the advantage of being completely independent from the type of material (austenitic steel, carbon steel, etc ...)	

Note on Table 1 above: It is conservative to give the same value for Sy and 1.5 Sm, because, in the ASME-Code (Ref. 1), 1.5 Sm is always equal to or greater than Sy.

Using the two Finite-Element Models mentioned above, three Load-cases have been performed. They are: 1.) the straight pipe with an applied moment, 2.) the Piping-Elbow with an applied in-plane bending moment, and 3.) the Piping Elbow with an applied out-of-plane bending moment, whereby this out-of-plane bending consists in a Pure out-of-Plane bending Moment in the Elbow mid-section of this 90-degree Elbow (see Figure 2). All the structural/stress analyses performed in this Paper are done without consideration of any Internal Pressure.

It has been verified that the first Load step of each Load case is in the purely elastic domain. This was necessary to have the purely-elastic stress and strain levels in the Elbow for comparison with the strain levels from the Elasto-Plastic domain.

Due to the fact that the load is a moment in all three cases, the associated deformation is the rotation of the Pipe. Figure 3 shows the relationships between Applied Moment and resulting rotation for the three cases mentioned above. As can be seen on Figure 3, once yield has occurred at one location of the straight pipe, the Moment variation shows a relatively abrupt change of slope, especially when compared with the two elbow bending cases. However, it seems that the difference in the slopes cannot be quantified just through those Global Behavior curves. Therefore, it was decided to follow the variation of the strain at mid-thickness as a function of the Moment Loading for all three load cases. This is being done in the following Section 4 (see Method 1, which is called in this paper the "Rigorous Method").

Also, Appendix A of this paper gives an Illustration of the different Moment load levels when considering the Revised C2 stress Indices (Impact on the Global Structural Behavior of the Piping Elbow).

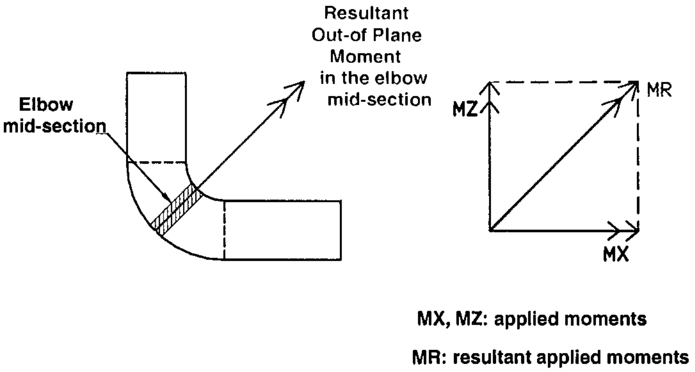

Figure 2: Sketch with Applied Out-of-Plane Moment on the Piping Elbow

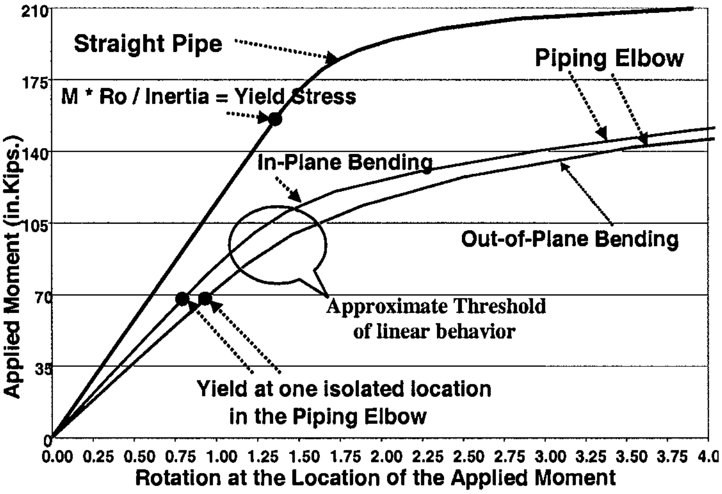

Figure 3: Applied Moment versus Global Rotation in the Plane of Application of the Moment

4.) THE THREE METHODS FOR THE CALCULATION OF THE PIPING ELBOW C2 STRESS INDEX

In this Section 4, the three possibilities for the calculation of the C2 stress index are presented in the reverse order of complexity. A comparison of C2 stress index values is performed in Section 5 of this Paper, where values of the Product C2 * K2 are also tabulated.

4.1.) Method 1 / Rigorous Method

As mentioned in Section 3 above, it was decided to study in detail, in the Elasto-Plastic Finite-Element Analyses, the path of the strain at mid-thickness in the elbow, and to do that at the most severely stressed mid-thickness location in the elbow.

The idea of studying the variation of the stress at mid-thickness as a function of the moment loading really came from two different sources: first, the secondary stress is really the maximum linear stress on the Stress Class Line to be analyzed. In the case of Piping Stress, the Stress Class Line, or more correctly the Stress Class Plane, is the cross-section of the Pipe, including in this case the mid-section of the Elbow. Therefore, keeping the stress at mid-thickness and ignoring the inside radius and the outside radius stress values makes sense, when compared with the Methodology of NB-3200. Second, in the case of the Straight Pipe, if we retain the stress at mid-thickness and somehow project it, through an Ro / Rm multiplication to the outside radius of the pipe, that resulting stress is exactly equal to the "Nominal" Bending stress M Ro / I, and therefore, the stress indices of C2 = 1.0 and K2 = 1.0 are the obvious results from this methodology for the straight pipe.

Figure 4 is what we have called the "hybrid" Bending Moment vs. Strain Graph. To be able to calculate the required C2 values for the Elbow, we decided to plot:

- on the X-axis, the dimensionless Strain measurement, equal to the maximum von-Mises, "distortion energy" based strain, at mid-thickness, divided by the Allowable Strain (on an elastic basis), which is equal to Sy / E, or 1.5 Sm / E,
- and on the Y-axis, the applied Moment required to generate that strain.

Note that Sy and 1.5 Sm are in this case equal, as the stress-strain curve used in these Finite-Element Analyses is the Elastic Perfectly-Plastic stress-strain relationship. From Figure 4, it can be seen that the Moment values corresponding to a value of 1.0 for the ratio "mid-thickness Strain / (1.5 Sm / E)", are 168 in.Kips. for the Straight Pipe, 132 in.Kips. for the Piping Elbow with the applied In-Plane bending, and 110 in.Kips. for the Piping Elbow with the applied out-of-plane bending. These Moment values are designated as $M_{(1.5\ Sm)}$.

Also, we would like to introduce now the Nominal Allowable Moment $M_{(Nom.,\ mid\text{-}th.)}$ based on the Yield stress at mid-thickness. This Allowable Moment can easily be calculated as follows (using the Input values from Table 1):

$$M_{(Nom,mid\text{-}th.)} = \frac{S_y * I}{R_m} = \frac{30*11.662}{2.031} = 172.3\, in.Kips$$

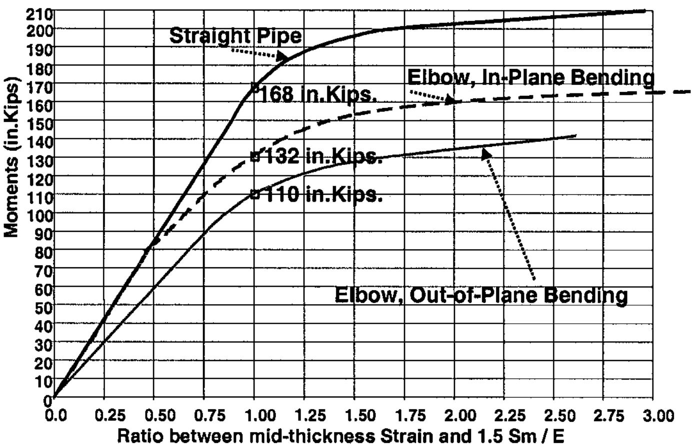

Figure 4: Applied Moment versus maximum Strain at mid-thickness anywhere in the pipe

As both the $M_{(1.5\ Sm)}$ values above and the $M_{(Nom.,\ mid\text{-}th.)}$ value of 172.3 in.Kips. are associated with the strain at mid-thickness, the C2 stress indices can be calculated easily as shown in Table 2.

Table 2: Calculation of the C2 stress indices, based on the strain at mid-thickness

Piping Component	Type of Loading	Moment $M_{(1.5\ Sm)}$ with Total elasto-plastic Strain = (1.5 Sm / E)	Ratio between $M_{(Nom.,\ mid\text{-}th.)}$ and $M_{(1.5\ Sm)}$
Straight Pipe	Bending	168 in.Kips.	1.03
Piping Elbow	In-Plane Bending	132 in.Kips.	1.31
Piping Elbow	Out-of-Plane Bending	110 in.Kips.	1.57

Note here that the Straight Pipe C2 stress index is slightly conservative, but still very close to its Code value of 1.0.

4.2.) Method 2 / Practical Method / Recommendation for the calculation of the Revised C2 stress indices

It is our experience that the C2 stress index developed above for Pure out-of-plane bending (in the elbow mid-section) is "appropriate". However, for Pure in-plane bending of the piping elbow, that C2 value is slightly too small. The reason for this is that, in the case of in-plane bending, the maximum stress at mid-thickness is at a level lower than 2/3 of the maximum stress at the inside radius (or outside radius), and the through-wall stress (bending through the thickness) goes totally plastic. That leads to an instability on the thickness due to the in-plane bending. As a result, the ovalization in the Elbow mid-section, and on both sides of that cross-section, can significantly impact the global stiffness of the elbow.

In summary, it can be said that the C2 stress index will be based on the most limiting between the mid-thickness (membrane) strain-yielding, and the through-wall bending going totally plastic.

As a result of the discussion above, the recommendation made in this Paper can be summarized as follows:

- First, calculate the maximum Tresca stress at the elbow mid-thickness, and multiply that stress by Ro / Rm,
- Second, calculate the maximum Tresca stress anywhere in the elbow, and divide that stress by 1.5,
- Third, take the highest stress between the first and second steps above, and divide that stress value by the Nominal Stress (= M * Ro / I)

The reason why, in the first two steps above, the Tresca stress (from the maximum shearing stress theory) is calculated is because it is mandated by the ASME-Code (see NB-3216 in Ref. 1). In general, it is also referred to as the "Stress Intensity".

The stress calculations required above can be performed through purely-elastic Finite-Element Analyses. However, the equations for the axial and hoop stress components are given in Table NB-3685.1-2 of the ASME-Code for a Piping Elbow submitted to Bending Moments. It has been verified, and documented elsewhere, that Table NB-3685.1-2 of the ASME-Code gives stress values which are higher than the stress values from the corresponding purely-elastic Finite-Element stress analysis of the 90-degree elbow. Also, ASME Code Table NB-3685.1-2 gives a very good approximation of the stresses in the elbow mid-section of the 90-degree elbow.

Therefore, it is recommended that the stress equations given in Table NB-3685.1-2 be used and that the required Stress Intensity values be calculated using the Tresca criterion. For the particular Piping Elbow analyzed in this Paper (4 in. Sch. 120, with Rc = 6 inches), the calculations have been performed. The results are given in Table 3 below.

4.3.) Method 3 / Simplified Method

A FORTRAN Program has been written to find simplified formulas for the Elbow stress index C2, based on the methodology presented in Sub-section 4.2 above, and for the Product C2 * K2 (for the total stress), also in the Elbow. The stress equations used in the Program are the equations of the ASME-Code Table NB-3685.1-2.

The range of values considered for the Elbow coefficient h is from h = 0.2 to h = 1.0, at intervals of 0.02. This range of h values should cover most of the 90-degree Piping Elbows used in practice. Unfortunately, it was found that the numerator (called *Num.*) of the C2 stress index formula [= $\frac{Num.}{h^{2/3}}$] is not constant in that range of h values. However, using the bounding *Num.* values in the range of the h values from 0.2 to 1.0, the C2 stress index and the C2 K2 product of the stress indices can be written as follows:

- For in-Plane Bending:

$$C_2 = \frac{\mathbf{1.24}}{h^{2/3}} \quad and \quad C_2\,K_2 = \frac{\mathbf{1.85}}{h^{2/3}}$$

- For out-of-Plane Bending in the Elbow mid-section:

$$C_2 = \frac{\mathbf{1.24}}{h^{2/3}} * \frac{Ro}{Rm} \quad and \quad C_2\,K_2 = \frac{\mathbf{1.70}}{h^{2/3}}$$

These four formulas are used in Section 5 below for the comparison between the three methods.

5.) COMPARISON BETWEEN THE THREE METHODS FROM SECTION 4

The comparisons of the C2 stress indices and of the C2 * K2 Products from the three Methods presented in Section 4 are performed in Table 3 below. The right hand side of this Table gives the Products C2 * K2, which are for the calculation of the maximum total stress (including Peak). All the stress values are Tresca-type stresses.

Table 3: Comparison between the different Methods (12 inch Sch. 120 90-degree Piping Elbows)

Methods	Basis for Method	C2 stress Indices		Products C2 * K2	
	Direction of Bending ➔	In-Plane	Out-of-Plane	In-Plane	Out-of-Plane
No. 1 : Rigorous	Finite Elements	1.31	1.57	2.11	2.08
No. 2 : Practical and Recommended	Table NB-3685.1-2	1.53	1.68	2.30	2.29
No. 3 : Simplified	Simplified Equations	1.67	1.86	2.50	2.30

Note that all the results in this Table 3 are from purely-elastic stress analyses, except for the C2 stress index values of 1.31 and 1.57 (Method No. 1). Also, an interesting point here is that, in Method No. 1, when correcting for bending on the thickness, the 1.31 value increases to a C2 stress index of 1.40 for In-Plane Bending, based on the Tresca criterion (2.11 / 1.5).

6.) COMPARISON WITH FATIGUE BASED ON ELASTO-PLASTIC FINITE-ELEMENT ANALYSES

Fatigue Analyses for piping elbows have been performed using the Reduced C2 stress index methodology. In these Fatigue/Stress Analyses, the current Fatigue Penalty Factors Ke were used to calculate the equivalent elastic strain range, then the alternating stress Sa, and finally the number of Allowable Cycles N from the ASME-Code Fatigue Curves. Out of curiosity, these Fatigue Analyses were then repeated, using exactly the same thermal transients, the same pressure variations and the same OBE seismic loads, but based on what we have called the “direct strain range” methodology. In this “direct strain range” methodology, a strain range is calculated for each range of “states of stress” in an elasto-plastic Finite-Element Analysis of the Piping Elbow. Then, without the necessity of having a C2 stress index or a Ke factor, this elasto-plastic strain range is used “directly” to calculate the “equivalent” alternating stress Sa required to find N from the Fatigue Curves.

When performing the comparison of the cumulative usage factors from the two methodologies, the “direct strain range” methodology was found to be less severe than the Revised C2 stress index methodology. This means, that, at least for this example, the Revised C2 stress index methodology is bounding, and therefore will provide higher cumulative usage factors than the more correct “direct strain range” method.

We are not presenting here the results from those comparisons because of their complexity. Instead, a comparison of Ke values can be found in Appendix B of this paper. In fact, we hope that this Appendix B will help the reader understand better the necessity for keeping the Ke values as they are now in the ASME-Code, and concentrate on more "appropriate" stress indices for the Piping components.

7.) ANALOGY WITH WORK PERFORMED BY OTHERS FOR THE B2 STRESS INDEX

In the past five years, a lot of work has been performed at N.C. State University on reduced B2 stress Indices for Piping Elbows. A general conclusion of that work is that the B2 stress index can be reduced by a large amount. For the In-Plane Bending Load Case, Ref. 3 gives a closed-form formula for the B2 stress index. Using that Formula, the B2 Stress Index can be calculated as being equal to:

$$B_2 = \frac{0.8}{h^{0.657}} = \frac{0.8}{0.64^{0.657}} = 1.08$$

If we return now to our work on C2, it is possible to approximate a value of B2, based on our Revised C2. Let us remember first that the B2 stress index is based on the Collapse mechanism of the entire cross-section, and that C2 is based on the stress at mid-thickness reaching Sy, after consideration of plasticity on the Pipe thickness. Therefore, the B2 stress index can be approximated as the Revised C2 stress index divided by 1.27 (exactly 4 / π), which is the Plastic Shape Factor for a thin Pipe. It could also be argued that, instead of 1.27, the slightly greater Thick Pipe Plastic Shape Factor should be used for the denominator. From Ref. 4, this Plastic Shape Factor P.S.F. is equal to:

$$P.S.F. = \frac{16\,Ro\,(Ro^3 - Ri^3)}{\pi\,(Ro^4 - Ri^4)} = \frac{16\,Ro\,(2.25^3 - 2.031^3)}{\pi\,(2.25^4 - 2.031^4)} = 1.40$$

Using either 1.27 or 1.40 at the denominator, and using the recommended In-Plane Bending C2 stress index of 1.53 from Table 3 of this paper, the Revised B2 stress index is then approximated as follows:

$$Based\ on\ 1.27\ :\ B_2 = \frac{1.53}{1.27} = 1.20 \qquad Based\ on\ 1.40\ :\ B_2 = \frac{1.53}{1.40} = 1.09$$

As can be seen, there is an excellent agreement between the Revised B2 stress index value from NCSU (1.08) and the smallest (1.09) of the two B2 values resulting from the Revised C2 Stress Index developed in this Paper.

8.) FINAL REMARKS

A lot more could be said on this subject, and the authors recognize that more evaluations are needed. For example, there is an urgent need at this time to perform similar elasto-plastic analyses for Class 1 tees and for Class 1 branch connections. We believe however that this Paper should be seen as a good "First Step" in the right direction for the calculation of "appropriate" C2 stress indices for Piping Elbows.

In addition, a previous technical paper (Ref. 5) points out to the fact that the C2 stress index is really the ratio between the proportional-limit moments of the straight pipe and of the piping component. It is interesting to note that this comparison of the global deformations of the straight pipe and, in this case, of the piping elbow is really the basis for the C2 methodology presented in this paper. This is shown here in the Figures 3 and A-1. Also, the validity of this C2 methodology is reinforced by the fact that a value just above 1.0 has been calculated in Table 2 for the straight pipe C2 stress index (1.03).

On a different topic, but still a related topic, the authors believe that, for Internal Pressure and Moments applied on the Piping cross-section, the current Ke formulation should stay as it is for now. As an illustration of that recommendation from us, Appendix B of this Paper shows that the current Ke formulation is "appropriate" not only for the Straight Pipe subjected to a bending Moment, but also for the 90-degree Piping Elbow, as long as the C2 stress index is reduced in accordance with the recommendations given in this paper.

9.) REFERENCES

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10.) ACKNOWLEDGEMENTS

The authors would like to thank Mr. Claude Heng and Mr. Dave Maxham, both from Framatome-ANP, for the discussions we had during the writing of this paper. Their help is very appreciated. Also, Thank You to Mrs. Kelly Stults and Mr. Nicolas Feraud for the arrangement of the text and of the Figures.

APPENDIX A : Impact of the Revised C2 stress Indices on the Global Structural Behavior of the Piping Elbow

In Section 3 of the main text, the Global Structural Behavior was evaluated, but could not be quantified without analyzing the variation of the strain in both the Straight Pipe and the Piping Elbow. That analysis has been performed in Section 4, and the recommended values for the stress index C2 are given in Table 3 of Section 5. These recommendations have been summarized here in Table A-1.

Table A-1: Overview of the Recommended Stress Indices

Structure and Loading type	Source	C2 Stress Index	Product C2 * K2	Resulting K2
Straight Pipe	ASME-Code	1.0	1.0	1.0
Piping Elbow, In-Plane Bending	Recommended Method	1.53	2.30	1.50
Piping Elbow, Out-of-Plane Bending	Recommended Method	1.68	2.29	1.36

Figure A-1 gives here the impact of these C2 and C2 * K2 values on the Global Structural behavior of the Straight Pipe and of the Piping Elbow. As can be seen on that Figure, after consideration of the "appropriate" margin of 1.3 (taken as round value for $\pi / 4 = 1.27$), the slope of increase of the Applied Moment is, percentage-wise, less severe for the two Piping Elbow load cases than for the corresponding Straight Pipe (in Figure A-1, slope 1 is smaller than both slope 2 and slope 3).

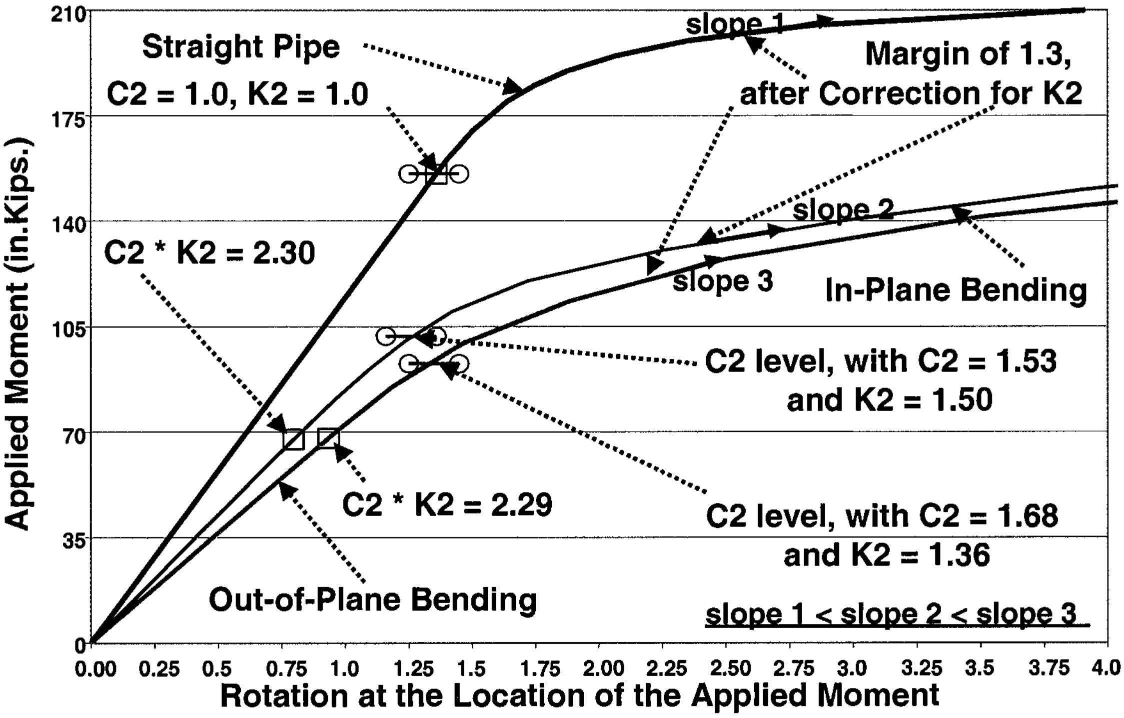

Figure A-1: Applied Moment versus Global Rotation, considering the Revised C2 Stress Indices

Conclusion from this Appendix A:

In the main body of this technical paper (see Section 4), the revised Piping Elbow C2 stress indices have been derived from the evaluation of the total mid-thickness elasto-plastic strain as a function of the applied moment. This Appendix A shows that these revised C2 stress indices are also supported by the observation of the Global Structural Behavior of the Piping Elbow, when compared to the Global Structural Behavior of the Straight Pipe.

APPENDIX B : Impact of the Revised C2 Stress Index on the Simplified Elasto-Plastic Fatigue Analysis of NB-3653.6

The current so-called "Simplified elasto-plastic Fatigue Analysis" from the ASME-Code (NB-3653.6) requires the calculation of an "equivalent" alternating stress Sa which is directly proportional to the Fatigue Penalty Factor Ke. This Ke Factor is a direct function of the primary plus secondary stress Sn, where the stress index C2 is used, in addition, for example, to the stress index C1 for internal pressure ranges.

The purpose of this Appendix B is to compare the Ke curves (as a function of Sn) when using the current C2 stress index of the ASME-Code $\frac{1.95}{h^{2/3}}$, with the Ke curve (as a function of Sn) when using the revised C2 stress index developed in this Paper. Both of these Ke curves are also compared to the Ke relationship from the current ASME-Code (NB-3653.6) and with the Ke curve from the Straight Pipe. All these comparisons are shown in Figure B-1 below. For the Piping Elbow and for the Straight Pipe, the Finite-Element stress analyses considered here are the same as the ones already mentioned in the main body of this Paper. The interesting point about the Straight Pipe Ke curve is that this curve is unique in the sense that for Straight Pipes both stress indices C2 and K2 are equal to 1.0, and cannot take any other value whatsoever.

Figure B-1 shows that, when using the current "classical" C2 stress index ($\frac{1.95}{h^{2/3}}$), the Ke curve is very far on the right hand side of the Figure. Therefore, using the Ke relationship of the ASME-Code, in concert with this "classical" C2 stress index, will lead to Fatigue Usage calculations which are overly conservative, especially when compared with the Straight Pipe. In fact, for the Straight Pipe, the ASME-Code Ke relationship is very "appropriate", as the Ke relationship of the ASME-Code will lead to Fatigue Usage values which are conservative, but not overly conservative. Now, when using the "revised" C2 stress index from this Paper, the Piping Elbow Ke curve is very close to the Straight Pipe Ke curve, and still under the current Ke relationship from the ASME-Code.

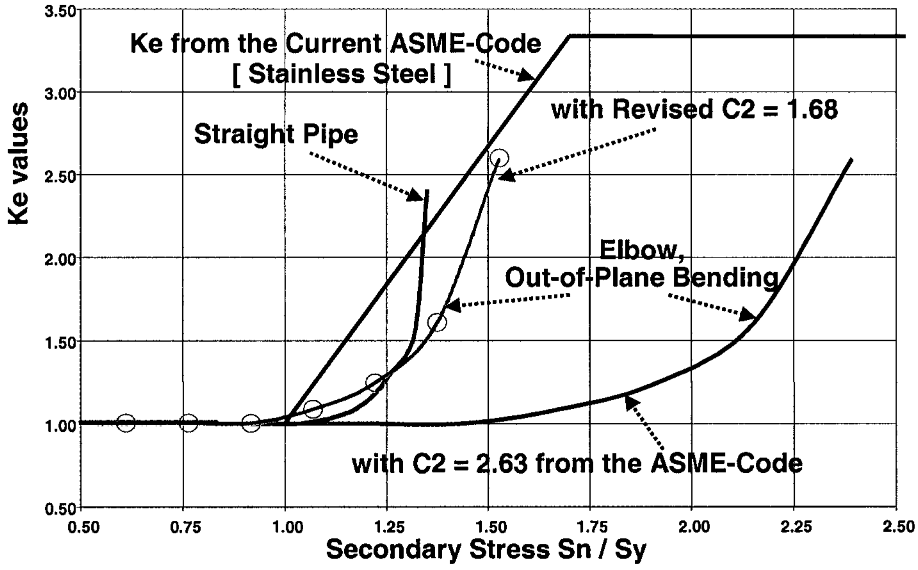

Figure B-1: Comparison of the Resulting Ke values from the elasto-plastic Finite Element Analyses

Conclusion from this Appendix B:

The use of the current Ke relationship from the ASME-Code is "appropriate" for both the Straight Pipe and the Piping Elbow, but under the condition that the "revised" Piping Elbow C2 stress index developed in this Paper is used, and not the current C2 stress index $\frac{1.95}{h^{2/3}}$ from the ASME-Code. The use of this current Elbow C2 stress index from the ASME-Code, together with the current Ke relationship (also from the ASME-Code), would lead to overly conservative Fatigue Usage.