SIFs and Orientations in CAESAR II

Versions of CAESAR II prior to Version 7.0 permit the user (or FEATools) to enter in-plane and out-of-plane stress intensification factors (SIFs). Starting with Version 7.0 the user can enter in-plane, out-of-plane, torsional, axial and pressure SIFs and SSI's for the B31.3 Piping Code. (The pressure SIF is not used in Version 7.0.) SSI's are "Sustained Stress Indices" defined in the 2010 and later versions of B31.3 in para. 320.

The most common "user-defined", or "FEATools defined" SIF description is for branch connections and the most commonly used advanced (more rigorous) piping model for branch connections is shown below. (See B31.3 300(c)(3).)

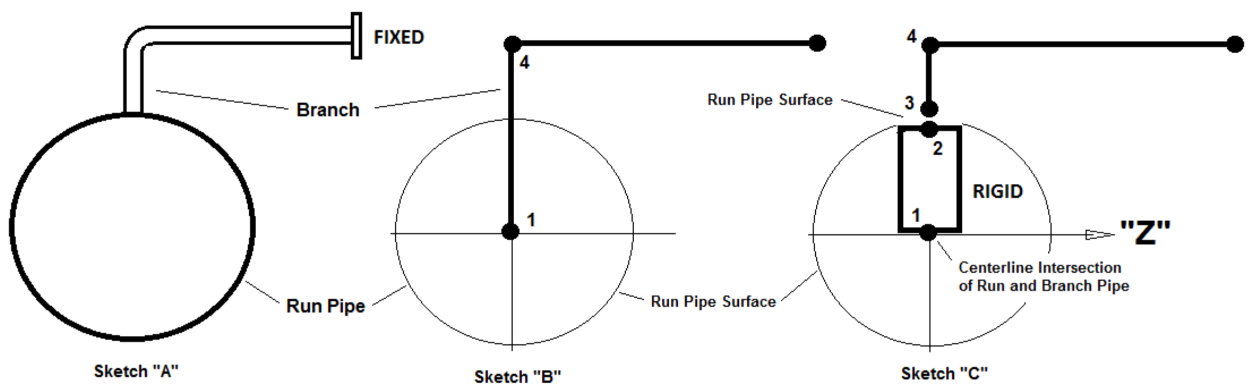


Figure 1 – Standard and "Advanced" Branch Connection Models

The standard elastic model for the branch used in most pipe stress programs (excluding ASME Section III Subsection NB – which expressly uses the "advanced" model here for branch connections) uses a single element from point 1 at the centerline intersection to some point removed from the junction. In the center diagram above, this is from point 1 to point 4. The reasons for this model are:

1)In general the distance from the centerline to the surface of the run pipe is considered negligible in the overall piping analysis, and so running the branch element from the centerline at point 1, to any other point external to the intersection is considered to provide acceptable accuracy.

2)The SIF defined by Markl and in B31J use the location of the crack to compute the applied moment, and in some cases the crack location occurs between the centerline intersection and the surface of the pipe. In this case, the larger moment found by using point 1 in the above figure, instead of point 3, to find the stress in the branch, gives a more conservative, and possibly more accurate evaluation. For small d/D branch connections (< 0.5), the failure occurs close enough to the surface so that using the model in "Sketch C" above is more accurate.

When applicable, "Sketch C" is the model most often selected for an improved analysis. In Figure 1 Sketch C the element from 3 to 4 defines the nominal branch pipe leaving the intersection. (It is important that the SIF be placed on the nominal branch pipe in all situations – and not any locally thickened pipe). The SIF and node 3 should be intensified, since it describes the stress at the intersection due to the external piping loads.

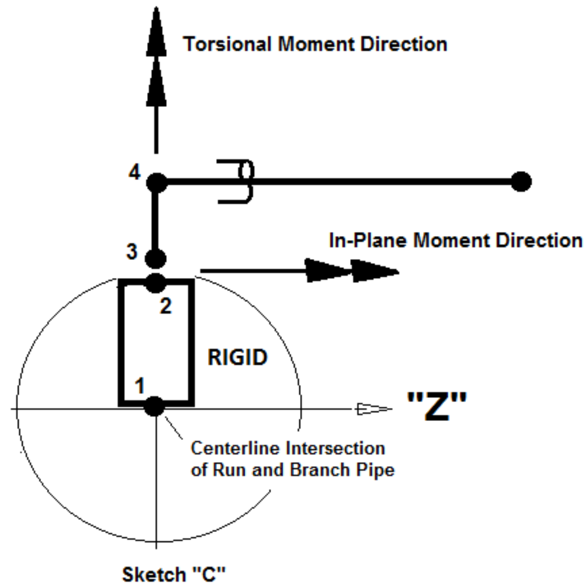


Figure 2 – Close-up of Figure 1 Sketch "C"

A portion of the CAESAR II SIF input data is shown below. For most piping Codes the in-plane and out-of-plane SIFs are used. For B31.3, the torsional and axial SIFs are also used along with the stress indices (SSIs) described in the 2010 version of B31.3 in para. 320.

Figure 3 – CAESAR II Version 7.0 SIF Panel

The straight piping element from node 3 to 4 in Figure 2 is connected to the rigid element at the branch on one end (node 3), and another piping element on the other end (node 4). **For a straight piping element, the in-plane and out-of-plane orientations are defined by the local axis of the element.** The user must be careful not to assume that the element from 3 to 4 has information about the orientation of the branch connection.

The local axis orientation for straight pipe in CAESAR II is constructed by using the following algorithm:

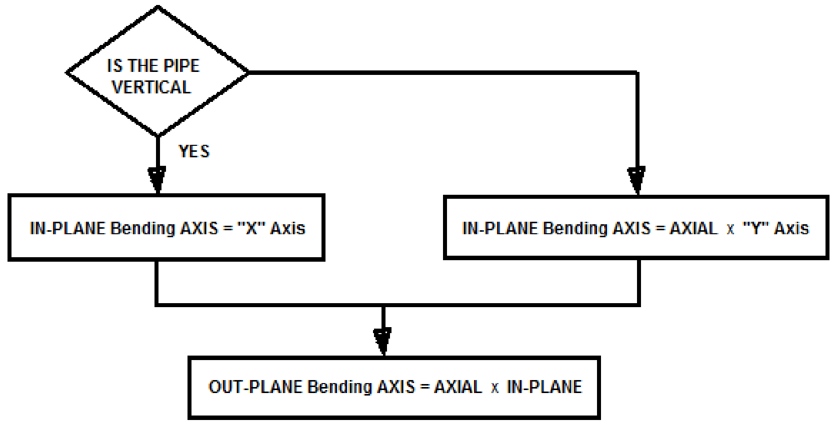


Figure 4 – Default Straight Element Bending Axis Definition

The geometry in Figure 5 below illustrates the need for user care when specifying in-plane and out-of-plane axis orientations.

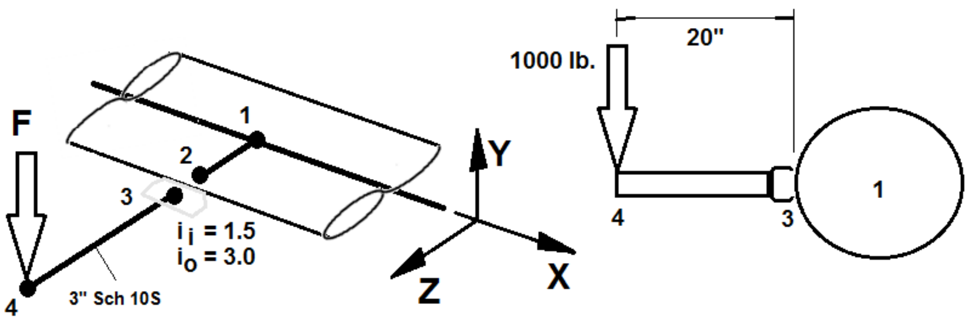


Figure 5 – Specialty Branch Fitting In-Plane SIF from test = 1.5, Out-of-Plane SIF from test = 3.0

In-plane and out-of-plane orientations for branch connections are given in Figure 6 below:

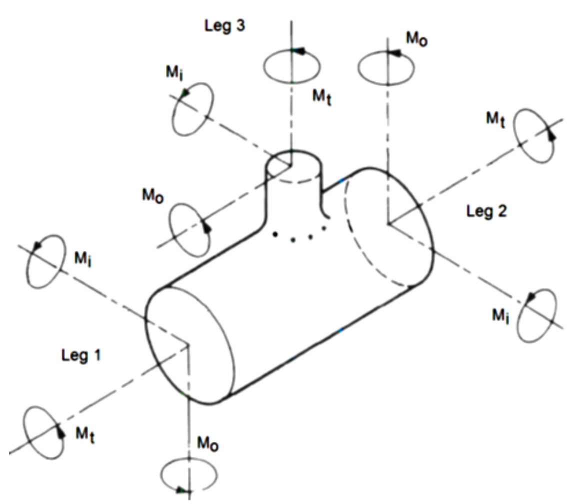


Figure 6 – Branch and Run Orientation Directions

By reviewing Figures 5 and 6, the force in Figure 5 can be seen to produce an out-of-plane moment about the branch and so the applicable i-factor is 3.0. The i-factor from test must be applied at the 3 end of the straight pipe defined as 3-to-4 in Figure 5. By studying Figure 5, the out-of-plane SIF should be applied to the MX moment at node 3, and the in-plane SIF should be applied to the MY moment at node 3. (Any torsional SIF would be applied to the MZ moment at node 3.)

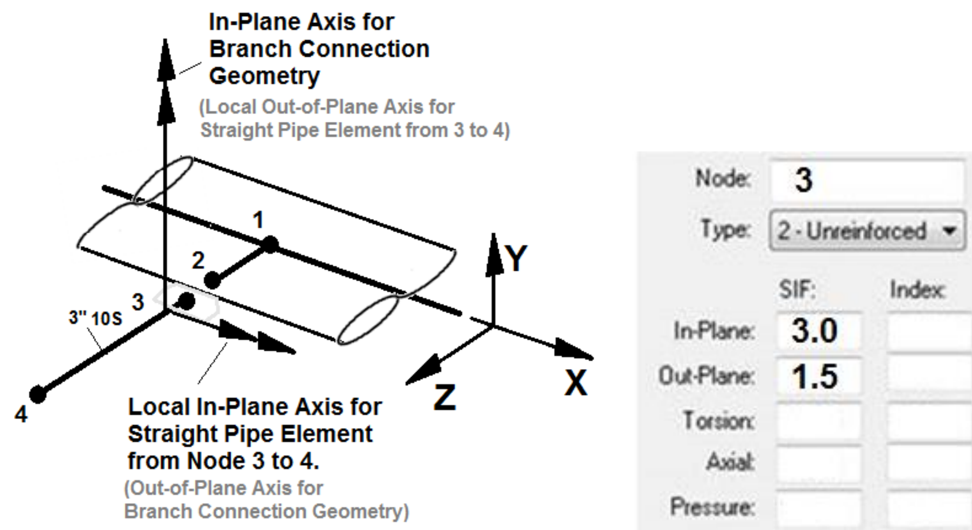


Figure 7 – In-Plane and Out-of-Plane Local Specifications

The node requiring the out-of-plane SIF for the 3-to-4 element is node 3, (i-factor = 3.0). The out-of-plane axis for this node 3 is along the global X axis. (See Figure 7.)

The local **<u>in-plane</u>** axis at node 3 is along the X axis however as shown in Figure 7 since the 3-to-4 element axial direction crossed with the y axis is along the X axis. (See the flow chart algorithm in Figure 4 above.) So in this example, we must put the out-of-plane SIF for node in the in-plane SIF slot on the CAESAR II spreadsheet as shown on the right in Figure 7.

The tendency would be to enter the in-plane SIF in the in-plane cell on the form, and the out-of-plane SIF in the out-of-plane cell on the form, but this would be incorrect, and the stress would be underestimated by two times.

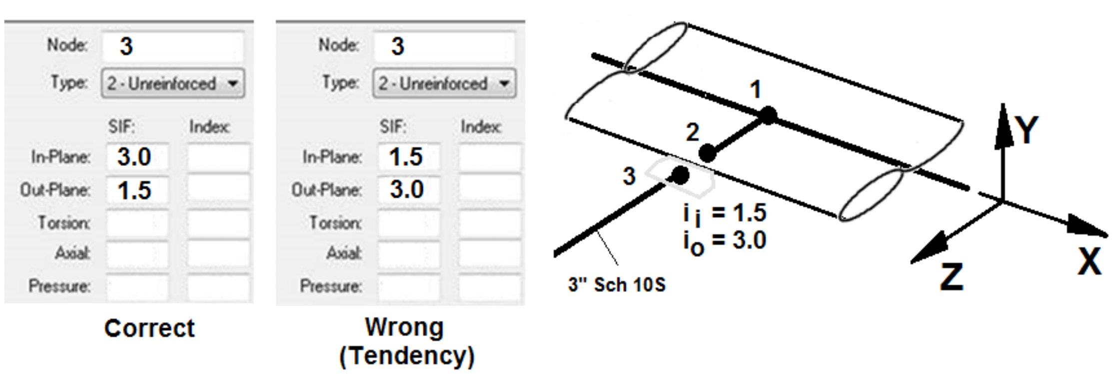


Figure 8 – Correct and Incorrect SIF Specifications for Example Branch Connection

The section modulus for the 3" schedule 10S pipe is approximately 1.04 cu.in., and so the out-of-plane stress due to the thermal load F=1000lb., is i x F x L / Z = 3 x 1000 x 20 / 1.04 = 57 ksi.

Stress from "Wrong" Input = 1.5 x 1000 x 20 / 1.04 = 28.5 ksi.

Stress from "Correct" Input = 3.0 x 1000 x 20 / 1.04 = 57 ksi.

A simple CAESAR II model of the above geometry verifies this behavior.

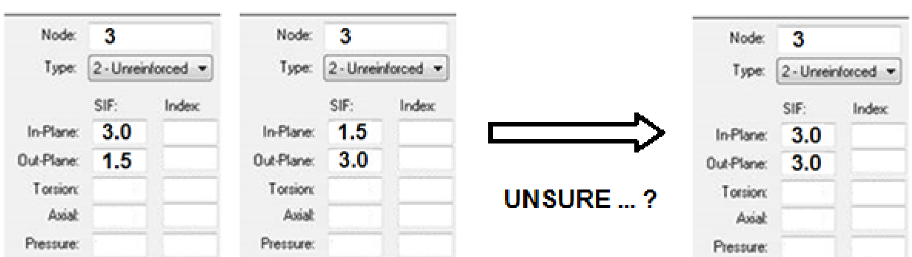
The user should note that the local SIF orientation is always a concern when the user is applying in-plane and out-of-plane SIFs at a single node on a straight pipe where the local in-plane and out-of-plane directions do not correspond to those defined by the particular geometry simulated. This can occur at:

a) Valves
b) Support Locations (Saddles and Pipe Shoes)
c) User entered SIFs at tees
d) Vessel heads
e) Cone connections
f) Hillside nozzles

In these cases, as shown in the example, the user must determine which of the local axes correspond to the geometry directions where the SIFs are obtained and then enter the SIFs appropriately.

In some cases, in-plane geometry SIFs must be entered in the out-of-plane SIF text cell on the CAESAR II form, (see Figure 8), and the out-of-plane geometry SIFs must be entered in the in-plane SIF text cell.

If the user is confused or unsure of the SIF orientations, then a conservative approach is to enter the highest of the in-plane or out-of-plane SIFs in both text cells.



If the user is unsure which of these inputs properly use the local default SIF axis for straight pipe ...

Branch Connection SIFs

For branch connections the SIF definition orientations require an understanding of the local SIF direction orientations also, and it is for principally this reason that FEATools, which automates the orientation process, can be most effective.

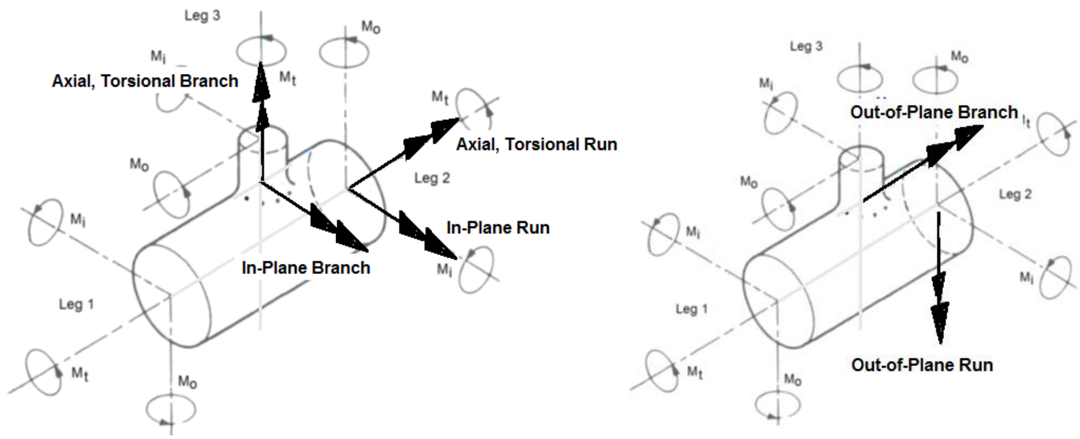


Figure 9 – Cross-Product Consistent Branch and Run Orientations

As seen in Figure 9 above, axial and out-of-plane orientations for the branch and run pipe are not the same, while the in-plane orientations for the both the branch and run pipes are the same.

Orientations for 90 degree branch connections are shown in Figure 10 below:

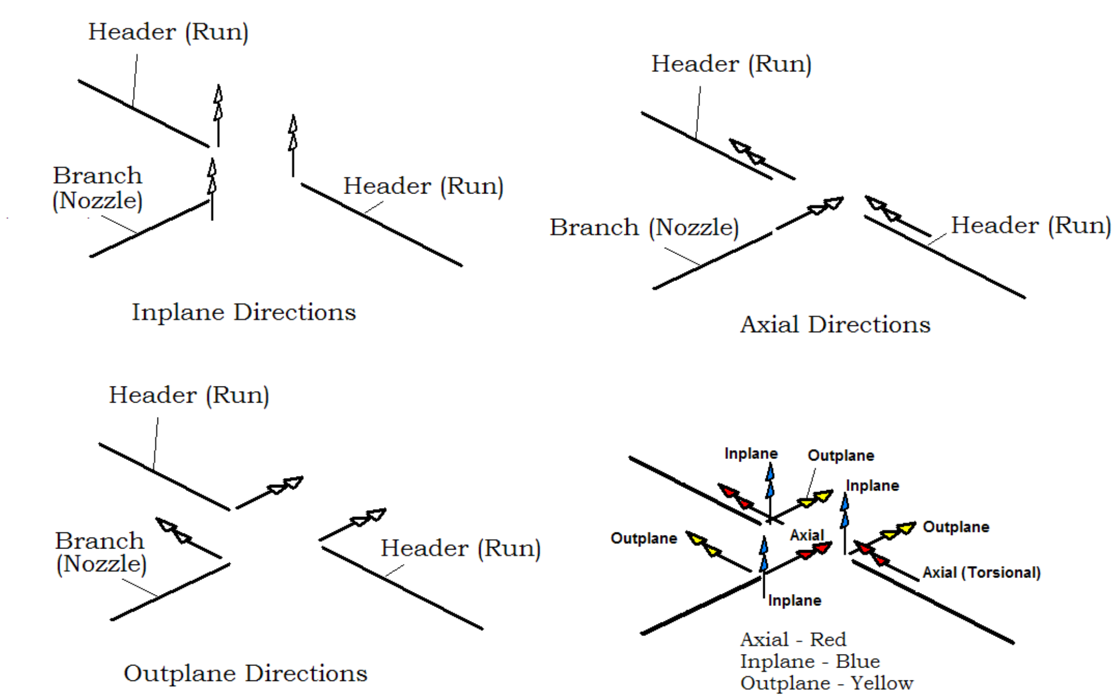


Figure 10 – Common Branch Connection SIF and Flexibility Orientations

When the d/D ratio is greater than 0.5, it is recommended that the branch location for stress computation remain at the branch and run centerline intersection while the flexibility of the point stiffnesses for the branch side of the branch connection is placed at the surface.

This can cause modeling confusion. The moment for stress evaluation is computed at the branch-to-run centerline, but the flexibility for the branch is placed at the surface. The element from the centerline to the surface should be stiff relative to the branch, and for the general case the stress should be calculated in the branch pipe at the surface of the run also to make sure that the highest moment location is properly identified. (The moment can vary in any direction along the branch pipe. The moment can increase in the direction of the intersection centerline, or can decrease in the direction of the intersection centerline.)

This can be accomplished several ways. The simplest approach to use with CAESAR II is to use the run pipe properties from the centerline to the surface, and then multiply the branch SIFs by the ratio of the section modulii.

This approach is demonstrated in the FEATools example model below given in at the bottom of this section.

For Laterals, the user should remember that in-plane and torsional directions for lateral and normal branch connections are easily identified for both the branch and run pipe. Once the axial (torsional) and in-plane directions are identified, the out-of-plane direction for both the branch and run elements is defined as the axial direction vector crossed into the in-plane direction vector.

Intersection Example Model:

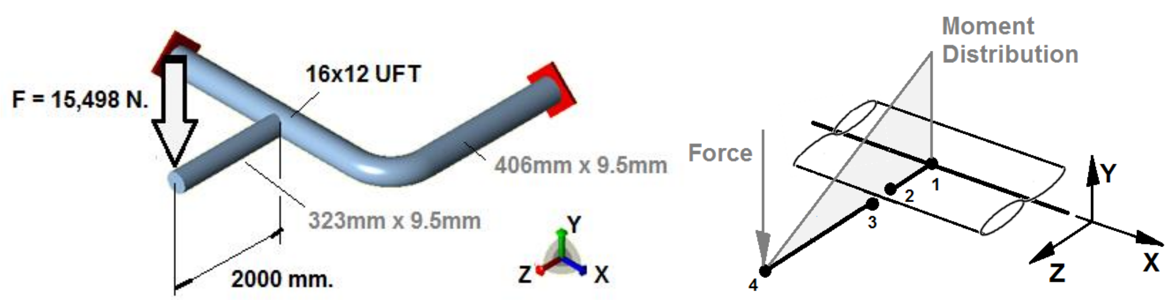


Figure 11 – Example Model Showing Non-Conservatism in Out-of-Plane Branch Loading

The simplified piping system shows an operating load of 15,498 Newtons acting at the end of the 12" branch. A schematic of the developed moment diagram is shown in the right. The moment is highest at point 1 and varies linearly along the branch pipe from the point of application of the load to the centerline intersection of the branch and the run at node 1.

```
Piping Code: B31.3      = B31.3 -2010, March 31, 2011


 CODE STRESS CHECK PASSED      : LOADCASE 1 (EXP) F1

Highest Stresses: (lb./sq.in.)
Ratio (%):                   82.9       @Node      20
Code Stress:               41446.6      Allowable Stress:      50000.0
```

Figure 12 – CAESAR II Stress Output 2010 B31.3 Appendix D SIFs

When a CAESAR II analysis is performed the calculated stress **satisfies the Code allowables**: S_E = 41.4 ksi and S_A = 50 ksi, the ratio of the calculated intersection stress to the allowable is 41.4/50 = 82.8%.

The stress can be manually calculated. The section modulus for the branch pipe is $\pi r^2 t$ = 733,311 mm^3. The moment at the branch connection is 15498 x 2000 = 30,996 N.m. in the out-of-plane direction. The out-of-plane i-factor from the CAESAR II calculation is 6.814. The 16x12 UFT intersection at node 1 is a reduced branch connection, so the i-factor should be multiplied by the t/T ratio to be used with the nominal stress (See WRC 329 for a thorough explanation of the use of the effective section modulus calculation for reduced branch connections.) The t/T ratio for this branch connection is 1.0, and so no adjustment for the effective section modulus calculation is required. (Where needed, FEATools automatically adjusts any B31 SIF calculation so that the displayed SIF can be compared to FEA, EPRI and ASME Section III NB peak stress factors and is based on the nominal stress in the pipe of interest.)

The stress due to an externally applied out-of-plane bending moment about this branch is:

$$iM/Z = (6.814)(30996)\times 1000 / 733{,}311 = 288 \text{ MPa } (41.7 \text{ ksi})$$

The d/D ratio for this branch connection is(232-9.5) / (406-9.5) = 0.7906. B31.3 Note 11 to table D-300 states that in this intersection range the SIF from the table may be non-conservative, and that selection of the appropriate SIF is the designer's responsibility. Note 11 is reproduced below.

(11) The out-of-plane stress intensification factor (SIF) for a reducing branch connection with branch-to-run diameter ratio of $0.5 < d/D < 1.0$ may be nonconservative. A smooth concave weld contour has been shown to reduce the SIF. Selection of the appropriate SIF is the designer's responsibility.

When FEATools is run for this branch connection the stress along the branch is computed at two locations. This is in the event the actual moment distribution is as shown on the rightmost sketch in Figure 13.

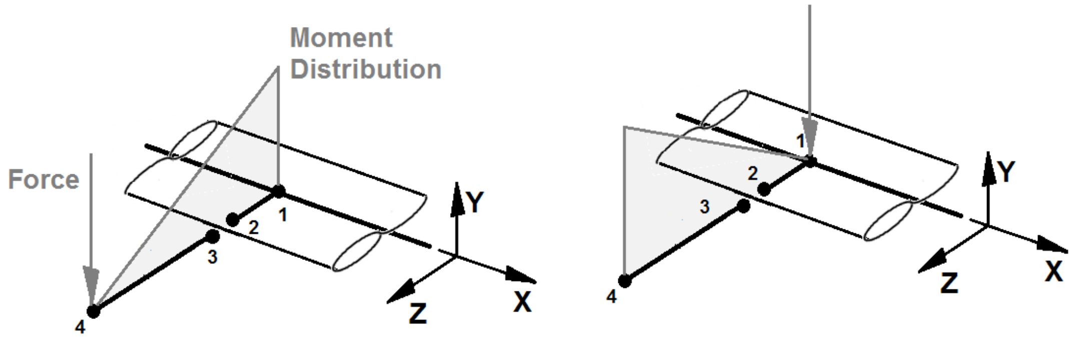


Figure 13 – Possible Out-of-Plane Moment Variations along Branch

There must be a "rigid" or "stif" element along the branch centerline from the centerline of the the run to the surface of the run. (Element 1-to-2 in Figure 13.) When the d/D ratio is greater than 0.5, FEATools uses an element from the center of the run to the surface of the run that has a diameter and wall thickness equal to the run pipe since the stress has to be calculated for the branch at point 1 on the 1-to-2 element., and at point 3 on the 3-to-4 element. (The run pipe od and thickness is 406mmx9.5mm for this problem.)

In the case where the out-of-plane branch moment at node 3 is the same as the out-of-plane branch moment at node 1, the stresses should be the same as shown in the equation below:

$$i_1 \, M/Z_1 = i_3 \, M/Z_3 \qquad [\text{ Eq. 1 }]$$

For this equation to be satisfied, $i_1 = i_3 \, Z_1/Z_3$.

FEATools makes all of these computations and SIF assignments automatically to properly simulate the branch connection.

The SIFs for the 12x16 branch connection calculated by FEATools are shown in Figure 14 below.

```
Intersection Node =    20       Type = Unreinforced, Fabricated UFT

     Run/Header Outside Diameter       =      406.400
     Branch Outside Diameter           =      323.850
     Run/Header Thickness              =        9.525
     Branch Thickness                  =        9.525
     Nozzle Angle (Degrees)            =        0.000
     Modulus Used                      =       203402.

     Branch Flexibility Factors (kax, kin, kout, ktor)
         1.674      5.552     17.703      4.392

     Header Flexibility Factors (kax, kin, kout, ktor)
         1.153      1.760      0.107      3.006
```

	BRANCH SIFs			RUN/HEADER SIFs		
	B31.3	STLLC07-02	FEA	B31.3	STLLC07-02	FEA
In	5.361	3.548	2.906	5.361	3.598	2.515
Out	6.814	10.119	8.558	6.814	1.476	0.941
Tors	1.000	3.204	2.336	1.000	3.524	2.727
Axial	-	-	8.726	-	-	3.050
Press	-	-	6.654	-	-	5.270

Figure 14 – FEATools SIF Table

A number of interesting observations can be made about this table:

1)STLLC07-02 is a correlation method based on an extension of the guidelines given in WRC 329.

2)The branch out-of-plane SIF from the correlation method is 10.11, and from the FEA method is 8.558. Both of these out-of-plane SIFs are greater than the value 6.814 used in the B31.3 Code and demonstrate the lack of conservatism in the out-of-plane branch SIF for the reduced branch connection.

3)The RUN SIFs are the same as the branch SIFs since the run SIFs for the 2012 (and earlier) versions of B31.3 do not adjust the SIF for the branch d/D ratio. In this case, for the out-of-plane run direction, this will result in an over-conservatism of 6.8/1.0 = 6.8! Rodabaugh in WRC 329 (p.21) describes this problem as “silly” and calls on the designer to make the appropriate correction. Both FEATools and the correlation equations are seen to make a more appropriate estimate of the run SIF.

4)Appendix P of B31.3 2012 suggests that $i_a = i_p$. As seen in Figure 14, this is over-conservative for the pressure stress contribution in the branch, and un-conservative for the pressure stress in the run.

5)The branch out-of-plane flexibility factor is 17.7. This can be interpreted to mean that there is 17.7 equivalent lengths of pipe concentrated at the run surface at the branch in the out-of-plane direction. Looking at the model to scale in Figure 11, it is clear that there is more effective pipe in the branch connection than there is in the branch pipe itself. If the critical stresses or loads in this model are due to the flexibility of the branch pipe, then including the flexibility of the branch connection is important.

In Figure 15 below, the model used for the branch connection when d/D>0.5 is shown. Note that to satisfy Equation 1, the i-factor at the branch must be multiplied by Z_{stiff}/Z_{branch}, where Zstiff is the section modulus of the element between the centerline and surface of the run pipe. For the FEPipe model, $Z_{stiff} = Z_{run}$ when d/D > 0.5. When d/D < 0.5 the stress is only to be calculated at the surface of the pipe. (See ASME Section III NB 3200, and ASME ST LLC 07-02.)

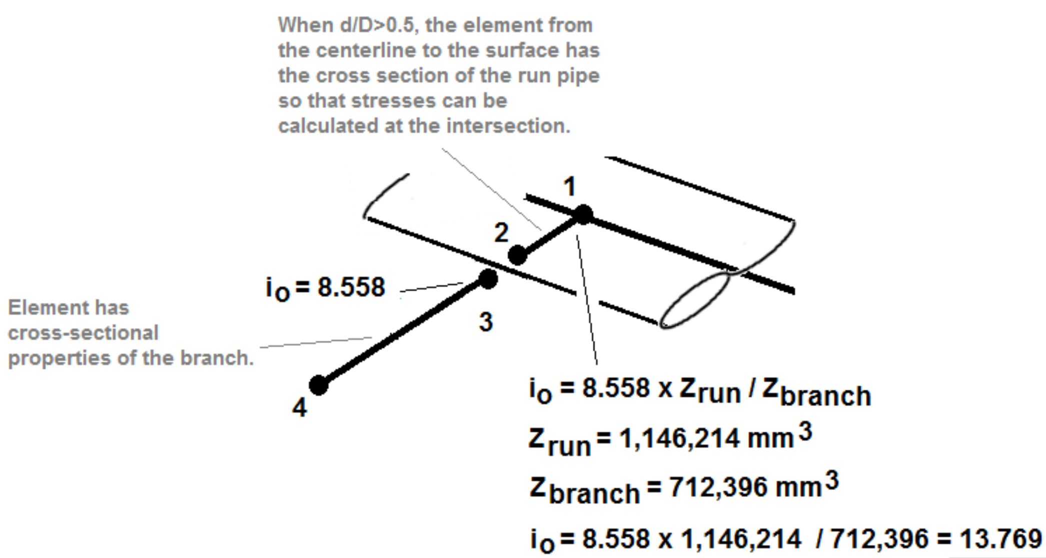


Figure 15 – i-Factor Adjustment at Branch Model when d/D > 0.5

As might be expected, when the designer selects more appropriate SIFs per Note 11, the branch connection is overstressed since the out-of-plane SIF is higher than the 2012 B31.3 Appendix D value.

```
Piping Code: B31.3      = B31.3 -2010, March 31, 2011


 CODE STRESS CHECK FAILED      : LOADCASE 1 (EXP) F1

Highest Stresses: (lb./sq.in.)
Ratio (%):                   107.2       @Node     20
Code Stress:               53579.0       Allowable Stress:      50000.0
```