Applicability of ANSYS ELBOW290 Element for Flexibility Calculation of Tight Radius Bends on Feeder Pipes in CANDU Reactors

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Abstract

A curved pipe element, ELBOW290, became available in ANSYS® 12. This element was developed based on a simplified shell theory, and maintains the ability to capture cross-sectional deformations of elbows. Numerical testing on the applicability of this element for the flexibility calculation of the tight radius bends in CANDU® reactors is carried out to determine the usability of this element in completing stress analyses for feeder pipes. Comparisons are made between the ELBOW290 and the shell element for various feeder bend types found in domestic and overseas CANDU reactors. The comparisons show that the ELBOW290 element is suitable for calculating the flexibility of the tight radius bends.

1. Introduction

In modern piping stress analysis, the flexibility of a piping system is often obtained using the finite element method with pipe or beam elements developed based on the Bernoulli beam theory. However, the beam theory is not capable of capturing cross-sectional deformation in pipes due to its rigid cross-section assumption. The cross-sectional deformation, e.g. ovalization, is significant in tight radius elbows (i.e., elbow with relatively small torus radius compared to the pipe diameter), and makes the flexibility of the elbow significantly higher than that of a straight pipe with the same length and pipe diameter. Flexibility factors are commonly used to match the Bernoulli beam solution with the actual elbow flexibility [1]. The flexibility factors can be calculated from empirical equations, such as those in NB-3686.2 of [2] or by finite element analysis using shell elements.

In the stress analysis of feeder pipes in CANDU reactors, complex piping models that include a significant number of the 380 to 480 feeder pipes are created and solved for various loading conditions. There is at least one tight radius bend in each feeder as well as a number of large radius bends. The flexibility factors need to be calculated for these bends. The flexibility factors calculated by the empirical equations, e.g. in the ASME BPVC NB-3686.2 [2], overestimate the elbow flexibility, since the equations were compiled for 90 degree elbows, but the elbow or bend torus angle is significantly less than 90 degree in feeders. The overestimated flexibility leads to potentially non-conservative results especially under thermal loading, since the bending moments are underestimated. In this case, the flexibility factors can be calculated using a more refined approach if an assessment of the overall conservatism of the calculated piping stress indicates the

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need to do so. One such method is to calculate the flexibility factors by matching the rotational deformation in three principal directions between the piping model and a shell model of the same geometry [3] despite omitting the insignificant pressure effect in the tight radius bends. This method can usually achieve a flexibility factor close to that of the shell model with less than 10% difference for the feeder tight radius bends. However, when the end-of-life (EoL) condition is evaluated, each feeder may have a unique thickness thus a unique flexibility factor at the bends. This makes the calculation of flexibility factors using the above method a sizable task. The effort becomes more considerable when there are iterations of thickness change during the analysis, e.g. to determine the minimum acceptable thickness.

An alternative approach is to obtain the bending moments directly for a model where the tight radius bends are represented using shell elements in a mixed shell-piping model. This approach can eliminate the modeling error on the flexibility factors, but the modeling effort and the computational cost is significantly higher than the aforementioned methods for the typical multi-feeder analysis. An alternative approach that provides a better balance between accuracy and efficiency is desired.

It would be ideal to combine the convenience of the beam element, and the accuracy of the shell element in one piping model. There have been many attempts towards the development of shell-type elbow elements based on the general thin shell theory and beam-like geometry, such as those in [4]-[7]. In the formulation of these elements, the elbow is characterized by the deformation of the two ends of the pipe centerline. The displacement field at any material point in the pipe wall is interpolated using high order (e.g. cubical) polynomial in the axial direction, and Fourier series is used to interpolate the displacement field in the circumferential direction. These elements showed satisfactory accuracy in the analysis of in-plane and out-of-plane deformation of the elbows. The computational cost is higher than for conventional pipe beams due to the presence of the Fourier series and multiple integration points in the circumferential directions, but lower than for a typical shell element model. More importantly, the piping modeling procedure is significantly simplified using the beam-like elements than the shell elements. This type of element may become a good solution in the feeder analysis.

Despite the advantages of the shell-type elbow element, these elements are complicated in their formulation, and thus did not become a standard element in the popular commercial finite element packages until recent years. ABAQUS® developed their ELBOW31/32 elements based on a number of research articles. ANSYS also added ELBOW290 element to their element library in ANSYS Version 12, which was developed based on [4] and [5]. With the advancing of the commercial packages, it is possible for the nuclear industry to attempt to implement the shell-type elbow elements in practical problems.

This paper is intended to investigate the suitability of the shell-type elbow element for the flexibility calculation of the feeder tight radius elbows. The ELBOW290 element from ANSYS is chosen to model a variety of feeder tight radius bends found in the CANDU reactors. The calculated flexibilities are compared to those obtained from shell element models. Both accuracy and

® ABAQUS is a registered trademark of Dassault Systèmes Simulia Corp efficiency will be discussed. The conclusion drawn in the paper will assist nuclear piping engineers to consider an alternative way of modeling the feeder bends.

2. Method for Feeder Elbow Flexibility Evaluation

2.1 ELBOW290 Element

The ANSYS ELBOW290 element, as shown in Figure 1, is a three-node curved pipe element. It has cubical interpolation on the displacement field along the pipe centerline, and Fourier series interpolation along the circumference. Two (2) to eight (8) Fourier terms can be selected as a user option. In general, a flexible elbow requires a higher number of the Fourier terms. At each axial location, there are five modes of cross-sectional deformation: 1) section radial expansion (SE); 2) section ovalization (SO); 3) section warping (SW); 4) local shell normal rotation about axial direction (SRA); and 5) local shell normal rotation about the tangential direction (SRT) according to the ANSYS User's Manual [8].

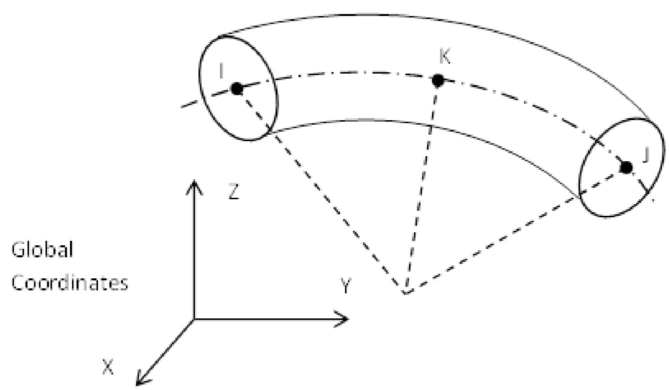

Figure 1 Illustration of ELBOW290 Element

2.2 Modelling of Tight Radius Bends

To investigate the flexibility calculation by the ELBOW290 element for various feeder tight radius curved pipe configurations, a series of finite element models were built for the compound structure, which extends from the hub seal surface to the second elbow or bend. The model includes the following components: 1) the Grayloc hub; 2) a small piece of straight pipe between the hub and the first bend; 3) the first bend; 4) the straight pipe between the first and the second bend, if applicable; 5) the second bend; and 6) a portion of the straight pipe beyond with a length of 5 times the outside diameter (OD).

The structure composed of the above components differs from feeders to feeders with each configuration being regarded as a "bend type". In this paper, various bend types are investigated that occur in operating CANDU plants, namely "Plant A" and "Plant B". In all cases, the bend thickness is assumed uniform.

Two models are built for each bend type; that is, one model is the three-dimensional shell model meshed with the SHELL181 element, and the other model is the one-dimensional piping model meshed with the ELBOW290 element. Both models include the aforementioned feeder components. The straight pipe after the second bend is to eliminate the effect of the local disturbance of the stress field at the loading point. Examples of typical compound bends are given in Figure 2 and Figure 3 for double tight radius bends and single tight radius bends, respectively. The mesh of the piping model is shown in Figure 4.

Different meshing schemes are tested on the piping models. For simplicity and consistency, only the pure ELBOW290 mesh is used in the numerical comparison tests. It is found that four elements on each elbow and five elements on the hub shall be sufficient.

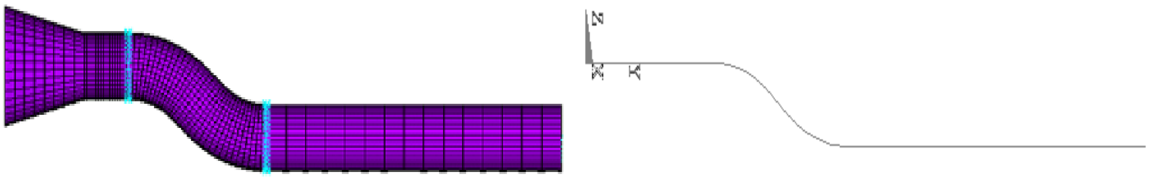

Figure 2 Representative Double Tight Radius Bend Modeled with Shell Elements (Left) and PIPE16/ELBOW290 Elements (Right)

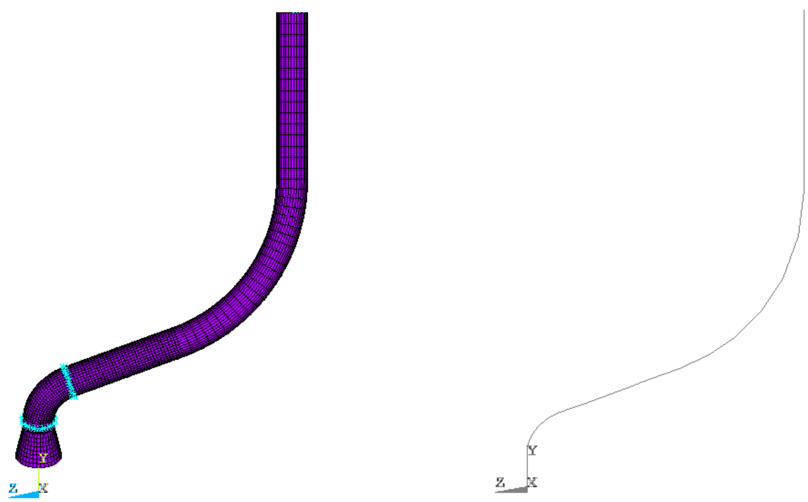

Figure 3 Representative Single Tight Radius Bend Modeled with Shell Elements (Left) and PIPE16/ELBOW290 Elements (Right)

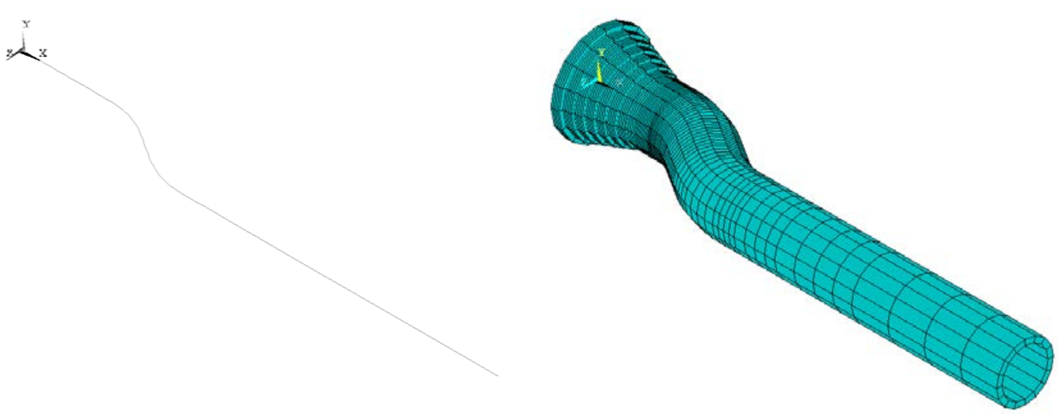

Figure 4 Typical Mesh of a Double Elbow with ELBOW290 elements: Plotted in Line Mode (Left); Plotted with Full Cross-section (Right)

It is well understood that the tight radius bends of the outlet feeders are subject to flow accelerated corrosion (FAC); therefore, wall thickness reduction must be considered in the feeder analysis. In the present example, an equivalent uniform thickness reduction down to 60% of the nominal thickness was considered. Therefore, the analyses of each bend type will be repeated 5 times with a uniform elbow thickness equal to 100%, 90%, 80%, 70% and 60% of the nominal thickness. For the bend types only applicable to inlet feeders, only the nominal thickness value is considered.

The material is assumed to be linear with a Young's modulus of $E = 26.5 \times 10^6$ psi, and a Poisson's ratio of $\nu = 0.3$.

The modeled feeders are fully restrained at the free end of the Grayloc hub. A unit moment load in applied at the free end of the straight pipe in each of the three directions in the global coordinates.

The calculations were performed using ANSYS 14 on a verified platform.

2.3 Flexibility of Tight Radius Bends

The flexibility of a bend, θ_{ab}, is defined as the difference of the rotational angle due to a bending moment at the two ends of the bend, as specified in ASME BPVC Section III NB-3682 (c).

In the shell model, the structure is fixed at the hub seal surface and a unit moment load (M_x, M_y and M_z) is applied at the free end in the X, Y and Z directions, respectively. A sets of rotation angles are generated in each model, which includes the rotational angles in the three direction, θ_x^x, θ_y^x and θ_z^x due to unit load in the X direction, three rotational angles θ_x^y, θ_y^y and θ_z^y due to unit load in the Y direction, and three rotational angles θ_x^z, θ_y^z and θ_z^z due to unit load in the Z direction. The flexibility matrix of the structure is defined as

$$[F] = \begin{bmatrix} \theta_x^x & \theta_y^x & \theta_z^x \\ \theta_x^y & \theta_y^y & \theta_z^y \\ \theta_x^z & \theta_y^z & \theta_z^z \end{bmatrix}$$

Then, following [3] the flexibilities in the three principal deformation directions, $f_i \ (i = 1, 2, 3)$, are found by conducting an eigenvalue analysis of $[F]$. The vector length of $(f_1\ f_2\ f_3)$ can be calculated as $R_{Shell} = \sqrt{(f_1)^2 + (f_2)^2 + (f_3)^2}$. Similarly, the same steps are completed for the ELBOW290 piping model, and R_{Pipe} is calculated. The difference in the flexibility between the two models is evaluated as:

$$\text{Error} = \frac{R_{Pipe} - R_{Shell}}{R_{Shell}} \times \% \qquad \text{Eq. (1)}$$

The comparison is conducted in the similar way that is used to calculate the flexibility factors. The difference between the ELBOW290 model and the shell model, as calculated in Eq. (1), is used to evaluate the accuracy of the ELBOW290 elements. The comparison results are given in Section 3.

3. Applicability of ELBOW290 Element

3.1 Plant A Tight Radius Bends

The comparison results for the bend types in Plant A are listed in Table 1. Statistics of the maximum and average differences are also given at the end of the table. It can be seen that the average difference for the ELBOW290 models, comparing to the shell models, is only 1.1%, and the maximum difference is limited to 3.2%.

Table 1 Comparison for CANDU Bend Types between ELBOW290 and Shell Models

Bend Type	**100% Nominal Thickness**	**90% Nominal Thickness**	**80% Nominal Thickness**	**70% Nominal Thickness**	**60% Nominal Thickness**
	Difference	**Difference**	**Difference**	**Difference**	**Difference**
1	1.9%	1.1%	0.4%	0.4%	0.9%
3	1.2%	0.4%	0.4%	1.0%	1.6%
4B	1.5%	0.8%	0.3%	0.4%	0.8%
4C	1.6%	0.7%	0.3%	0.7%	1.0%
5A	1.5%	0.9%	0.4%	0.4%	0.8%
6	0.9%	0.8%	1.3%	2.0%	2.7%
7	1.1%	0.2%	1.0%	1.9%	2.6%
9	1.4%	0.5%	0.3%	1.0%	1.5%
10B	1.5%	0.8%	0.3%	0.2%	0.4%
10C	1.5%	0.4%	0.5%	1.2%	1.6%
11A	1.5%	0.8%	0.2%	0.3%	0.6%
12	0.8%	1.0%	1.6%	2.4%	3.2%
13	1.4%	--	--	--	--
15	1.9%	--	--	--	--
16B	2.4%	--	--	--	--
17A	2.3%	--	--	--	--
17C	2.1%	--	--	--	--
18	2.1%	--	--	--	--
Max. Difference	3.2%				
Avg. Difference	1.1%				

3.2 Plant B Tight Radius Bends

Similar comparisons are conducted for outlet feeder bend types from Plant B. The results are listed in Table 2. The average difference is 1.4% and the maximum difference is 5.8%.

Table 2 Comparison for Outlet Feeder Bend Types between ELBOW290 and Shell Models

Bend Type	**100% Nominal Thickness**	**90% Nominal Thickness**	**80% Nominal Thickness**	**70% Nominal Thickness**	**60% Nominal Thickness**
	Difference	**Difference**	**Difference**	**Difference**	**Difference**
1	0.8%	1.1%	1.7%	2.5%	3.2%
2	0.9%	0.2%	0.6%	1.1%	1.6%
3	1.3%	0.6%	0.1%	0.5%	0.8%
4	1.3%	0.6%	0.1%	0.6%	0.9%
5	0.9%	0.4%	0.6%	1.3%	1.9%
6	1.2%	0.5%	0.4%	0.9%	1.5%
7	1.0%	0.3%	0.5%	1.1%	1.5%
8	0.9%	1.6%	2.5%	3.5%	4.6%
20	2.0%	2.9%	3.9%	4.9%	5.8%
22	1.9%	1.3%	0.7%	0.4%	0.7%
Max. Difference	5.8%				
Avg. Difference	1.4%				

3.3 Accuracy and Computational Cost

The accuracy of the ELBOW290 element is controlled by the number of Fourier terms used in its formulation. The number of terms can vary from 2 to 8. The more terms used, the better accuracy will be achieved with a price of higher computational cost. In general, when the wall thickness becomes thinner, more Fourier terms are needed. The above results were produced with the same number of Fourier terms.

For the computational cost, the ELBOW290 model was found efficient. The CPU time used for solving three load cases, with a unit moment applied at the free end in each of the three coordinate directions, was found comparable to that of the PIPE16 element, and much lower than that of the shell element.

4. Conclusion

Numerical comparison tests were conducted for various CANDU tight radius bends to assess the flexibility calculation. The comparison showed that satisfactory results could be obtained using the ELBOW290 element. The thinning effect of the elbow thickness was examined by applying five different uniform thickness values from 100% of nominal thickness down to 60% of nominal thickness. The average differences of the ELBOW290 models were as low as slightly above 1%. The maximum differences were between 4% and 6%. The conventional practice for elbow flexibility calculation is to calculate the flexibility factors by matching a Bernoulli beam model with a shell model, in which the average difference was often found to be 5%~6% and the maximum difference up to 10%~15%. Compared with the conventional approach, calculating tight radius elbow flexibility using the shell-type elbow element is more accurate for a variety of CANDU feeder bends. The efficiency is higher than using the typical shell elements: firstly, the computational cost of the shell-type elbow element is lower; secondly, the modeling effort is also lower since no three-dimensional pipe cross-sections need to be created. In summary, it is beneficial to calculate the flexibility for the feeder tight radius bends in CANDU reactors using the shell-type elbow element. Candu Energy Inc. is considering a compatible stress evaluation procedure to match the flexibility calculated by the shell-type elbow element. CANDU station insight into areas to be explored is welcomed.

5. References

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