Effects of Pipe-System Restraint on COD Calculations of Axial Loaded Pipes for LBB Applications – Finite Element Round Robin Results

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ABSTRACT

Typical LBB analyses require calculations of the crack-opening displacement (COD) for pipe under bending and axial tension loads. These models all assume that the pressure loads are essentially modeled as an end-capped pressure vessel. There are natural rotations that occur due to the presence of the crack that are restrained in a real pipe system by the presence of nozzles, elbows, pipe hangers, and other boundary conditions. Other axial tension loads also introduce the rotational effects on the crack-opening displacement that will be restrained by the pipe-system boundary conditions. Earlier sensitivity studies on this restraint of the pipe rotations showed that the crack-opening displacement could be significantly reduced by the pipe system boundary conditions. This effect could be highly detrimental to achieving LBB conditions.

This paper describes a round-robin effort conducted as part of the on-going Battelle Integrity of Nuclear Piping (BINP) Program to characterize the piping system restraint effects on the crack-opening displacement for different pipe diameters, crack lengths, pipe radius-to-thickness ratios, and distances from the crack plane to the restraining boundary location (both symmetric and non-symmetric restraint lengths). These efforts are leading to an analytical correction to the existing crack-opening displacement analyses for improved LBB analyses.

INTRODUCTION

Among the factors that are most critical to leak-before-break (LBB) of nuclear piping systems is an effect called *restraint of pressure induced bending on crack-opening displacement* [(1)]. The existence of a through-wall circumferential crack will result in a bending moment at the crack region for a pipe loaded axially, due to the eccentricity from the neutral axis in the cracked plane versus the center of the uncracked pipe. The presence of nozzles, elbows, pipe hangers, and other boundary conditions restrain this pressure-induced bending phenomenon. The restraining effect in general results in an increase in the load-carrying capacity of the cracked pipe, but, on the other hand, a decrease in the crack-opening displacement when compared with that of the same cracked pipe free from the restraints [(2)]. Hence, the beneficial load-carrying capacity increase has a corresponding decrease in the cracking-opening area for leak detection that is detrimental to LBB. The trade-offs between the two effects appeared to be case-dependent, and are influenced by the pipe diameter and crack length [(3)].

The common analysis practice for LBB is to determine the *center crack-opening displacement* (COD) by using the solution for an end-capped vessel. The so-called end-capped vessel models, although relatively simple to analyze, allow the ends of the vessel to freely rotate. Furthermore, it ignores the ovalization restraint at the crack plane from any boundary conditions. Therefore, the end-capped vessel model may over-estimate the COD more than if the pipe is not allowed to rotate in the real world piping systems. By overestimating the COD, the postulated crack size for a given leak rate is smaller than it might actually be.

In a real piping system, the ends of the pipe can be restrained from free rotation. The amount of the restraint will depend on the geometry of the pipe system. In general, the restraint of end rotation will be a function of:

- the magnitude of the load (elastic or plastic effects),
- the length of the crack (short cracks typically postulated for LBB in primary pipe loops are not affected, but long cracks for smaller-diameter pipe or steam lines may be effected), and
- the boundary conditions of the pipe on either side of the crack location.

In this program, six organizations from three countries participated a finite element (FE) round-robin analysis. The objective of this round-robin program was to compare and evaluate the results and modeling approaches from different participants. Each participant was further assigned to solve some additional problems. This resulted in a large matrix of FE results, which would lend themselves to a closed-form analytic expression that will be developed later in this on-going international nuclear pipe integrity program.

The program was coordinated by Engineering Mechanics Corporation of Columbus, as part of the Battelle Integrity of Nuclear Piping Program (BINP). The other five participating organizations were: Battelle Columbus, Central Research Institute of Electric Power Industry of Japan, Korea Electric Power Research Institute, Sung Kyun Kwan University of Korea, and the U.S. Nuclear Regulatory Commission.

PROBLEM STATEMENT

This set of round-robin problems was to perform linear-elastic finite element analysis to determine the center crack-opening displacement at the mid-thickness of a circumferentially through-wall cracked straight pipe restrained at both ends (Figure 1). The pipe was allowed to move vertically and horizontally in the crack plane (rotation in the crack plane and ovalization were not restricted), but it was pinned of any axial displacements in the ligament. An axial force was applied through the center of the pipe at the end of the pipe. The applied load values were arbitrarily chosen since the analysis is linear-elastic and the COD results were normalized with respect to the unrestrained COD values. There was no pressure on the crack faces, and no internal pressure present for all the analyses. The elastic modulus and the Poisson's ratio were assumed to be 200 GPA and 0.3, respectively.

The basic variables investigated in the program included the pipe outside diameter (*OD*), pipe mean radius to thickness ratio (R_m/t), crack length (θ), and the distance between the restraint planes to the crack plane (L_1, L_2). These variables are depicted in Figure 1.

A total of 144 cases were included in the analysis matrix of the program. The problem matrix covered a wide range of pipe diameters and R_m/t ratios. The effects of different restraint length on the two sides of a crack plane (the asymmetric restraint condition) were considered also. The analysis matrix included the cases that were analyzed before [(3)] to evaluate the validity of the prior calculations.

The specifics of each case in the analysis matrix are provided in Table 1 and Table 2. The analysis matrix was grouped into three major case groups, namely, Case 1, Case 2 and Case 3. Case 1 considered the symmetrically restrained pipe with a constant R_m/t ratio of 10, but varying pipe diameters. Case 2 was also the symmetric restraint case, but with a constant pipe outside diameter of 711.2 mm and varying R_m/t ratios. Case 3 covered the asymmetric restraint case, with a R_m/t ratio of 10 and varying pipe diameters.

The program was carried out into two phases. The first phase was the round-robin phase in which all participants were required to solve all the cases in Case 1. The modeling approach and COD results from each participant were compared. In the subsequent phase (Phase II), the participants were assigned to solve a different subset of cases in Case 2 and Case 3. This resulted in a COD database which would be used to develop a closed-form analytical expression in the future phases of the program. Table 3 summarizes the cases solved by each participant of the program.

It should be noted that, although the problem statement was very specific about other aspects of the problem, it deliberately avoided stipulating how the restraint conditions in a pipe system and the axial load should be applied in the finite element model. This modeling freedom reflects the complex nature of the restraint conditions in various piping systems. The round-robin participants would have to decide on how the restraint and loading conditions would be imposed in their finite element models according to their own interpretations of the piping system. Indeed, different participants imposed the boundary and loading conditions differently, which was one of the causes for the observed discrepancies of the COD results in the round-robin cases.

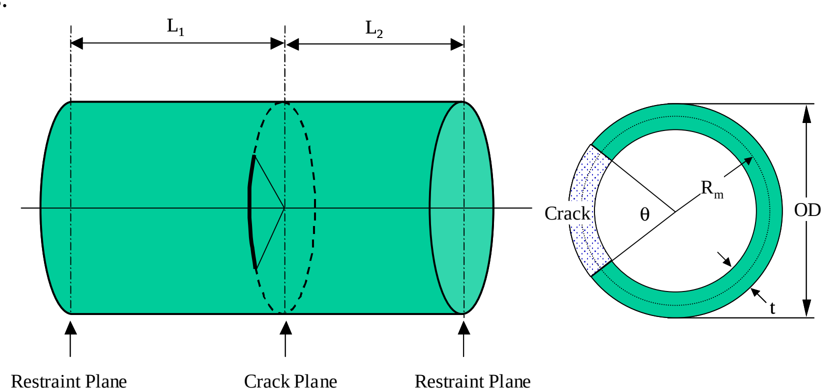

Figure 1 Cracked-pipe geometry

Table 1 Symmetric restraint cases

	OD (mm)	R_m/t	Axial Force (kN)	Total Crack Length (radians)			Restraint Length (L/OD)			
Case 1a	711.2	10	50,000	π/8	π/4	π/2	1	5	10	20
Case 1b	323.85	10	5,000	π/8	π/4	π/2	1	5	10	20
Case 1c	114.3	10	500	π/8	π/4	π/2	1	5	10	20
Case 2a	711.2	5	50,000	π/8	π/4	π/2	1	5	10	20
Case 2b	711.2	20	50,000	π/8	π/4	π/2	1	5	10	20
Case 2c	711.2	40	50,000	π/8	π/4	π/2	1	5	10	20

Table 2 Asymmetric restraint cases

	OD (mm)	R_m/t	Axial Force (kN)	Total Crack Length (radians)			Restraint Length (L_1/OD)			L_2/OD
							5	**10**	**20**	
Case 3a	711.2	10	50,000	π/8	π/4	π/2	X	X	X	1
	711.2	10	50,000	π/8	π/4	π/2		X	X	5
	711.2	10	50,000	π/8	π/4	π/2			X	10
Case 3b	323.85	10	5,000	π/8	π/4	π/2	X	X	X	1
	323.85	10	5,000	π/8	π/4	π/2		X	X	5
	323.85	10	5,000	π/8	π/4	π/2			X	10
Case 3c	114.3	10	500	π/8	π/4	π/2	X	X	X	1
	114.3	10	500	π/8	π/4	π/2		X	X	5
	114.3	10	500	π/8	π/4	π/2			X	10

Table 3 Problems analyzed by the participants

	Participant A	Participant B	Participant C	Participant D	Participant E	Participant F
Case 1a	X	Partial	X	X	X	X
Case 1b	X	X	X	X	X	X
Case 1c	X		X	X	X	X
Case 2a						X
Case 2b					X	
Case 2c			X	X		
Case 3a						X
Case 3b		X			X	
Case 3c			X	X		

MODELING APPROACHES

Table 4 summarizes the major features of the FE modeling approaches used by the round-robin participants. There are some marked differences in the modeling approaches among the participants. Except for Participant D, all other participants used 20-noded second-order solid-brick elements. Most participants used the focused mesh around the crack tip that is typical for fracture mechanics analysis. The number of element layers through the pipe wall thickness was divided: four participants used 1 layer of elements whereas the other 2 participants used 2 layers. Moreover, different approaches were employed to deal with the restraint length and the application of the axial load, reflecting the differences in participants' interpretation of the restraint condition in the actual pipe systems.

RESULTS AND DISCUSSIONS

Comparison of Round-Robin (Case 1) Results

The problem statement did not specify the pipe length for COD calculation of the unrestraint pipe (i.e., the end-capped vessel). Theoretically, it should be infinitely long. Both Participants C and F investigated the effect of the pipe length on COD of the unrestraint pipe. It was found that a pipe length greater than $40R_m$, as used by all the participants, was sufficiently long for the COD calculations of the unrestraint pipe.

Figure 2 compares the COD values of the unrestraint pipes (the end-capped vessel case) obtained by all participants for the round-robin cases ($R_m/t = 10$). The COD values are normalized by the mean COD value of all participants of the same case. Overall, the results from Participant C, E, and F are consistent among each other. The discrepancies are within 1% from the mean COD value averaged among these three participants. For the two shorter crack lengths ($\theta=\pi/8$, and $\theta=\pi/4$), the COD values from Participant A are close to the average. However, the CODs of the longest crack length ($\theta=\pi/2$) are only 80% of the averaged values. Participant B also did reasonably well, expect only for a particular case (Case 1a, $\theta=\pi/8$) where the COD is about 120% of mean value. The biggest discrepancies are from Participant D for the two long crack cases ($\theta=\pi/4$ and $\theta=\pi/2$). Its COD values are over 20% higher than the mean values.

Table 4 Summary of model features

	Participant A	Participant B	Participant C	Participant D	Participant E	Participant F
Pipe length	Restraint length	$60R_m$, $100R_m$ (*)	Restraint length	20xOD, 30xOD (*)	Restraint length	Restraint length
Simulation of restraint	At pipe end	On restraint length	At pipe end	On restraint length	At pipe end	At pipe end
Application of axial load	Concentrated force at the TIE node	Uniform stress at restraint plane	Concentrated force at the TIE element	Uniform stress at restraint plane	Uniform displacement at pipe end	Concentrated force at the tying node
Element type	3D 20-node brick	3D 20-node brick	3D 20-node brick, reduced integration	3D 8-node brick, reduced integration	3D 20-node brick	3D 20-node brick
Layers of element through wall thickness	1	2	1	1	2	1
Mesh refinement	Refined regular mesh	Focused mesh at crack tip	Focused mesh at crack tip	Regular mesh	Focused mesh at crack tip	Focused mesh at crack tip
FEM code	ABAQUS	ABAQUS	ABAQUS	ABAQUS	ABAQUS	MARC

(*) for symmetric and asymmetric restraint, respectively.

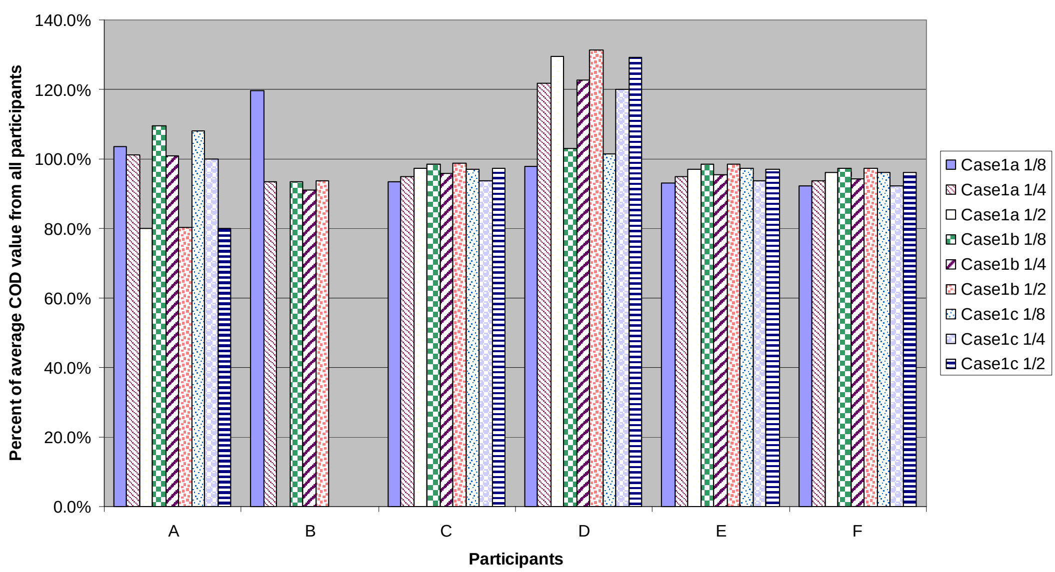

Figure 2 Comparison of the unstrained COD values for Cases 1a-1c. The COD values are normalized with respect to the averaged COD value of all participants

Despite the fact that the COD values for a specific case could be different among different participants, all participants reported that the pipe diameter has no noticeable effects on the **normalized** COD values for all the cases in Case 1. The normalized COD only depends on the crack length, R_m/t ratio, and the restraint length. This is illustrated in Figure 3.

The independence of COD on pipe diameter simplifies the comparison of the round-robin results (Case 1) – it is unnecessary to distinguish the results from different diameter pipes.

Figure 4 compares the normalized CODs for the crack length of π/4. Comparisons for the other two crack lengths were similar. Overall, all participants reported the same trends on the effects of the restraint length and crack length on the normalized COD. The results from Participant C and F are always consistent for all the cases in the round-robin. The normalized COD calculated by Participant D were consistently lower than these by the other five participants. This might be attributed to the use of the one-layer, first-order elements and the non-focused mesh around the crack tip by Participant D. Also troublesome was the use of uniformed stress to apply the axial load by Participant D. For this reason, the results from Participant D were excluded from further round-robin comparisons.

Excluding the results from Participant D, the results from all other five round-robin participants are plotted in Figure 5, for all the round-robin cases. The results are quite consistent for the two short lengths (θ=π/8, and θ=π/4), with the exception of one data point from Participant B at (L/D=1 and θ=π/4). On the other hand, there is noticeable scatter for the pipe of the longest crack length (θ=π/2). Table 5 provides general comments on the round-robin results among all participants.

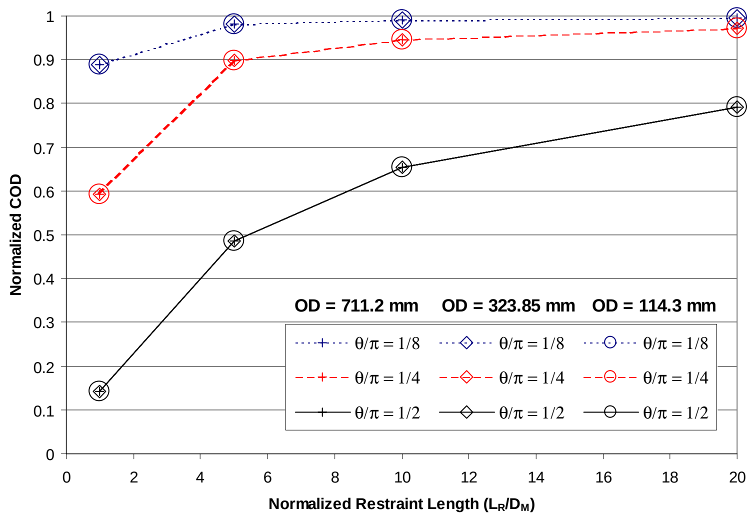

Figure 3 Normalized COD values for Case 1a-1c

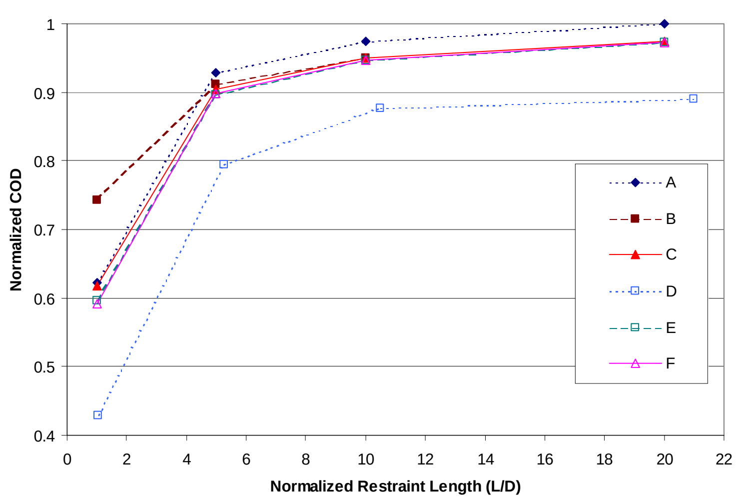

Figure 4 Comparison of normalized COD in Case 1, crack length = π/4

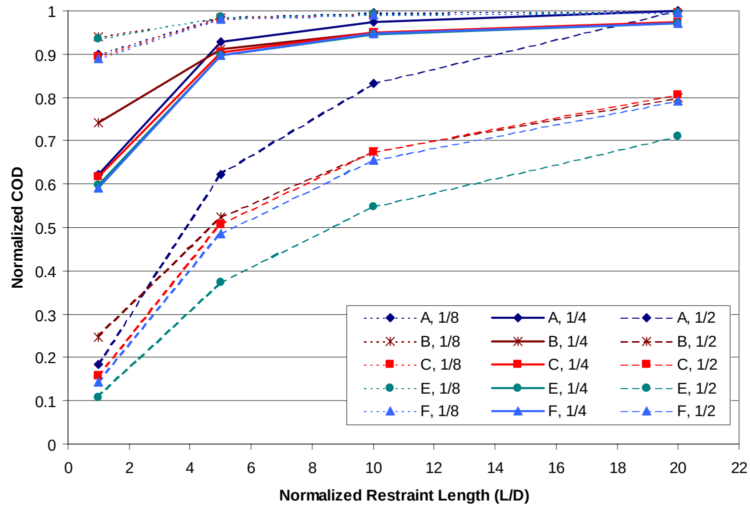

Figure 5 Comparison of normalized COD for all round-robin cases in Case 1, excluding Participant D

Table 5 Observations on the round-robin case comparisons

Participant	Comparison to Average from Group
A	Agrees with C, F for θ=π/8 and π/4 but higher for θ=π/2
B	Agrees with C, F except for shortest restraint length
C. F	Agree with each other all the time and in the middle of entire group results
D	Generally lower than others
E	Agrees with C, F for θ=π/8 and π/4 but lower for θ=π/2

Effect of R_m/t Ratio (Case 2)

The effects of R_m/t ratio on the normalized COD are analyzed by comparing the results in Case 1 and Case 2. The normalized COD increases as R_m/t ratio decreases, as illustrated in Figure 6. This trend was observed by all participants.

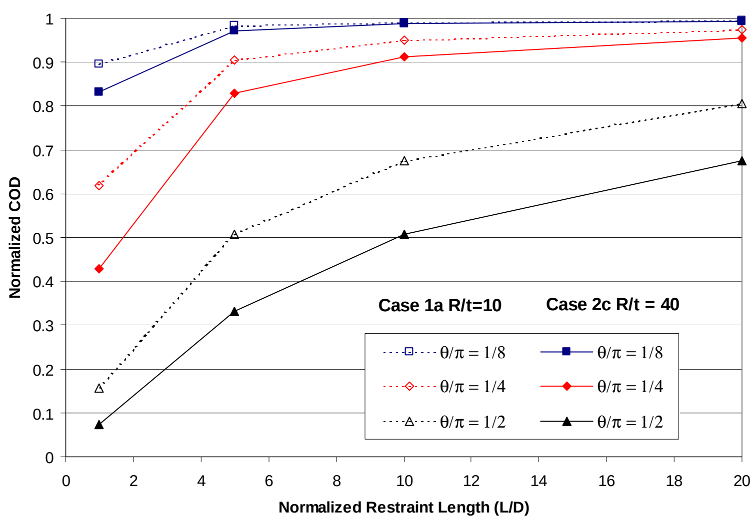

Figure 6 Effect of R_m/t ratio on normalized COD. OD=711.2mm

Effect of Asymmetric Restraint Length (Case 3)

Similar to Case 2, each participant was assigned to solve a subset of Case 3. The effects of non-symmetric restraint are depicted in Figure 7 to Figure 9, using a subset of the results. Similar to the effect of reducing the symmetric restraint length from both sides of the crack plane, the normalized COD value decreases as the restraint length from one side of the crack plane is shortened. The effect of the asymmetric restraint length is more pronounced as the asymmetry in the restraint length increases. However, significant reduction from the normalized COD of symmetrically restrained pipes only exists when the crack length is longest ($\theta=\pi/2$), or the restraint length on one side of the crack plane is very short ($L_2/D=1$).

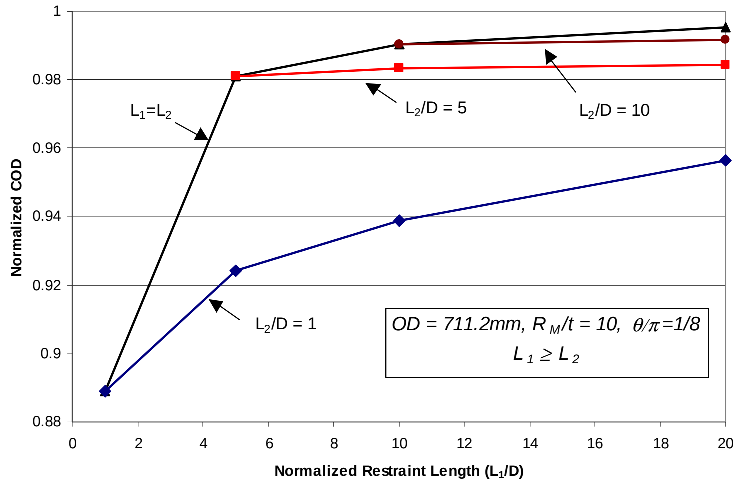

Figure 7 Normalized COD under asymmetric restraint length from Participant F

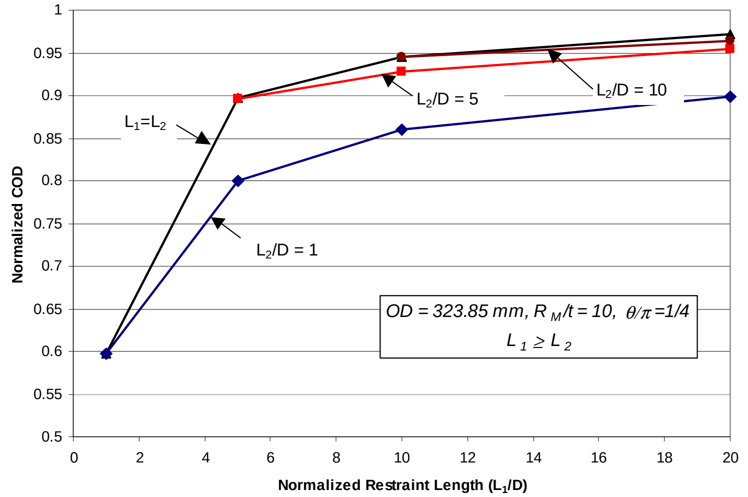

Figure 8 Normalized COD under asymmetric restraint length from Participant E

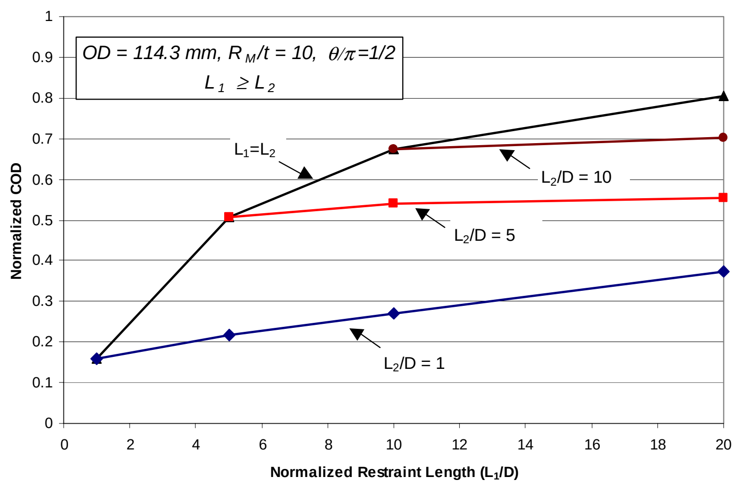

Figure 9 Normalized COD under asymmetric restraint length from Participant C

The trends due to the crack length changes from θ=π/8 to π/4 to π/2 does not appear to be as smooth as desired. This may be due to differences between the different participants. In the round-robin case (Case 1), participants C and F agreed all the time, but there was a slight differences with Participant E. Further evaluations appear to be needed for this consideration.

CONCLUDING REMARKS

Six organizations from three countries participated in this program to investigate the effect of pipe-system restraint on the linear elastic COD in axially loaded pipe systems. The effects of the pipe=system boundary conditions on the COD were normalized by the COD from the pressure vessel analysis equations that are used in virtually all LBB analyses. The results from the round-robin cases revealed that:

- With the exception of Participant D, the normalized COD values obtained by other five participants are generally consistent with each other, unless the crack becomes very large (θ=π/2).
- The pipe diameter correctly normalized the COD results for the restraint length with constant R_m/t ratio.
- As the R_m/t ratio increases, the restraint effect increases, resulting in lower normalized COD.
- As the difference in the restraint lengths from the two sides of the crack increases, the asymmetric restraint effect on the normalized COD increases. The effect become significant once one of the restraint lengths is reduced to L/D=1, or the crack length is longest (θ=π/2). The results to date need to be interrogated further to establish a smooth analytic relationship.

Future efforts will involve establishing an analytical relationship and validating the asymmetric case with a pipe system geometry.

ACKNOWLEDGEMENT

This work was performed for the Battelle Integrity of Nuclear Piping Program (BINP) being managed by Mr. P. Scott at Battelle. Members of the BINP program are the U.S. NRC (Drs. Nilesh Chokshi and Tsun-Yung Chang have been the NRC-RES representatives), CRIEPI in Japan for various Japanese utilities (Mr. N. Miura is the representative), and KINS/KOPEC/KEPRI in Korea (Young-Hwan Choi is the representative). We thank Battelle and the BINP members for their support of this effort as well as their participation in the round-robin analyses.

DISCLAIMER

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