Evaluation of Flawed Piping under Dynamic Loading

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ABSTRACT

This paper describes analytical studies of one of the large-scale flawed pipe experiments conducted for the International Piping Integrity Research Group (IPIRG). Dynamic excitation of increasing amplitude leads to failure at a large manufactured flaw. Here, elastic analysis is shown to describe the system behavior reasonably well, if an appropriate value of damping is selected. A simplified 2-dimensional model displays sensitivity to damping. Discussion includes comparisons to some ASME Code limits.

1 INTRODUCTION

Experiments and analysis have shown that the margin against failure for undegraded piping and piping system components subjected to severe static and dynamic loading is very large (Tagart et.al. 1990), well in excess of that inherent in the design as a result of ASME Code, Section III, Class 1 piping design-by-analysis requirements (ASME 1989). These experiments also have demonstrated that the governing failure mode for reversed dynamic loading is not ductile rupture or plastic collapse of the piping cross section, but is instead low-cycle fatigue and progressive deformation of the pipe wall. These findings have led to the issuance of ASME Nuclear Code Cases (ASME 1987 and 1988) for the reclassification of bending stresses caused by low- or mid-frequency dynamic loads.

Dynamic tests of degraded piping were conducted for IPIRG by Battelle Columbus Operations as described elsewhere in this session. EPRI, as a participant in IPIRG, pursued a program of analytical evaluation using in-depth simulation of experiment IPIRG 1.3-4 as the basis. The degraded section for this experiment was a submerged-arc weld (SAW) in ASTM A106 Gr. B ferritic steel with a large circumferential part-through flaw. The results of elastic calculations and their comparison to test measurements are presented. The predicted response was found to depend on the value of assumed damping, with some displacements extremely sensitive in the range between low damping (0.5% of

SMiRT 11 Transactions Vol. G (August 1991) Tokyo, Japan, © 1991

critical damping) and relatively high damping (5% of critical damping). In order to further study the effect of damping found in the ABAQUS calculations, a two-degree-of-freedom (2 DOF) model of the IPIRG 1.3 piping system was developed. Damping of about 5 percent of critical damping results in a reasonably good match of the experimental data.

Such a large damping value for the IPIRG 1.3 support conditions can only be interpreted as a result of plastic deformation at highly-stressed locations in the piping system, such as at the degraded cross section itself or at the long-radius elbows. Damping caused by piping supports and constraints alone can range between 0.5 to 10%, depending on support types and numbers. Damping in the undegraded low-friction IPIRG 1.3 system with small motion was reported by Battelle to be only 0.5 percent. Therefore, reliable predictions of system dynamic response based on elastic models cannot be expected unless system damping under severe loading conditions can be determined with some certainty. Without such determination, the calculation of elastic-plastic fracture mechanics parameters and the assessment of flaw stability is problematical.

2 IPIRG 1.3 SYSTEM AND MODEL

The piping system (Fig. 1) consisted of an expansion loop with a hydraulic actuator on one side, a degraded section on the other side, and a mock valve in the middle of the loop cross leg represented by a block mass. The east-west displacement (Fig. 2) was represented by a monotonically increasing sinusoidal function.

$$u_x = St + A\ [1-\exp\ (-bt)]\ \sin\ (\omega t)$$

where the constant S is 9.53 mm/sec., A is 152 mm, b is 0.0404 sec.$^{-1}$ and ω is 24.8 radians/sec. The system was pressurized to 15.5 MPa and heated to 288°C (Quiñones, Nickell and Norris, 1990).

The general-purpose finite-element code ABAQUS Version 4-7-22 (Hibbitt, et. al., 1991) was used to calculate the dynamic response (Quiñones, Nickell and Norris, 1990).

3 ELASTIC ANALYSIS

Only the damped elastic response in an undegraded dynamic system was modeled. The elastic bending plus axial stresses at the degraded section are compared to similar load-cell-determined experimental stresses and also compared to stresses from ASME Code Section III Equation 9 (NB-3652).

An initial static step with pressure and thermal loads was excluded since Equation 9 adds pressure effects separately and since thermal stress is treated as secondary stress.

Damping studies on a simplified 2 DOF conceptual model suggested that damping values in the range of five to six percent are appropriate for the high-level response portion of IPIRG 1.3-4. Based on this information, Raleigh damping calculations, 0.5 and 5 percent, were performed. The five percent damping value corresponds to the Code Case N-411 value for Class 1 piping and also corresponds to the 2 DOF model damping value.

The dynamic displacement range at Elbow 3 is compared to ABAQUS results in Fig. 3. The displacement range is measured from adjacent peaks and troughs. For times less than two seconds, the 0.5 and 5 percent damping cases reproduce the experimental displacements to within 10 percent, but, as the actuator displacement becomes larger, the five percent damping case compares better with IPIRG 1.3-4 data. Note that the five percent case was run half as long as the 0.5 percent damping case. The damping has a stronger effect on the Elbow 3 north-south y displacement than on the east-west x displacement, because the latter is controlled by the actuator. The time of through-wall penetration is indicated by the arrow in Fig. 3.

Moments and stresses at the degraded section are of interest for fracture mechanics stability predictions. Peak dynamic moments at the degraded section for ABAQUS are compared to experimental data in Fig. 4. Again, the 0.5 percent damping case compared better with experimental data prior to two seconds, but, the 5 percent damping case compares better after 2 seconds.

Finally, the peak Equation 9 stress at the location of the degraded section was calculated from the ABAQUS moments for both damping cases (Fig. 5). Note that IWB 3610(d) of ASME XI requires that shakedown conditions be satisfied for the degraded section, which means that the "flawed" Equation 9 stress in Fig. 5 is limited to 2 Sy.

4 DAMPING EFFECTS

The ABAQUS model of IPIRG 1-3.4 produced results showing that at least a portion of the piping system dynamic response is extremely sensitive to the assumed value of the damping, as a percentage of critical damping. In particular, the north-south (y direction) motion of Elbows 3 and 4, and the associated cantilever portion of the pipe run between Elbows 4 and 5, are strongly affected. In order to study the issue of damping effects more closely, a simple 2 DOF model was developed to represent the essential behavior of the IPIRG 1-3.4 piping system.

The dominance of two degrees of freedom in the dynamic response of the IPIRG 1-3.4 piping system was observed previously (Quiñones, Nickell and Norris, 1990). The behavior was described as that of a portal frame connected to a long cantilever. As a result, the two degrees of freedom were taken to be: (1) the east-west sidesway (x direction) motion of the portal frame represented by the expansion loop between Elbows 1 and 4; and (2) the north-south cantilever motion of the horizontal pipe run between Elbows 4 and 5. This 2 DOF conceptual model is shown in Fig. 6.

The model is simplified by using two lumped masses to represent the effective mass of the expansion loop in the portal frame sidesway vibration mode, and the effective mass of the expansion loop plus the long horizontal pipe run in the cantilever beam vibration mode. The coupling between the two degrees of freedom is then restricted to the stiffness coupling through the deformation of Elbows 3 and 4, and by the pipe run connecting these two elbows.

In order to determine the masses and stiffnesses for this simple model, the static east-west deflection of the actuator driving the piping system under a known force was used.

Member masses and stiffnesses are selected to satisfy one additional condition - that the two undamped natural frequencies of vibration of the 2 DOF system should approximate the first two vibrational frequencies calculated for the more complex ABAQUS model - 3.34 Hz and 5.67 Hz. These frequencies were found to be

$$f_1 = 2.92 \text{ Hz}, \ f_2 = 5.56 \text{ Hz}$$

By adjusting model stiffnesses slightly, the 2 DOF model first two frequencies are

$$f_1 = 3.29 \text{ Hz}, \ f_2 = 5.85 \text{ Hz}$$

The agreement with ABAQUS results is adequate. Using the damped equation of motion, the actuator displacement function, the Newmark integration operator, and a 10 ms integration time step, the solution for the time of interest has been obtained.

It should be noted that the east-west actuator displacement has been equated to the portal frame sidesway displacement in this 2 DOF model. While the sidesway of the expansion loop is in global coincidence with the prescribed actuator displacement, the actuator driving frequency (3.95 Hz) is greater than the first fundamental frequency of the system (about 3.3 Hz). Therefore, expansion loop sidesway will be out of phase with actuator displacement much of the time.

The simple 2 DOF model results with 2% of critical damping are compared to ABAQUS calculations. The north-south displacement at Elbow 3 is shown in Fig. 7. A similar displacement plot for 10% damping is shown in Fig. 8.

With these comparisons in hand, the 2 DOF model was rerun with ζ = 5%, 6%, 7%, 8%, and 9% damping. The correlation with IPIRG 1.3-4 results was best at ζ = 5 to 6% as shown in Table 1. At 5 percent damping(t = 6 sec.), the maximum negative displacement predicted by the model was -145 mm, while the experimental result was -148 mm. The maximum positive displacement predicted was 87.4 mm while the experimental result was 73.0 mm.

At times of three and six seconds, the 2 DOF model north-south displacement range near Elbow 4 matches the experimental displacement range best when the damping is about 5.5%. However, at times less than one second, when the piping actuator displacement range is less than 25.4 mm, the damping is about 0.5% (an order of magnitude smaller). For comparison purposes, the ABAQUS results for 0.5 and 5% damping are also included in Table 1. At three seconds the Elbow 4 north-south displacement range matches the experimental value (within four percent) for 5% damping.

5 CONCLUSIONS

From these calculations and comparisons, we draw two conclusions. First, the damping for such increasing-amplitude dynamic loading events is apt to vary during the event itself, with lower values at early response times and higher values at later response times. Depending upon the particular time of interest, a different damping value would have to be assumed in order to calculate accurate stresses and deformation of damping-sensitive components.

Second, without experimental results with which to compare, a priori damping assumptions are apt to lead to inaccurate and misleading dynamic response calculations. However, damping values of 5 to 6% give reasonable results over a wide range of strong motion dynamic response for the IPIRG 1.3 system.

It is worth noting that Table N-1230.1 of the non-mandatory Appendix N (Dynamic Analysis Methods) of the ASME Code, Section III recommends 2% damping for Operating-Basis Earthquake (OBE) loads and 3% damping for Safe Shutdown Earthquake (SSE) loads. These values include both material and structural damping for large-diameter (> 305 mm diameter) piping. The small-diameter piping values of 1% and 2%, respectively, are to be used for large-diameter-piping systems with only one or two spans. For the relatively simple IPIRG 1.3 piping system, the 1% value is probably reasonable for low-amplitude motion (OBE), but the SSE damping values are far too low to lead to accurate elastic response calculations.

The response at a time of three seconds is typical of that which would be experienced for an SSE event, and 5% damping is the appropriate value to be used for reasonable IPIRG 1.3-4 response calculations.

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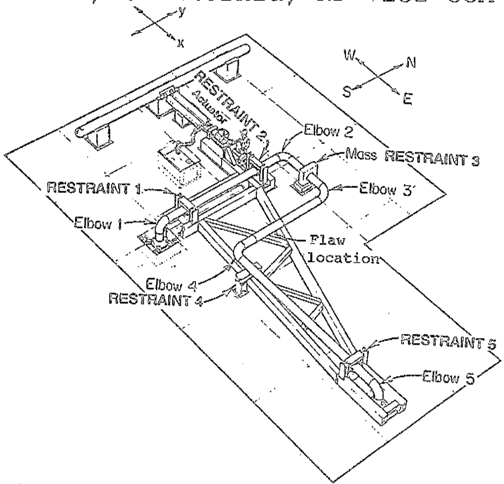

Fig. 1 IPIRG 1.3 System

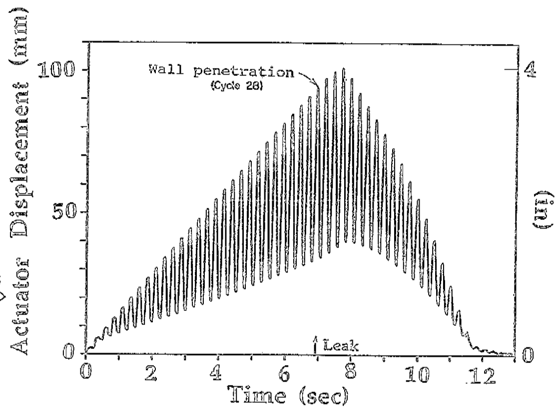

Fig. 2 Actuator displacement

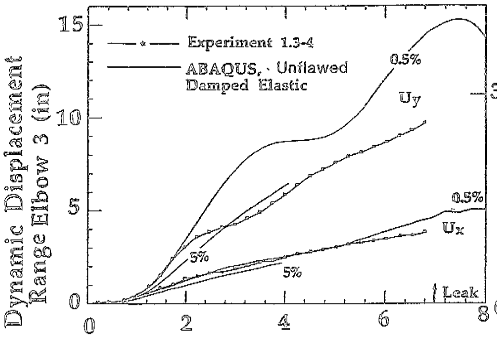

Fig. 3 Displacement range history

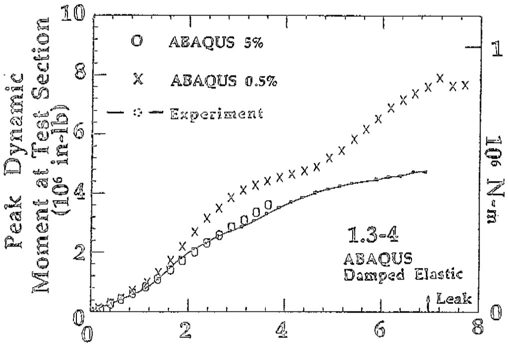

Fig. 4 Moment history

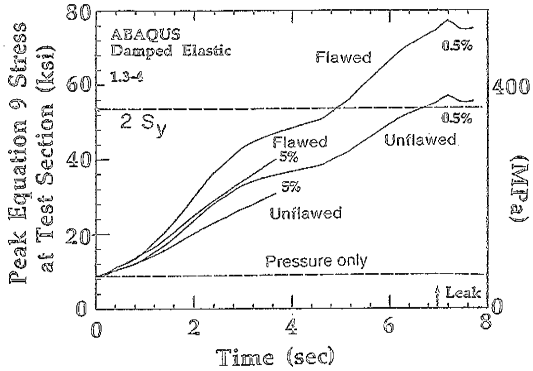

Fig. 5 Equation 9 stress history

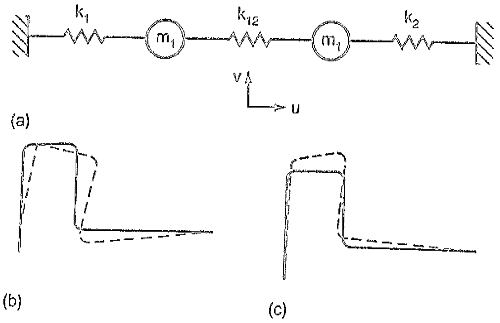

Fig. 6 2 DOF conceptual model

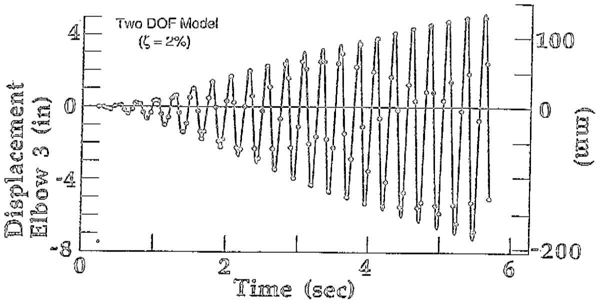

Fig. 7 Elbow 3 displacement, 2%

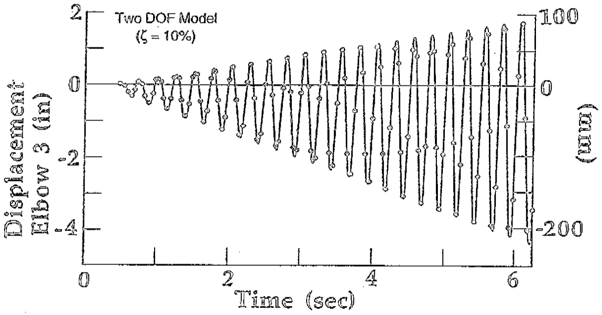

Fig. 8 Elbow 3 displacement, 10%

Table 1. Comparison of 2-DOF damping model and IPIRG 1.3-4 elbow u_y displacements.

Damping %	Displacement range $\|u_y \text{ max.} - u_y \text{ min.}\|$ (mm)	
1	——	
2	175	
3	——	t=3 sec.
4	——	
5	117	
6	105	
7	95.0	
8	86.4	
9	79.2	
10	73.4	
IPIRG1.3-4	114	
0.5 (ABAQUS)	185	
5 (ABAQUS)	109	
1	——	
2	325	t=6 sec.
3	——	
4	——	
5	233	
6	213	
7	193	
8	176	
9	161	
10	148	
IPIRG 1.3-4	221	
0.5 (ABAQUS)	312	