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Lessons learned about seismic time-histories on pipe fracture

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ABSTRACT

One of the primary objectives of the International Piping Integrity Research Group (IPIRG) programs[1, 2], was to assess pipe fracture behavior under seismic loading for LBB and in-service flaw evaluation criteria. An aspect of interest in these programs was possible differences in material response that may occur during a seismic event, when compared to the fracture behavior under simpler loading conditions. This paper, in comparing the fracture behavior of surface cracks under single-frequency dynamic loading and simulated-seismic loading, presents some interesting observations about how the specific features of a seismic event can affect the apparent fracture resistance of a cracked pipe system.

INTRODUCTION

In the IPIRG-1 program[1], pipe-system experiments were conducted with single-frequency increasing amplitude excitation. This excitation was at about 90 percent of the first natural frequency of the pipe system. In the IPIRG-2 program[2], a seismic time history was used. At the early stages of designing the seismic load history, it was suggested that any time history with a frequency content from 2 to 8 Hz might be sufficient. A more rigorous procedure was eventually followed that was reviewed by numerous experts in the field and was judged to be technically reasonable.

The experimental pipe fracture results with the two dynamic loadings showed that the apparent fracture resistance of a cracked pipe is very much a function of the specific seismic load history. Time histories, in spite of being equal in terms of g level, frequency content, energy content at a frequency band, duration, etc., can be more or less damaging to a crack, depending on the specific ordering of load cycles.

THE IPIRG PIPE-SYSTEM TEST FACILITY

The effects of dynamic and seismic loading under combined inertial- and displacement-controlled stresses at circumferential piping cracks was experimentally studied in the IPIRG pipe loop experimental facility[3, 4]. The IPIRG pipe loop is constructed in the shape of an expansion loop with five long-radius elbows and approximately 30 meters (100 feet) of 406-mm (16-inch) nominal diameter pipe. Figure 1 is an artist's conception of the overall facility while Figure 2 shows the overall dimensions. For the most part, the straight pipe used in the construction of the pipe loop is Schedule 100 pipe. Elbows 1, 2, 3, and 5 are also Schedule 100. The straight pipe in the loop is fabricated from ASTM A710, Grade A, Class 3 pipe steel and Elbows 1, 2, 3, and 5 are WPHY-65 material. Elbow 4, for the experiments of interest in this paper, was also made of WPHY-65 but was Schedule 160. The materials (A710, Grade A, Class 3 and WPHY-65) were chosen for their strength and weldability.

The IPIRG pipe loop incorporated features such as hydrostatic bearings and spherical bearings to make boundary conditions very simple for finite element analyses. Doing this, attention could be focussed on the behavior of the crack in the test specimen, rather than on any accompanying stress analysis. Loading was applied as a displacement time history at one point in the pipe loop (the actuator in Figure 1). Cracks, for the cases of interest in this paper, were located just north of Elbow 4 in short welded-in straight pipe sections.

SINGLE-FREQUENCY FORCING FUNCTION

The objective of the single-frequency pipe-system experiments conducted in IPIRG-1 was to develop data to assess the margin of safety in fracture analysis predictions for circumferential cracks in a representative piping configuration under combined inertial- and displacement-controlled loading. The principal interest was to establish whether or not combined loading behavior was substantially different from monotonic quasi-static loading.

The displacement forcing function time history used in the single-frequency pipe-system experiments was an increasing amplitude sinusoidal function with a superimposed ramp:

$$U(t) = St + A\left(1 - e^{-bt}\right)\sin\omega t \tag{1}$$

where the frequency ω was chosen to be 90-95 percent of the first natural frequency of the pipe loop in order to get dynamic amplification. Constants S, A, and b were selected so that the hydraulic accumulators had adequate reserve capacity at the end of a test and the predicted maximum moment would occur after about 10 cycles of loading with roughly equal inertial- and displacement-controlled stresses at the crack. Figure 3 shows a typical IPIRG-1 single-frequency forcing function which includes a soft shut-down after surface crack penetration.

SIMULATED-SEISMIC FORCING FUNCTION

The global objective of the simulated-seismic experiments conducted in IPIRG-2 was to determine what effect, if any, variable amplitude, multi-frequency loading had on cracked pipe in a pipe system. The principal parameters of interest were maximum moment and propensity for a double-ended guillotine break (DEGB) after maximum moment was achieved.

The ideas governing the design of the seismic forcing function were embodied in three premises:

1. The objective of the design process was merely to define an actuator displacement time-history, and not to necessarily explore the full probabilistic nature of true seismic events.
2. Accepted seismic design procedures were to be used.
3. The criteria for selecting a particular forcing function were principally based on the engineering requirements for the test system, i.e., servo-hydraulic constraints.

This design approach provided a framework for selecting possible technical approaches, limiting the scope of the design effort, and a rationale for assessing the merits of competing design alternatives.

The specific steps taken to implement the design approach were as follows:

1. The U.S. NRC Regulatory Guide 1.60 ground acceleration response spectrum provided the basic description of the seismic input.
2. An artificial time-history of ground acceleration was generated that is spectrum-consistent with Step 1 using the SIMQKE computer program. The artificial time-history was forced to be consistent with U.S. NRC Standard Review Plan 3.7.1 prescriptions for duration, frequency spacing, power spectral density (PSD), and spectra enveloping.
3. A simple, 9 degree-of-freedom model of a pressurized water reactor (PWR) plant was used as a transfer function between the time-history ground acceleration and an assumed location for the pipe system.
4. The relative motion between two "floors" in the PWR model represented the displacements to be applied to the pipe system.
5. The time-history of actuator motion for the IPIRG pipe loop was selected by finding a single-point excitation displacement time history that would give the same moment-time response at the crack location as the multi-point excitation defined in Step 4.
6. Scaling of the input ground acceleration was fixed by a desire to have the surface crack penetration be due to ductile tearing, to not have numerous loading blocks where low-cycle fatigue complicates the analysis, and a need to maintain an adequate margin on servo-hydraulic capacities.
7. A finite element model of the pipe system, including a nonlinear representation of the cracks, was used to predict the response of the pipe system to the simulated-seismic loading. The predicted response was the basis for Step 6.

Following these basic steps, a reasonably realistic seismic forcing function was developed. The forcing function included all of the essential elements of a true seismic event at a plant in a relatively simple fashion. Additional details related to the design of the IPIRG-2 simulated-seismic forcing function can be found elsewhere[5].

Each of the simulated-seismic experiments was conducted in two phases. For the first phase, the crack was loaded with a relatively low-level excitation representative of a safe shutdown earthquake (SSE). The amplitude of the SSE excitation was fixed using actual U.S. nuclear plant design stress values. It was expected that the SSE level of excitation would not cause the crack to extend and post-test examination of the data indicated that such was the case.

The second loading phase for the simulated-seismic pipe-system experiments involved application of a scaled-up amplitude version of the basic SSE excitation. To define the load level for this "Test" forcing function, nonlinear spring, cracked-pipe finite element analyses were used. In these analyses, the cracked section was modeled as a nonlinear moment-rotation spring[6, 7]. The amplitude of the forcing function was scaled to achieve predicted surface-crack penetration some time during the 20-second load history. The "Test" level excitation required to achieve surface-crack penetration for the carbon steel and stainless steel base metal experiments was 1.25 g for the free field acceleration.

Figure 4 shows the actuator displacement-time history for the "Test" level excitation. The seismic forcing function lasted 20 seconds: 5 seconds of build up, 10 seconds of stationary signal, and 5 seconds of decay. Compared to the IPIRG-1 single-frequency forcing functions, the seismic functions are rich in frequency content and they show significant negative displacement excursions.

Figure 5 shows the peak-broadened response spectra for the simulated-seismic load history. The damping values shown in this figure are representative of values for floor response spectra for nuclear power plants and are not equivalent to the damping associated with the IPIRG pipe loop. From Figure 5, it can be seen that the simulated-seismic load history contains frequencies up to 40 Hz, with most of the large amplitude motions occurring in the 1 to 10 Hz range. Comparing these data with floor response spectra from actual plants, the IPIRG spectra are quite similar to actual plants.

Although the seismic forcing function and the design of the pipe loop are rooted in plant practice, it is reasonable to question how representative the resulting stresses actually are. In order to make that assessment, Battelle obtained elastically-calculated stress data from actual plant piping system stress analyses and compared those data with the elastically-calculated crack section stresses for the IPIRG-2 pipe system. For this comparison, the actuator displacement-time history from the stainless steel base metal simulated-seismic pipe-system experiment was used as input. Battelle obtained the actual plant piping system stress data from two sources. One source of data was a presentation made by Mr. Nate Cofie of Structural Integrity Associates, Inc. to the ASME Section XI Working Group on Pipe Flaw Evaluation in January 1994. As part of that presentation, elastically-calculated stresses for locations corresponding to a number of welds in a number of piping systems were presented for four different plants. The welds chosen for comparison were from 12-inch nominal diameter pipe, because the pipe diameter was close to the

16-inch nominal diameter pipe in the IPIRG loop. The piping system stresses were broken down into four basic stress components: pressure, deadweight, thermal, and seismic due to the operational basis earthquake (OBE). In discussions between Battelle and Mr. Cofie, it was determined that he assumed that the stresses due to a safe shutdown earthquake (SSE) would be twice those due to an operational basis earthquake. As a result, the seismic stresses he presented were adjusted accordingly in order to allow for an equal comparison between his stresses and those calculated for the IPIRG pipe system subjected to a simulated SSE load history. Additional stress data were obtained from Mr. Steve Gosselin, the IPIRG Technical Advisory Group representative from EPRI. Mr. Gosselin presented some data he had obtained from Mr. Seth Swamy and Mr. Dulal Bhowmick of Westinghouse. Westinghouse presented elastically calculated normal operating (deadweight, thermal expansion, and pressure induced stresses) plus the safe shutdown earthquake (SSE) stresses for the weld connecting the hot leg to the nozzle on the reactor pressure vessel for two different plants.

Figure 6 shows a comparison of elastically-calculated stresses for actual plant piping systems and elastically-calculated stresses for the IPIRG pipe system using the actuator displacement-time history from the stainless steel base metal simulated-seismic experiment as input. The IPIRG pipe-system stresses are presented for both the "SSE" and "Test" forcing functions. As can be seen in Figure 6, the stresses due to the "SSE" excitation agree very well with the calculated stresses from the actual plant piping systems. As should be expected, the calculated stresses due to the "Test" forcing function are quite a bit higher than the calculated stresses from actual plant piping systems.

PIPE-SYSTEM TEST RESULTS

Cracked pipe-system experiments were conducted in the IPIRG pipe loop on nominal 406 mm (16-inch) diameter Schedule 100 TP304 stainless steel base metal specimens with nominally identical 180-degree 66-percent deep internal surface cracks using single-frequency loading and simulated-seismic loading. Figures 7 and 8 show the moment versus crack-mouth-opening displacement behavior for the two loadings.

Looking at Figure 7, it is clear that the each succeeding load cycle caused an increasing amount of plasticity in the single-frequency loading. On the other hand, for seismic loading, Figure 8, there were a number of elastic cycles at the beginning of the loading followed by one very large plastic cycle. In effect, this makes the seismic loading appear to the crack as a monotonic loading, i.e., there is little or no cyclic degradation prior to the start of ductile tearing.

Consistent with the lack of cyclic degradation from the particular seismic load history that was used, the maximum moment for the seismic experiment was substantially above the maximum moment for the single-frequency experiment. In fact, normalizing for crack size, test temperature, etc., by finding the ratio of the experimental maximum stress to an analytically predicted stress for the given crack size, etc., the simulated-seismic experiment is remarkably similar to a companion quasi-static TP304 stainless steel base metal experiment, see Table 1. Thus, there is compelling evidence to support the fact that the IPIRG-2 simulated-seismic forcing function was not particularly challenging to fracture resistance. In a broader context, this

Table 1 Comparison of fracture behavior for various TP304 stainless steel surface crack experiments

Expt. No.	Load Type	OD, mm	WT, mm	a/t	2c/πD	Test Press., MPa	Test Temp., C	Max. Moment, kN-m	Fract. Ratio⁽¹⁾
EPRI-13S	QS	413.5	28.3	0.66	0.58	0	18	1260	1.316
1.3-3	SF	415.8	26.2	0.66	0.55	15.5	288	426	1.165
1-1	SS	417.1	25.5	0.63	0.53	15.5	288	598	1.291

(1) Fracture ratio = $(\sigma_{Bexpt} + \sigma_m)/(\sigma_{Banalysis} + \sigma_m)$ using SC.TNP2 J-estimation scheme analysis with monotonic J-R curve data and quasi-static stress-strain data.

suggests, from a fracture resistance perspective, that all seismic loadings that are traditionally considered "equal" are not the same.

ANALYTICAL CONSIDERATIONS

As part of the IPIRG-2 program, round-robin analyses were conducted in which the IPIRG-2 members and Battelle submitted solutions to a series of problems to try to form consensus opinions on how to solve or evaluate certain problems[8]. One of the round-robin problems involved generation of displacement time histories from a peak-broadened acceleration response spectrum of the IPIRG-2 simulated-seismic forcing function. Four different but "equal" displacement-time histories were created by the round-robin participants.

Using the various displacement-time histories, the maximum moments induced in a linear finite element model of the IPIRG piping system were similar (to within 20-percent), but the timing, number, and build-up of moment peaks were substantially different, see Figure 9. The loading shown in Figure 9b would likely be more damaging from a fracture resistance perspective because of the more pronounced build-up of moment amplitude.

CONCLUSIONS AND CONSIDERATIONS FOR THE FUTURE

From the work done in the IPIRG program, it is not clear that merely being consistent with a given input spectrum is any guarantee that one will have an upper-bound, lower-bound, or average crack-driving force potential due to differences in loading rate and load history effects. Other prescriptions are probably required to give bounding crack-driving force behavior. This work showed that although the IPIRG-2 program seismic displacement time-history forcing function met all of the current ASME, NRC, etc. design requirements, it did not guarantee an upper-bound, average, or even lower bound in terms of crack-driving force. Supplementary considerations such as how the cycles build up and how negative the stress ratios are play a dominant role in the apparent fracture resistance that a specimen will exhibit.

Since seismic events have probabilistic time-histories, events may range from being a dynamic monotonic event (which may be reflective of the Kobe and Northridge seismic signatures) to an event where cyclic damage occurs during multiple cycles of increasing amplitude. Based on the data at hand, the worst case cyclic damage seismic time-history can be hypothesized to be as follows: Rise time, 3 to 5 seconds with building amplitude; large amplitude cycles close to the natural frequency; strong motion duration 4 to 15 seconds. Assuming a 4 Hz natural frequency piping system and single-frequency loading, 12 to 20 cycles of loading would occur during the build-up phase of the time history. This would be a bounding history for determining the cyclic damage prior to the start of ductile tearing. There would be 16 to 60 cycles during the strong motion phase, which are the cycles that continue to grow the crack once it has initiated. Such a loading is estimated to be a bounding case as far as cyclic degradation to material properties is concerned for flawed pipe.

ACKNOWLEDGMENTS

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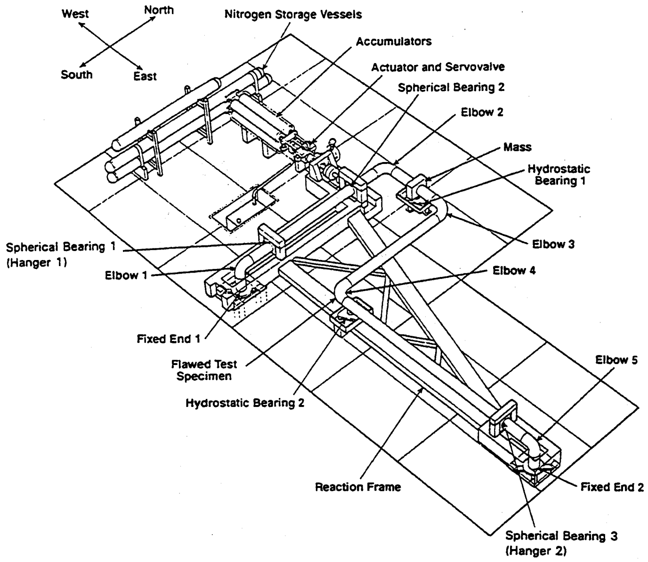


Figure 1 Artist's conception of the IPIRG pipe loop experimental test facility

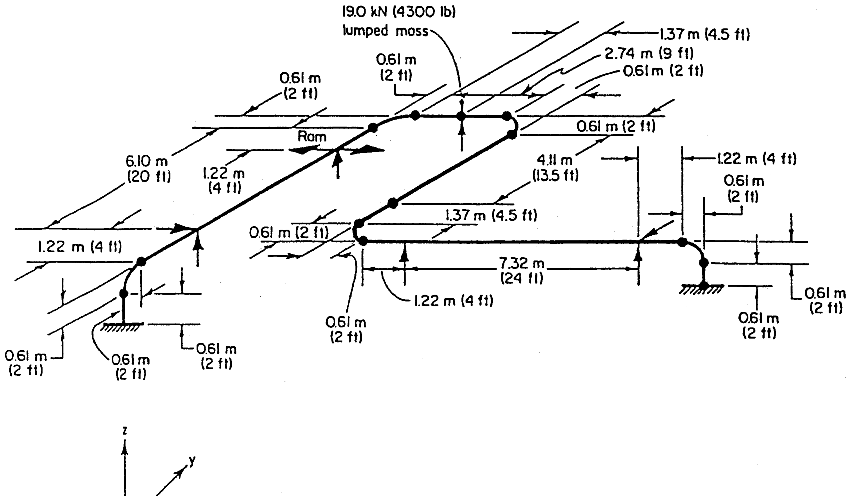


Figure 2 Overall dimensions of the IPIRG pipe loop test facility

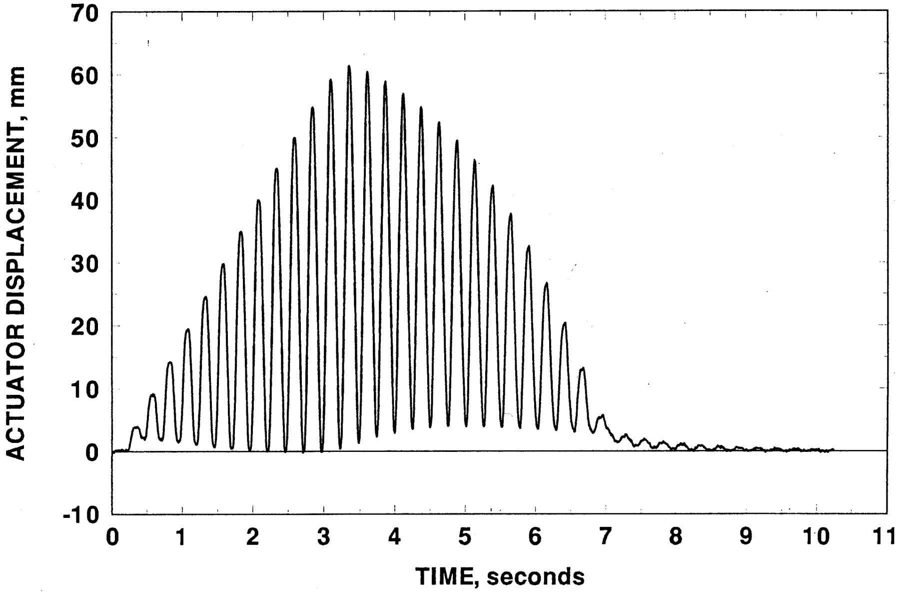


Figure 3 Typical IPIRG-1 single-frequency pipe-system forcing function

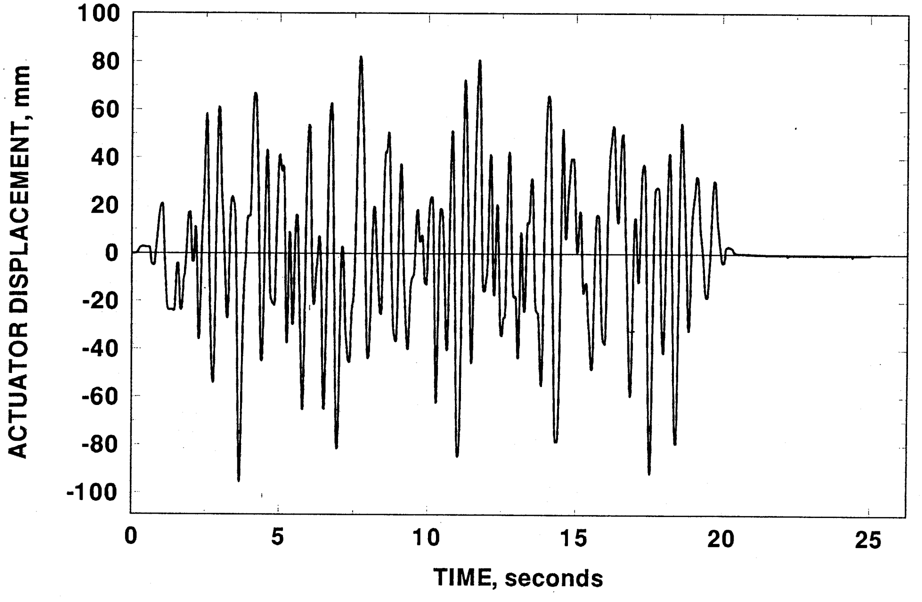


Figure 4 IPIRG-2 simulated-seismic "Test" level pipe-system forcing function

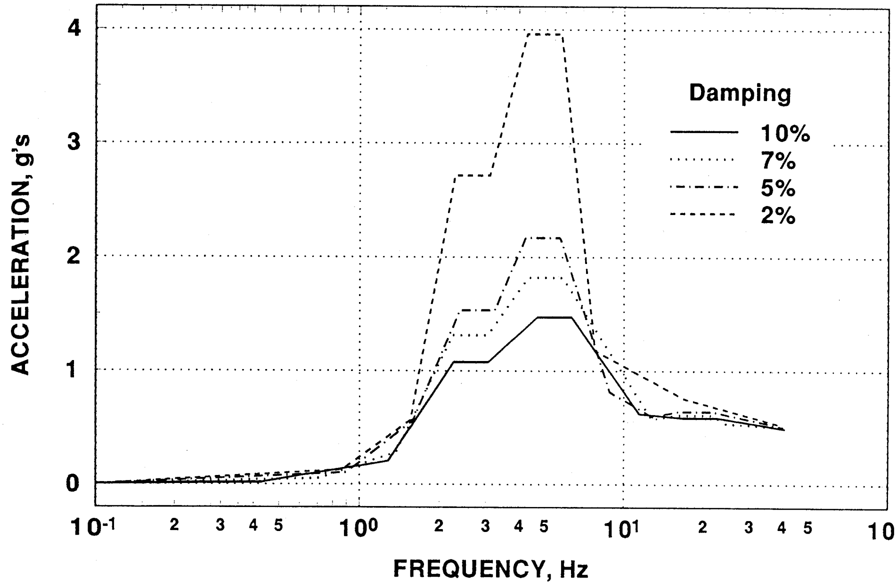


Figure 5 **Response spectra of actuator motion for the IPIRG-2 simulated seismic "SSE" pipe-system forcing function**

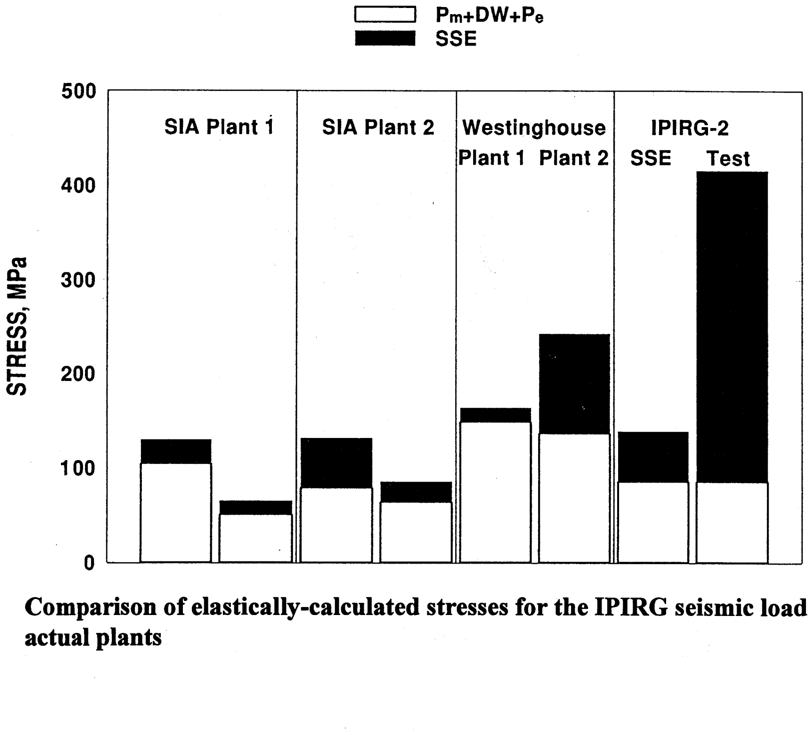


Figure 6 **Comparison of elastically-calculated stresses for the IPIRG seismic loading and actual plants**

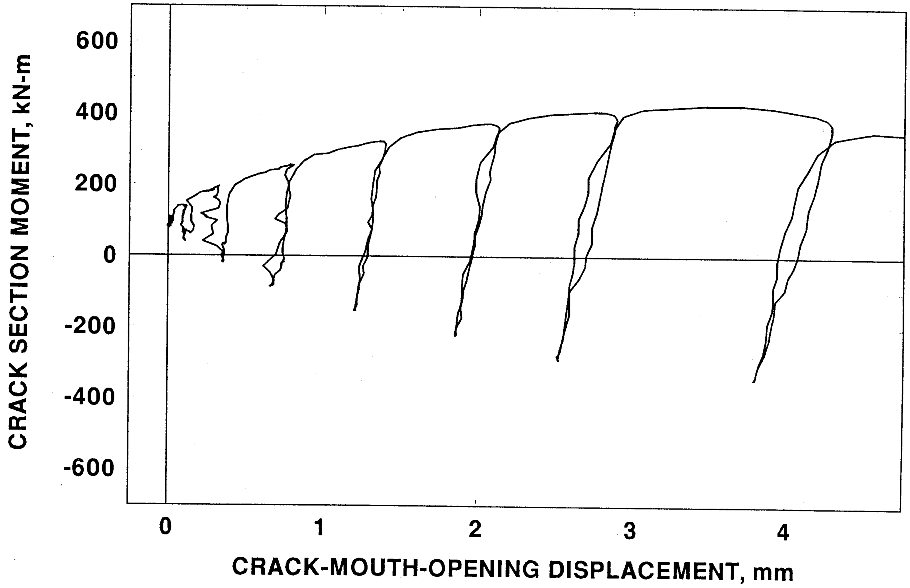


Figure 7 Cracked-section behavior under single-frequency loading for a surface crack in TP304 stainless steel base metal (IPIRG-1 Experiment 1.3-3)

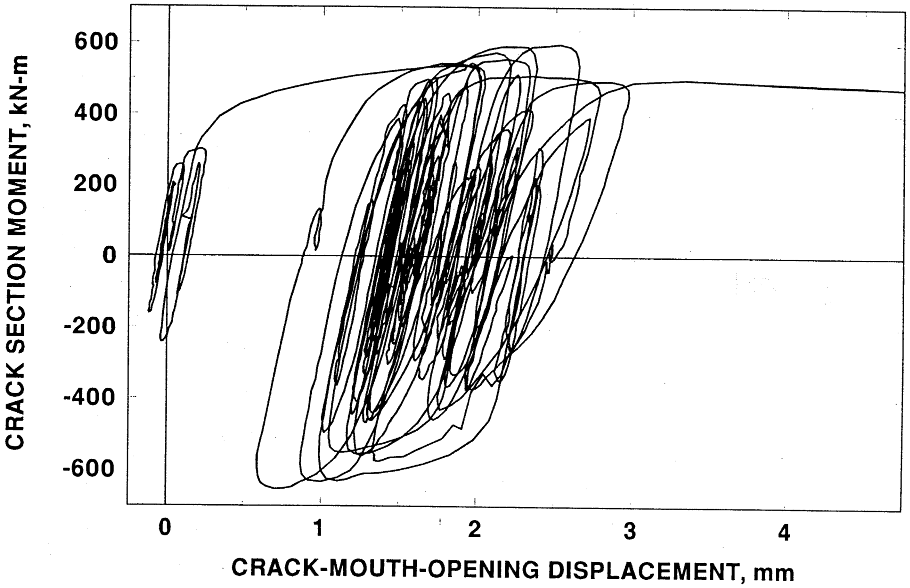
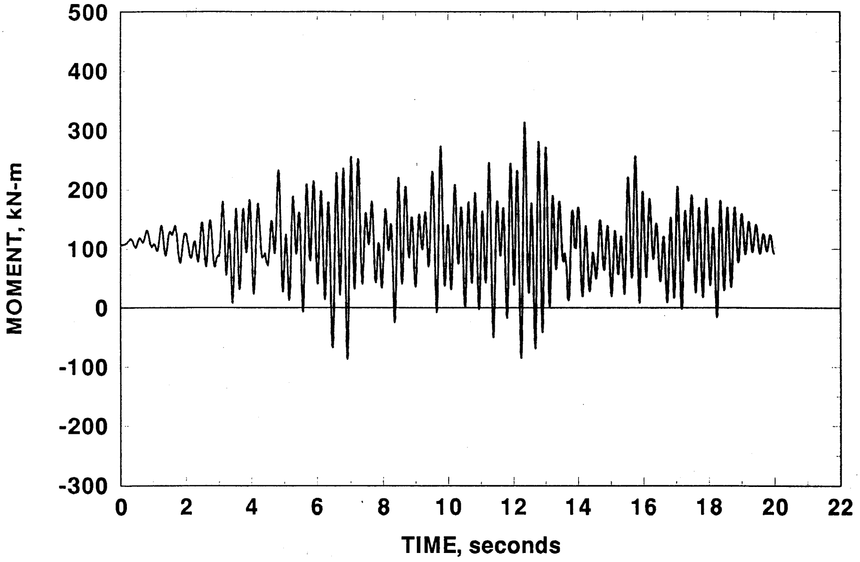
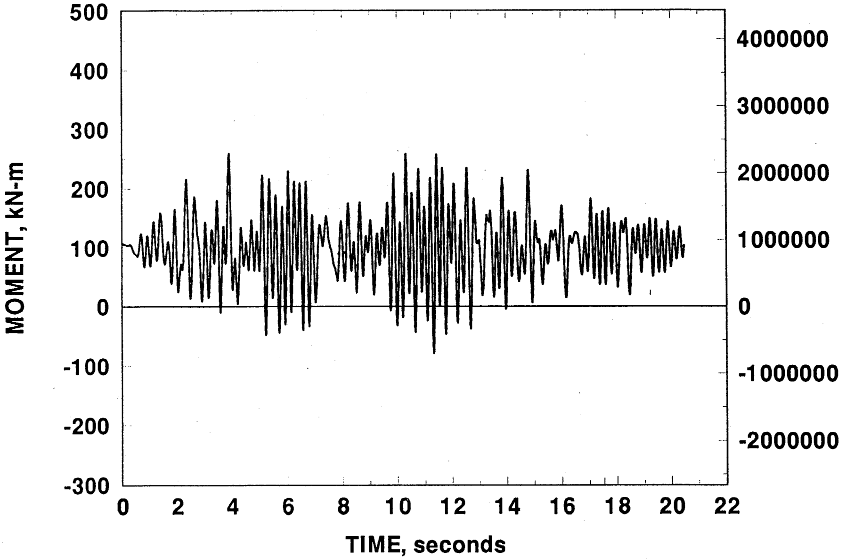


Figure 8 Cracked-section behavior under simulated-seismic loading for a surface crack in TP304 stainless steel base metal (IPIRG-2 Experiment 1-1)



(a) Solution D



(b) Solution F-3b

Figure 9 **Various moment response histories derived from time histories "equal" to the IPIRG-2 simulated seismic loading**