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OVERVIEW OF COOPERATIVE INTERNATIONAL PIPING BENCHMARK ANALYSES

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ABSTRACT

This paper presents an overview of an effort initiated in 1976 by the International Working Group on Fast Reactors (IWGFR) of the International Atomic Energy Agency (IAEA) to evaluate detailed and simplified inelastic analysis methods for piping systems with particular emphasis on piping bends. The procedure was to collect from participating member IAEA countries descriptions of tests and test results for piping systems or bends (with emphasis on high temperature inelastic tests), to compile, evaluate, and issue a selected number of these problems for analysis, and to compile and make a preliminary evaluation of the analyses results. The Oak Ridge National Laboratory coordinated this activity, including compilation of the original problems and the final analyses results.

Of the problem descriptions submitted three were selected to be used. These were issued in December 1977. As a follow-on activity, addenda were issued that provided additional data or corrections to the original problem statement.

A variety of both detailed and simplified analysis solutions were obtained. A brief comparative assessment of the analyses is contained in this paper.

BACKGROUND AND GENERAL GUIDELINES

The increasing use of sophisticated computer programs to analyze the deformation behavior of structural components subject to inelastic behavior requires that a greater emphasis be placed on assuring that the results are valid for the geometries and loading histories analyzed. An accepted method of increasing confidence in the results obtained is through the use of structural benchmark problems for both verification and qualification.[1]

Piping represents one of the most complex structural systems that the analyst must consider. In addition, the degree of confidence required in the results of these structural analyses imposes additional demands on both the analyst and the validity of the methods used. Recognizing this problem, the participants of the IWGFR Specialists' Meeting on High-Temperature Structural Design Technology, which was held April 27-30, 1976, recommended that an international benchmark problem effort be undertaken to evaluate both detailed and simplified inelastic analysis methods for piping bends as well as for entire piping systems.[2] Several problems for which experimental results are available were to be collected and then solved by analysts in IAEA member countries. The Oak Ridge National Laboratory (ORNL) agreed to compile the problems and to collect and evaluate the benchmark problem solutions. A final report [1][3] summarizing the various analyses and comparing them with experimental data was prepared and issued by the IAEA. This paper is a summary of that report. It's intent is to basically sketch an overview of the organization, execution, and results of the piping benchmark activity. The interested reader is referred to other sources for specific details of the experimental and analytical efforts.

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[1] *Verification* is defined as the demonstration that a computer program actually does correctly what it is supposed to do; that is, it solves correctly the model that was programmed, regardless of whether the model is a valid representation of any particular system. *Qualification* is concerned with the use of computer programs for solving the real problems encountered in design. Given that a computer program does what it is supposed to do, does the combination of mathematical model, geometric discretization, description of material properties, representation of the loading and temperature histories, and boundary conditions, all consistent with the program limitations, give an acceptable solution to the physical problem?

[2] "International Working Group on Fast Reactors — Specialists' Meeting on High-Temperature Structural Design Technology of LMFBRs," Champion, PA, U.S.A., April 27-30, 1976, IWGFR/11, International Atomic Energy Agency (October 1976).

PROBLEM SELECTION AND ORGANIZATION

Several criteria were used in selecting those problems that were to be presented from the large group submitted. One of the assets of benchmark problems is that they provide the analyst the opportunity of comparing his results with the solutions obtained by other analysts and/or other computer programs. Thus, one of the first criteria was to select only a few problems to ensure that more analysts would be doing the same problems and more opportunities for comparisons would then be available. Second, the completeness of the problem was considered. It was important that the essential ingredients were available to the analyst for setting up the problem to adequately describe the geometry, load, boundary conditions, and materials behavior and for making provision for output of selected stress, strain, or deformation quantities to be compared. Finally, some judgment was exercised as to the complexity of problems allowed for benchmark use.

Three piping benchmark problems that best suited the above criteria were chosen and issued to participants. The three problems were: (1) a 90°-elbow tested at elevated temperature and loaded with an in-plane transverse force, (2) a 90°-elbow tested at elevated temperature and loaded with an in-plane moment, and (3) a 180°-elbow tested at room temperature and loaded with a reversed, cyclic, in-plane transverse force. These represented both room-temperature elastic-plastic behavior and elevated-temperature elastic-plastic-creep behavior of elbow-pipe assemblies. To be consistent from problem to problem, a common format was used to present the problems to the analysts. Basically this format was:

1. Problem description. Geometry and dimensions, load type and load history, and the measurements made.
2. Material properties data. Time-independent and time-dependent materials behavior data required to analyze the problem.
3. Results. Tabularized stress, strain, or displacement data or structural response curves. Note that these were selected results representative of the structural response of the component and were not necessarily all of the results obtained by the investigators (contributors of the experimental problems).

The resulting package of the three problems was issued by ORNL in November 1977 [2]. Subsequent addenda were issued to provide necessary comments, corrections, and additional information, as supplied by the participants. The problem descriptions as presented in the final report included all the above information. Thus, the problem descriptions provided in Ref. 1 can be considered to be complete and constitute a valuable resource for other analysts.

PARTICIPATION

The response to the analysis effort was quite good. Table 1 provides a summary of participants and indicates the distribution of problems analyzed. Each participant group prepared a descriptive report detailing the analyses performed. These reports were reproduced in their entirety in Ref. 1 and usually included both a description of the methods used and a discussion of the results obtained.

SUMMARY OF RESULTS

The solutions to all problems fell into two general, but somewhat oversimplified categories; detailed analyses and simplified analyses. The detailed analyses were characterized by development of a complex structural model using, for example, three-dimensional finite-element techniques, by analyzing large segments or all of the load histogram, and by utilization of detailed materials constitutive equations and models. The simplified analyses generally relied on a composite of specialized and simplified structural elements to model parts or all of the entire structure as well as on simplifications to constitutive equations and materials models. In assessing results, it was not the intent to evaluate analyses as being "right" or "wrong" but to make relative comparisons as to predictions and techniques used. In this context it was quite appropriate to compare a detailed analysis with a simplified analysis. However, to assess specific features of a given problem, the two categories of solution methods should be segregated.

A brief summary of each problem is presented below. This summary includes a synopsis of the problem followed by presentation of key analysis results.

Benchmark Problem No 1: Elevated-Temperature Elastic-Plastic-Creep Test of an Elbow Subjected to In-Plane Moment Loading [1,3]

An elbow-pipe assembly was tested at 600°C (1112°F) under elastic, plastic, and creep deformation conditions. The test article was a 304.8-mm (12-in.), sched-20, 90° elbow and pipe assembly with the configuration shown schematically in Fig. 1. The elbow and pipe material were AISI type 304 stainless steel. One end of the assembly was rigidly constrained so that a transverse concentrated force applied at the other end produced an in-plane bending moment in the elbow. The load history for the assembly is shown in Fig. 2. Seven load steps, totaling approximately 340 h, were used, each being load application followed by a period of constant load creep. For steps 1 through 5, the load was completely removed at the end of the creep period. For step 6, the load was increased directly into step 7. Loads were applied using a deadweight system and were measured using an in-line load cell. The loads were applied at an approximate rate of 22 mm/min based on deadweight movement.

The specimen was heated by circulating hot air through the pipe-elbow assembly. The outside surface was insulated to minimize heat losses to the atmosphere. Generally, there was a 5 to 10°C temperature differential between the inner and outer surfaces of the specimen. The temperature of each point remained steady within ±2°C for the duration of the test. Measurements were made of free-end deflection and of radial displacements around the outside circumference of the elbow (Sect. A-A, $\phi = 0°$, Fig. 1).

Analysis of this problem requires, as a minimum, monotonic stress-strain curves and an equation of creep for the material at 600°C (1112°F). Supporting materials properties data were not available for the specific material used to fabricate the elbow. Properties available in the literature were thus recommended. Tensile properties consisted of a constant yield stress and stress-strain relationship of the Ramberg-Osgood type. The creep equation was taken from Ref. 4.

Creep characterization tests were performed on a material comparable to that used in the test article although the data were not generated in time to impact the benchmark analyses. It was found that, at stresses less than approximately 137 MPa (20 ksi), the recommended creep equation gave a reasonable representation of material behavior whereas, at larger stresses, the equation would underpredict observed behavior by a large margin. This was important for the interpretation of results as will be discussed below.

Solutions from three different sources were submitted for this problem. Both simplified and detailed inelastic analyses were performed as summarized in Table 2. The agreement between experiment and analyses was generally good. Figure 3 shows a comparison between measured and predicted values of assembly end deflection. Note that no free-end deflection values were available from the BENDIN analysis. It can be observed that, for the first three load steps, the analyses capture the essential creep response. The lack of agreement for this segment of the test seems to be due primarily to underpredicting the loading deflections. Since these first three load steps involve essentially elastic loading, it would be expected that the analyses should be in good agreement with the data. However, the analyses shown predicted a "stiffer" structure than was measured. Figure 4 shows a comparison of circumferential strain around the plane $\phi = 0°$ at the end of the third load step. The analyses also indicated a "stiffer" structure here although PACE more appropriately predicts the maximum and minimum strain values. Observe also that the analyses do not totally capture the shape of the measured strain distribution around the elbow circumference.

For load steps 4 through 7, accumulation of plastic strain becomes increasingly important. In addition, the predicted creep rates diverge from those measured in the test. Use of a creep equation based on the characteriztion data would yield higher creep strains for load steps 4 through 7. This may explain why the more exact three-dimensional analysis predicted much less creep strain at the high stress level load steps.

For this type problem, structural nonlinearities may play a significant role in the overall deformation of the assembly. These nonlinearities could arise from such factors as ovalization of the elbow and pipe stress regions around welds and supports. Not all such nonlinearities were considered in these analyses. Also, some evidence indicates that cyclic loading interspersed with creep hold periods can lead to both enhanced creep and plasticity. All these factors could lead to underpredicting the deformation.

In summary, the analyses seemed to capture the essential features of the deformation behavior for the assembly. Using the materials data originally recommended, the simplified analyses gave better agreement with experimental results. However, had materials properties been used that were more representative of the actual elbow and pipe legs material, this may not have been the case. The value of this problem would have been greatly enhanced if a set of cyclic plastic and creep data on the specimen material had been supplied.

Benchmark Problem No. 2: Tests at 593°C (1100°F) on a 101.6-mm (4-in.), Sched-10, Elbow-Pipe Assembly Subjected to In-Plane Moment Loading [1,5]

A constant, in-plane moment, produced by symmetric application of opposite forces, was applied to an elbow-pipe assembly maintained at 593°C (1100°F). The test assembly was composed of a 102-mm (4-in.), sched-10, 90° elbow with a 152-mm (6-in.) bend radius welded to two 324-mm (12.75-in.) lengths of sched-10 pipe. Both elbow and pipe were made of type 304 stainless steel, and were specially fabricated for the tests performed. The assembly is shown schematically in Fig. 5.

A system of deadweights was used to load the assembly with either a constant in-plane bending moment or a constant in-plane bending moment in combination with an axial thrust. For these analyses, a loading program involving only a stepwise constant moment was considered. The specimen was installed in a manner that minimized out-of-plane loadings due to the weight of the assembly.

The load histogram for the test is shown in Fig. 6. From the unloaded state a bending moment of 843 N-m (7458 in.-lb) was applied. The rate of loading was not controlled and full load was reached within 10 s. The specimen was held for a constant load creep period of 295 h. The applied moment was then increased to 1114 N-m (9858 in.-lb). This load was held for an additional 44 h which ended the test.

Heating was accomplished by use of a heating element inside the test assembly. Insulation applied to the outside of the specimen minimized heat loss and permitted more uniform temperature control. The temperature of the elbow was maintained at 593°C ± 5.6°C (1100°F ± 10°F) during the test although the temperatures of the pipe legs dropped off toward the ends of the assembly.

Displacements and rotations of the free end of the assembly were measured as shown in Fig. 5. Surface strains were also measured using special resistance type high-temperature strain gages mounted both circumferentially and longitudinally on the elbow. (A more complete discussion of the gages is available in

Ref. 5.) Loads were monitored using electrical load cells mounted in line between the specimen and the applied weights.

The minimum material properties required by the analyst for solution of this problem are the initial elastic-plastic tensile curve for the material and an equation of creep for uniaxial constant stress conditions, both at 593°C (1100°F). The test article material has been characterized in great detail [6]. Monotonic tensile data were provided in three alternate forms, a graphical stress-strain curve, tabular stress-strain values, and a Ramberg-Osgood type relationship. Also, cyclic stress-strain data were provdied for analytical methods where the yield stress was updated based on path-dependent accumulated plastic strain or total inelastic strain.

Creep data were provided in the form both of tabulated values of creep strain vs time and stress and of a three term exponential creep equation. Test results from other sources [6] had indicated the adequacy of these material properties data.

This problem was extensively analyzed using both simplified and detailed inelastic analyses. In all, ten analyses were performed as summarized in Table 3. A large amount of information on the overall deformation response of the elbow-pipe assembly was provided by the various analysts. The one parameter, however, that is most graphic in comparing the different techniques is free end rotation vs time. This parameter was available (directly or indirectly) from all of the analyses.

Four detailed analyses were performed using three computer codes. The assembly was modeled using idealizations ranging from one quarter to the entire elbow-pipe structure. Both small and large deformation analyses were employed although there was no appreciable difference in results obtained.

A comparison of the results for free-end rotation of the assembly vs time from the different detailed inelastic analyses is shown in Fig. 7. For the first load step, it is observed that the analysis predictions are all consistent with one another and do a credible job or predicting the experimental results. Plastic strain and creep strain are both about equally overpredicted. It is noted that Iwata et al. used a bilinearized stress-strain curve with an initial yield stress substantially lower than that used in the other anlayses. This would yield a larger plastic deformation on loading as is indicated in Fig. 7. The deformation during the second load step is observed to be less predictable. This may be due in part to the plasticity-creep interaction rules (some analyses did not consider this) and in part to structural nonlinearities, e.g., geometric changes.

A comparison of outside circumferential strain at gage location 10 (see Fig. 5) is shown in Fig. 8. Comparing Figs. 7 and 8, it is seen that the individual analyses are internally consistent; that is, the predicted magnitudes of end rotations and strains occupy the same relative positions compared to other analyses and experiment. Thus, the analyses are assessed to predict structural behavior reasonably well and, also, as being conservative with respect to evaluating deformation limits. The magnitude of deformations predicted might also be particuarly important in evaluating strain fatigue damage, for a cyclically loaded structure.

Six simplified inelastic analyses were performed for this problem. The general feature of these analyses was to model the complete assembly using beam type curved and straight pipe elements [7]. These elements are, in general, very simple and require flexibility factors to provide each element with the desired response under plastic and creep deformation. Dhalla and Newman utilized a slightly more complex element that combines the features of thin shells with beams.

The results for assembly free-end rotation vs time and circumferential outside surface strain at gage location 10 are shown in Figs. 9 and 10, respectively. Two factors in combination make it difficult to assess these results; the idealizations and the materials properties used. Of the analyses, those using TEDEL and MARC were the most detailed and adhered most closely to the materials properties recommended. Both these analyses overpredict the deformation, particularly plasticity, by a large margin. Since the same properties representations yielded reasonable results when used with the detailed analyses (TRICO and MARC), it is felt that the simplified methods utilized in TEDEL and MARC are "softer" than comparable detailed methods with respect to predicting plasticity. That is, the detailed analyses have demonstrated that the materials properties reasonably represent the specimen material properties. Thus, attributing variation between analysis and experiment to materials properties alone is not totally valid.

The other simplified analyses did a much better job of predicting both plasticity and creep but were based on plasticity and creep formulations that would generally predict less strain. For example, the creep equation recommended by Blackburn for type 304 stainless steel [8], used in several analyses, will predict creep strains at low stress levels to be as much as two orders of magnitude less than those of the recommended equation (or creep data matrix). This discrepancy disappears at higher stress levels. Also, other simplified procedures, such as in PACE 2 and PIRAX, are based on use of a secondary creep term only. It would be expected then that these type analyses would predict lower creep strains than analyses where the primary creep was also included.

In summary, through the first step of the test, the detailed analyses provided a reasonable and conservative (with respect to evaluating deformation limits) prediction of the deformation of the elbow assembly. In addition, the analyses were consistent with one another. In the second step, more deviation was seen both among analyses and between analyses and experiment. The results from the simplified analyses indicated a wide variation in predictions. The greatest deviation seemed to be encountered in predicting plastic strain. While these analyses were generally conservative, more consistent predictions would be desirable particularly if these techniques were being applied to longer or more repetitive load histograms.

Benchmark Problem No. 3: Room-Temperature Elastic-Plastic Response of a Thin-Walled Elbow Subjected to In-Plane Bending Loads [1,9]

An elbow-pipe assembly was tested at room temperature by imposing cyclic, in-plane, opening and closing moments (forces) in conjunction with internal pressure at selected points in the load histogram. The test article was a thin-walled, large diameter elbow of ICN 472-SP-304 type stainless steel with a 180° bend. The external diameter of the elbow was 570 mm (22.4 in.) and the mean thickness of the wall was 12 mm (0.47 in.). The mean fiber radius of the U-bend was 762 mm (30 in.). Sections of pipe were added to each end of the elbow to provide extensions for load application. One end of the elbow-pipe assembly was fixed while a transverse load was applied to the other end. The load fixture permitted application of both opening and closing moments. Additionally, for selected load steps the specimen was pressurized using water. A schematic of the test assembly is shown in Fig. 11.

The moment load history is shown graphically in Fig. 12. The response of the elbow was characterized by three phases: (a) fully elastic behavior under reversed cycling, (b) elastic-plastic behavior up to incipent plastic instability in closing for reversed, increasing magnitude moments, and (c) large deformation elastic-plastic behavior up to plastic instability for increasing magnitude cyclic opening moments. For load step 0, an internal pressure of 2.7 MPa (392 psi) was applied. To measure the effect of internal pressure on elbow response to bending, the assembly was pressurized to 2.01 MPa (292 psi), load steps 30 through 33, and a positive moment was applied, load step 31. Throughout these tests, the test article was maintained at room temperature.

The deflection of the elbow was determined by measuring the in-plane displacement of the free end with respect to the fixed end. These measurements were made at the ends of the elbow portion of the specimen (see Fig. 11). The applied loads were also measured such that a moment-deflection history was obtained.

One cross-sectional plane of the elbow was extensively instrumented using surface strain gages. The plane chosen was at 45° to the end of the elbow (see Fig. 11). At selected locations around the circumference, three strain gages were mounted on the outside and inside surfaces of the elbow to provide the information required to determine the principal surface strains at each point.

An analysis of this problem should include the use of cyclic stress-strain data for this material. However, only uniaxial monotonic data in the form of a stress-strain curve were available. It was recommended that the cyclic yield be taken equal to the initial monotonic yield.

The third benchmark problem was analyzed by three groups using both detailed and simplified methods as is shown in Table 4. This proved to be a difficult problem to analyze due in part to the complex loading history and to the fact that large deformations were present. None of the analyses were complete in the sense of accounting for all combinations of loading. However, comparisons can be made with the available results.

Two detailed analyses were performed using the codes TRICO and BERSAFE. Problems associated with the handling of large deformations prevented solving the complete load histogram using TRICO. The solution was thus performed in two parts, one utilizing the end load histogram including load reversal to load step 41 but with no pressure, and one to load step 58 with the end load treated as a monotonically increasing load, i.e., no unloading. The BERSAFE analysis only went to step 26 and did not encounter large deformation difficulties.

A comparison of elbow end deflection vs load step is shown in Fig. 13. As can be seen, the elastic response and the initial plastic behavior of the elbow is predicted quite well. This is supported by the predicted longitudinal and circumferential strains as shown in Fig. 14 (outside surface strains for cross section of elbow formed by transverse plane inclined at 45° to horizontal). However, for subsequent reversed plastic cycling, the predictability of the experimental results is not as good. Referring to Fig. 13, two important observations are made. First, the analyses seem to predict a net positive (opening deflection) growth (ratchetting) for the elbow whereas the data indicate increasing negative (closing) deformation. Second, the analyses underpredict the amplitude of the deformation cycle. This could be very important in performing a fatigue analysis if the predicted stresses and strains in the elbow followed the same pattern as the end deflections.

These problems were associated with reversed loading and were probably caused by inadequate modeling of increasing structural nonlinearities with increasing compressive moment magnitude. Bung et al. were able to establish reasonable predictability of end deflection for steps 40 through 58 where the cyclic load histogram was replaced by a monotonically increasing moment with only two unloading steps.

Two simplified analyses were performed as shown in Table 4. The PACE 2 analysis was carried to load step 28 and displayed good agreement for both end deflection, Fig. 13, and circumferential strain, Fig. 14. The TEDEL analysis applied to load steps 25 to 58. The problem was modeled as a deformation-controled situation, i.e., the measured end deflections were used as input and the moment was calculated. These results are shown in Fig. 15. The calculated moments are much less than the measured moments which could lead to a nonconservative result.

In summary, IPBP-3 was an exacting problem to analyze. Good results were obtained using both detailed and simplified methods for elastic and small plastic-deformations. Large deflections were not predicted well. This was caused in part by the large deformation capability of the techniques used (or lack thereof), by structural nonlinearities of the problem, and by lack of representative materials data, i.e., room temperature cyclic stress-strain results.

CONCLUSIONS AND DISCUSSION

In general, detailed inelastic analyses methods provided greater predictability of deformation. Some detailed methods encountered difficulty where nonconstant loading, large deformations, or nonlinear structural behavior were present. The simplified methods, as a rule, predicted greater amounts of deformation than measured, although the results varied widely. The simplified methods were less capable of predicting structural response to load changes (subsequent to initial loading) involving plasticity or creep. This lack of capability sometimes led to large disagreement between analysis and experimental results.

As several analysts pointed out, however, the relative expense of performing a simplified analysis may be as much as an order of magnitude less than that for a detailed analysis. Thus, there is an important role for such simplified techniques where applicable. However, a thorough understanding of the simplifications and the ramifications on results obtained is essential in utilization of such techniques.

Variability between analytical and experimental results depends to a large extent on the quality of the experimental structural data and of the materials deformation data available to the analysts. It is felt that, so far as these three problems are concerned, the structural data provided were state-of-the-art at the time the tests were performed. The materials data available, however, were not always as complete or as representative as desirable. For this type of benchmark analysis, materials properties should be used that typify the material used in the structure.

This discussion will be concluded with a few comments on the organization and role of benchmark problems. A good benchmark problem should be based on a well executed and documented structural test where meaningful measures of deformation are made using state-of-the-art methods. For benchmark use, the experimental results should be limited to selected quantities representative of the structural response of the test article. The structural test should be supported by materials properties data representative of the structural material and of the type loadings imposed. Where materials properties data are not available, guidance should be provided on the most appropriate procedures to follow. If the above conditions are satisfied, the analyst will have a complete, consistent package. With this common basis, he can compare his results with confidence to the experimental data and to other analytical results. In the organization of this activity, the above criteria were utilized although they were not met in all cases.

The role of benchmark problems should be considered in the context "Benchmarks are necessary but not sufficient to establish the validity of an analysis" [7]. In an interpretation of results, the analyst should always be aware of the variability in materials properties data used for analysis, in the deformation behavior of the structure, and, to some degree, in experimental techniques. Thus, the experimental data should not be considered "exact". The analyst should then first consider how well the analysis captures the basic trends for deformation behavior of the structure and only then consider the magnitudes. In this respect, comparison with other analyses can be of immense value.

ACKNOWLEDGMENT

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Table 1. Summary of international piping benchmark problem participants

Author(s)	Problem(s) solved		
	1[a]	2[b]	3[c]
Osamu Watanabe and Hideomi Ohtsubo Through Power Reactor Nuclear Fuel Development Corporation, Japan	X		
H. Bung, G. Clement, A. Hoffmann, and H. Jakubowicz Centre D'Etudes Nucleaires, De Saclay, France	X	X	X
J. Boyle and J. Spence University of Strathclyde through UKAEA	X	X	X
Hans-Peter Knapp and Jan Prij Cooperative Effort Between Interatom and ECN		X	
A. K. Dhalla and S. Z. Newman Westinghouse Advanced Reactors Division, USA		X	
K. Iwata, S. Asai, and H. Takeda Through Power Reactor and Nuclear Fuel Development Corporation, Japan		X	
Akihiko Suzuki Through Power Reactor and Nuclear Fuel Development Corporation, Japan		X	
Shinji Sakata, Tasuku Shimizu, and Masaharu Sumikawa Through Power Reactor and Nuclear Fuel Development Corporation, Japan		X	
T. K. Hellen Central Electricity Generating Board, UK			X
R. C. Gwaltney and W. J. McAfee Oak Ridge National Laboratory, USA		X	

[a] Room-temperature elastic-plastic test of a thin-walled elbow subjected to in-plane bending loads — submitted by D. Brouard et al.

[b] Elevated Temperature test of elbow-pipe assembly subjected to in-plane moment loading — submitted by W. I. Griffith and E. C. Rodabaugh.

[c] Elevated-temperature elastic-plastic-creep test of an elbow subjected to in-plane moment loading — submitted by A. Imazu et al.

Table 2. Summary of sources for solutions to problem 1

Investigator(s)	Analysis code	Analysis method
Watanabe and Ohtsubo (Japan)	BENDIN	Simplified inelastic analysis using finite ring elements.
Bung, Clement, Hoffmann, and Jakubowicz (France)	TRICO	Three-dimensional finite-element analysis using 3 node triangular constant stress elements.
	TEDEL	Simplified inelastic analysis using pipe segments modeled on beam theory.
Boyle and Spence (United Kingdom)	PACE 2	Simplified inelastic analysis for piping systems modeling pipe segments using beam theory.

Table 3. Summary of sources for solution to problem 2

Investigator(s)	Analysis code	Analysis method
Watanabe and Ohtsubo (Japan)	BENDIN	Simplified inelastic analysis using finite ring elements.
Bung, Clement, Hoffmann, and Jakubowicz (France)	TRICO	Three-dimensional finite-element analysis using 3 node triangular constant stress elements.
	TEDEL	Simplified inelastic analysis using pipe segments modeled on beam theory.
Boyle and Spence (United Kingdom)	PACE 2	Simplified inelastic analysis for piping segments using beam theory.
Knapp and Prij (Interatom/ENC)	MARC	Three-dimensional finite-element analysis using element Type 4 of the MARC element library.
Dhalla and Newman (United States)	MARC	Three-dimensional and simplified two-dimensional finite-element analyses using elements Type 4 and Type 17, respectively, from the MARC library.
Iwata, Asai, and Takeda (Japan)	FINAS	Three-dimensional finite-element analysis using special elbow element, Elbow 6, and assumed small strains.
Suyuki (Japan)	SINAP	Simplified finite-element analysis using special purpose pipe and elbow elements.
Sakata, Shimiya, and Sumikawa (Japan)	HI-EPIC-4	Simplified analyses using straight and curved pipe beam elements.
Gwaltney and McAfee (United States)	PIRAX2	Simplified inelastic analysis using straight and curved pipe elements.

Table 4. Summary of sources for solution to problem 3

Investigator(s)	Analysis code	Analysis method
Bung, Clement, Hoffmann, and Jakubowicz (France)	TRICO	Three-dimensional finite-element analysis using 3 node triangular constant stress elements.
	TEDEL	Simplified inelastic analysis using pipe segments modeled on beam theory.
Boyle and Spence (United Kingdom)	PACE 2	Simplified inelastic analysis for piping systems modeling pipe segments using beam theory.
Helen (United Kingdom)	BERSAFE	Three-dimensional analysis using both solid, 20 node isoparametric brick element and semiloof shell element.

Fig. 1. Schematic of test assembly for IPBP-1.

Fig. 2. Load histogram for IPBP-1.

Fig. 3. Comparison of predictions and data for the time response of the assembly end deflection, IPBP-1.

Fig. 4. Comparison of circumferential strain for plane $\phi = 0^\circ$ in elbow at beginning of third load step, IPBP-1.

Fig. 5. Schematic of test assembly for IPBP-2.

Fig. 6. Load histogram for IPBP-2.

Fig. 7. Comparison of experimental and calculated detailed analyses results for free end rotation of assembly, IPBP-2.

Fig. 8. Comparison of experimental and calculated detailed analyses results for circumferential strain (gage 10), IPBP-2.

Fig. 9. Comparison of experimental and calculated simplified analyses results for free end rotationof assembly, IPBP-2.

Fig. 9. Comparison of experimental and calculated simplified analyses results for free end rotation of assembly, IPBP-2.

Fig. 10. Comparison of experimental and calculated simplified analyses results for circumferential strain (gage 10), IPBP-2.

Fig. 11. Schematic of test assembly for IPBP-3.

Fig. 12. Moment histogram for IPBP-3.

Fig. 13. Comparison of experimental and analytical results for elbow end deflection versus load step number, IPBP-3.

Fig. 14. Comparison of experimental and analyses results for outside surface strain for plane at 45° to end of elbow, step 26, IPBP-3.

Fig. 15. Comparison of applied moment to moment calculated using measured end deflections, IPBP-3.

ORNL–DWG 82–5163 ETD

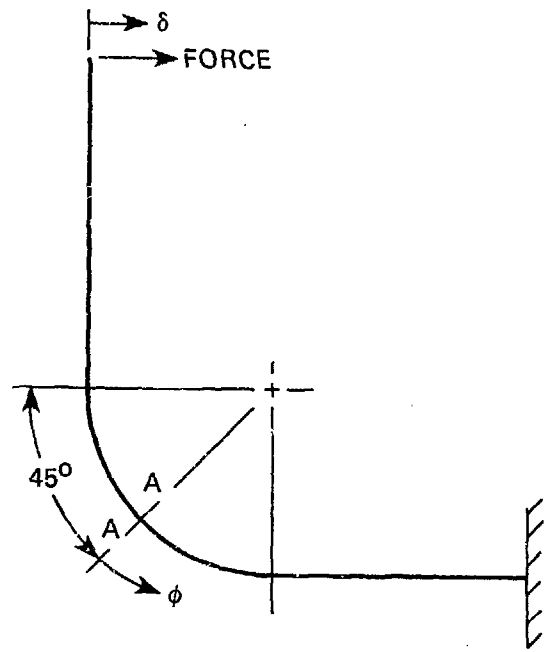
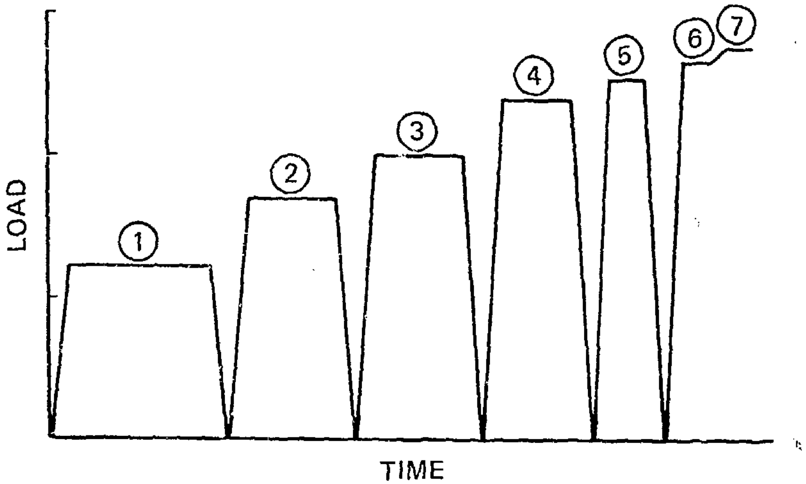


FIG 1

ORNL–DWG 82–5164 ETD



LOAD STEP	FORCE kN (kips)	TIME (h)
1	6.031 (1.355)	96
2	8.365 (1.881)	70.5
3	9.737 (2.189)	69.5
4	11.767 (2.646)	68.5
5	12.454 (2.800)	19.5
6	13.091 (2.943)	1.5
7	13.552 (3.047)	4.5

FIG 2

ORNL–DWG 79–5324R ETD

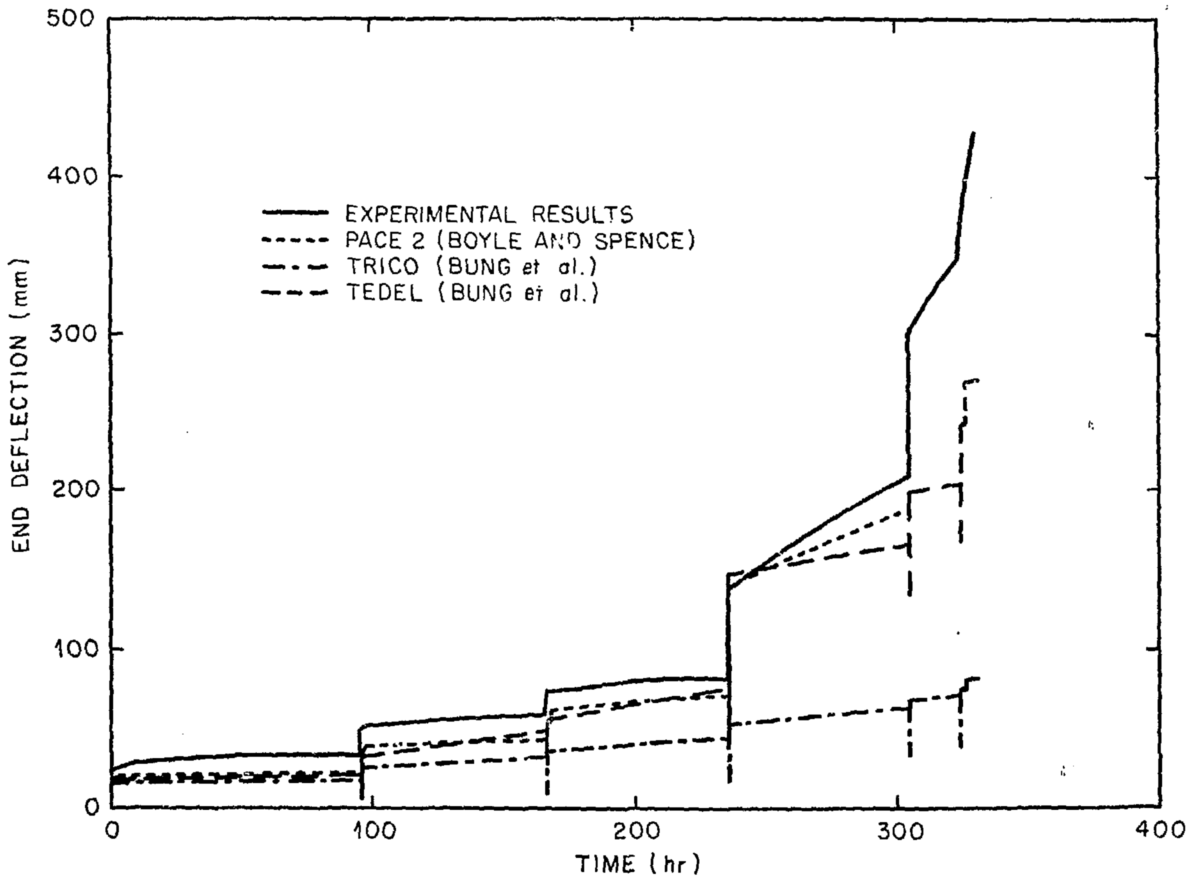


Fig 3

ORNL–DWG 79–5633R ETD

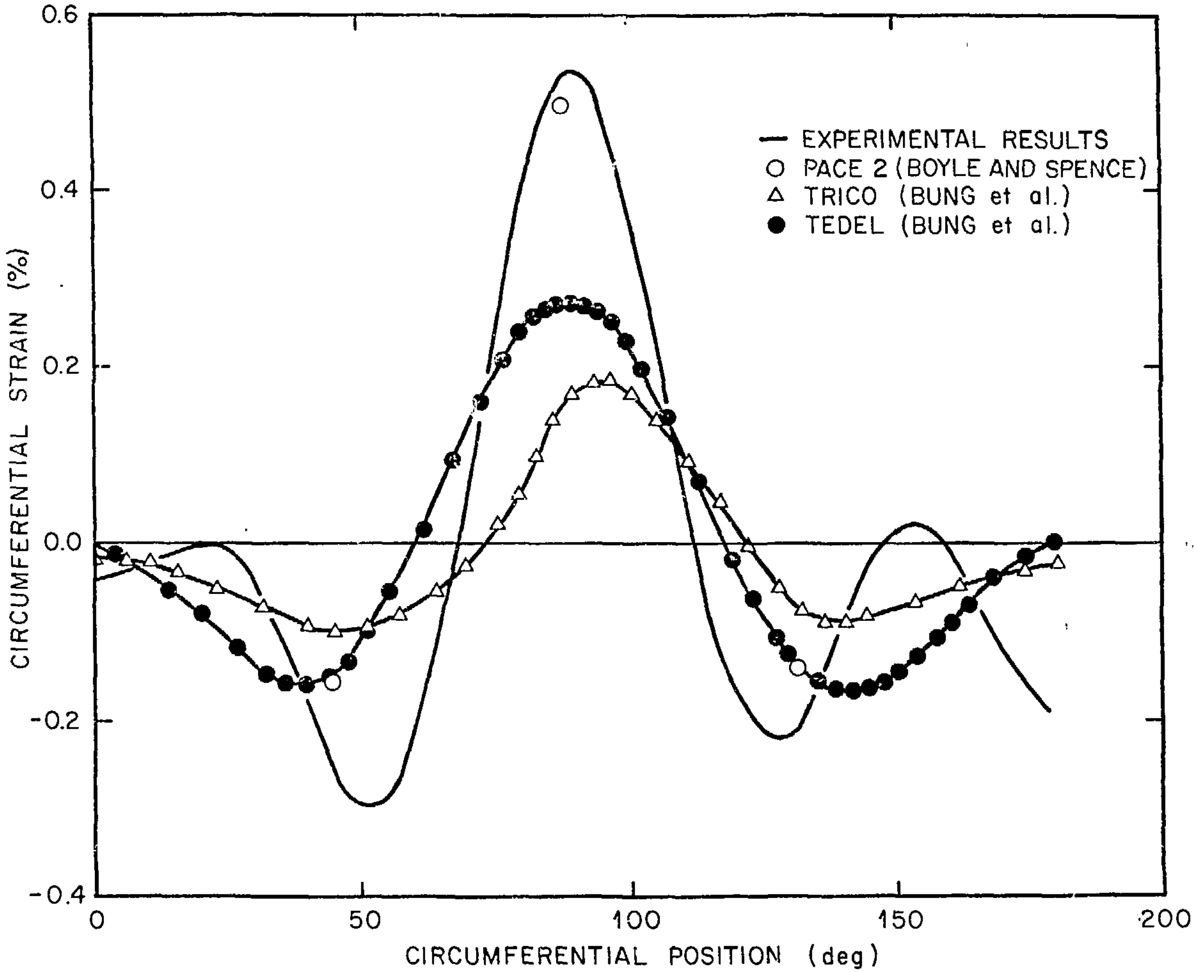


Fig 4

ORNL DWG 79-5631 CTD

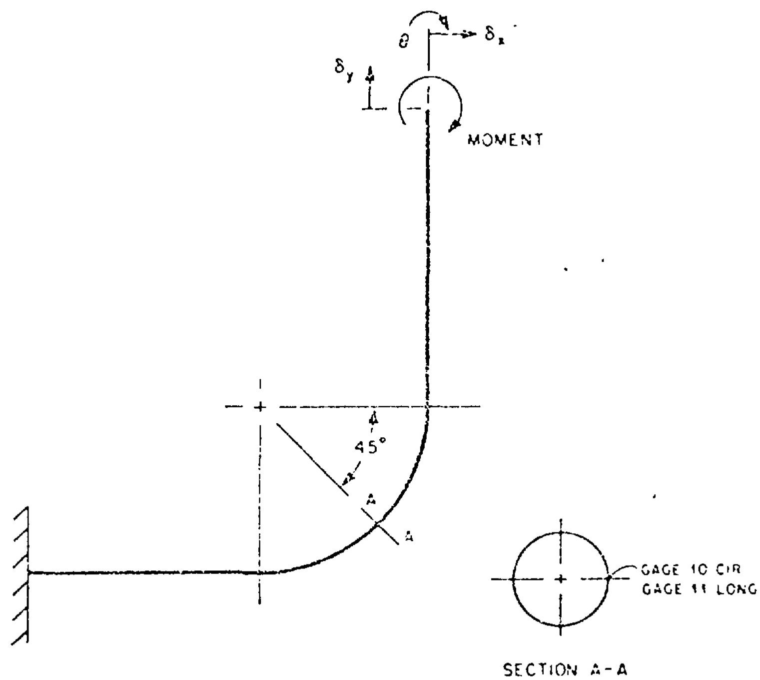


Fig 5 Schematic of Test assembly for IPBP-2

Use left half of ORNL Dwg 79-5631.

ORNL–DWG 79–5778 ETD

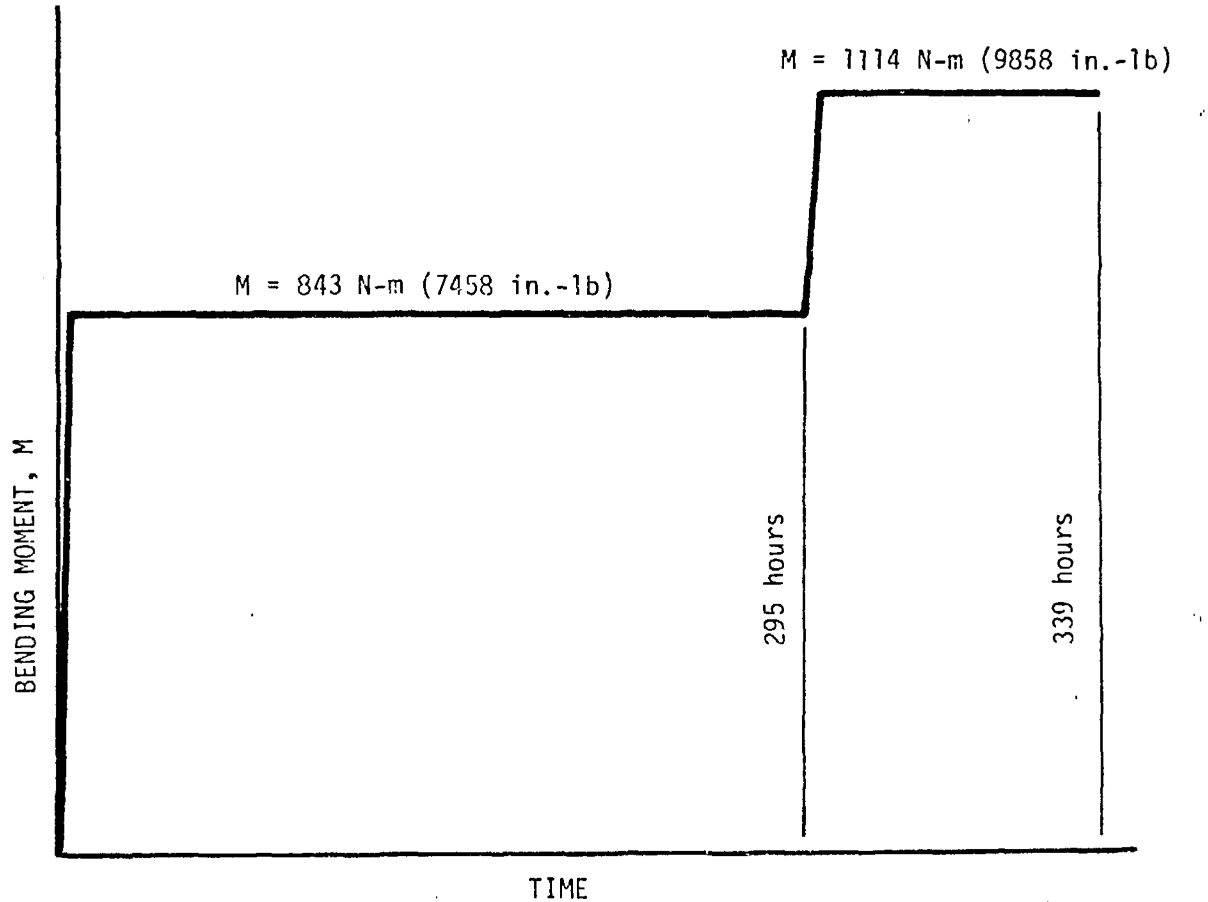


Fig. 2. Load histogram for test.

Fig 6

ORNL–DWG 79–5634R2 ETD

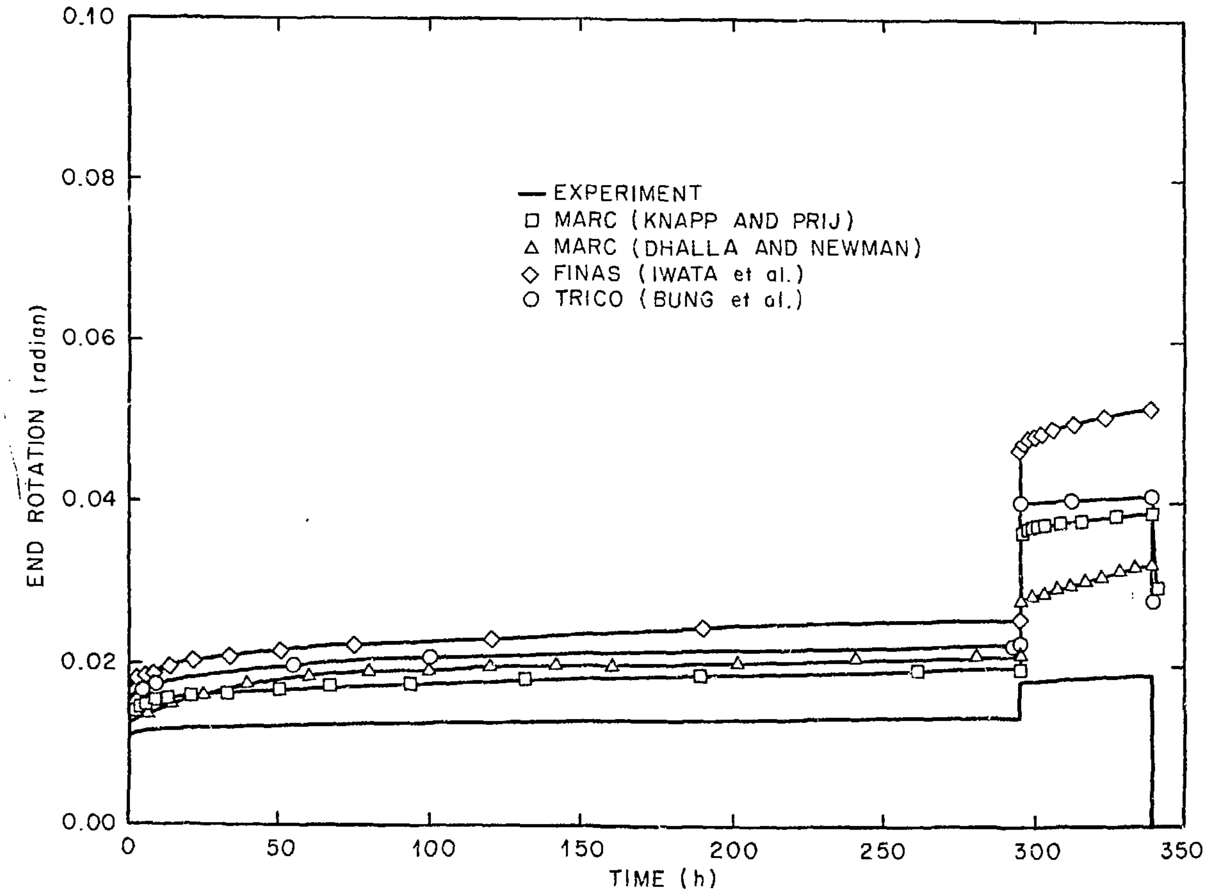


FIG 7

ORNL-DWG 79-5635R2 ETD

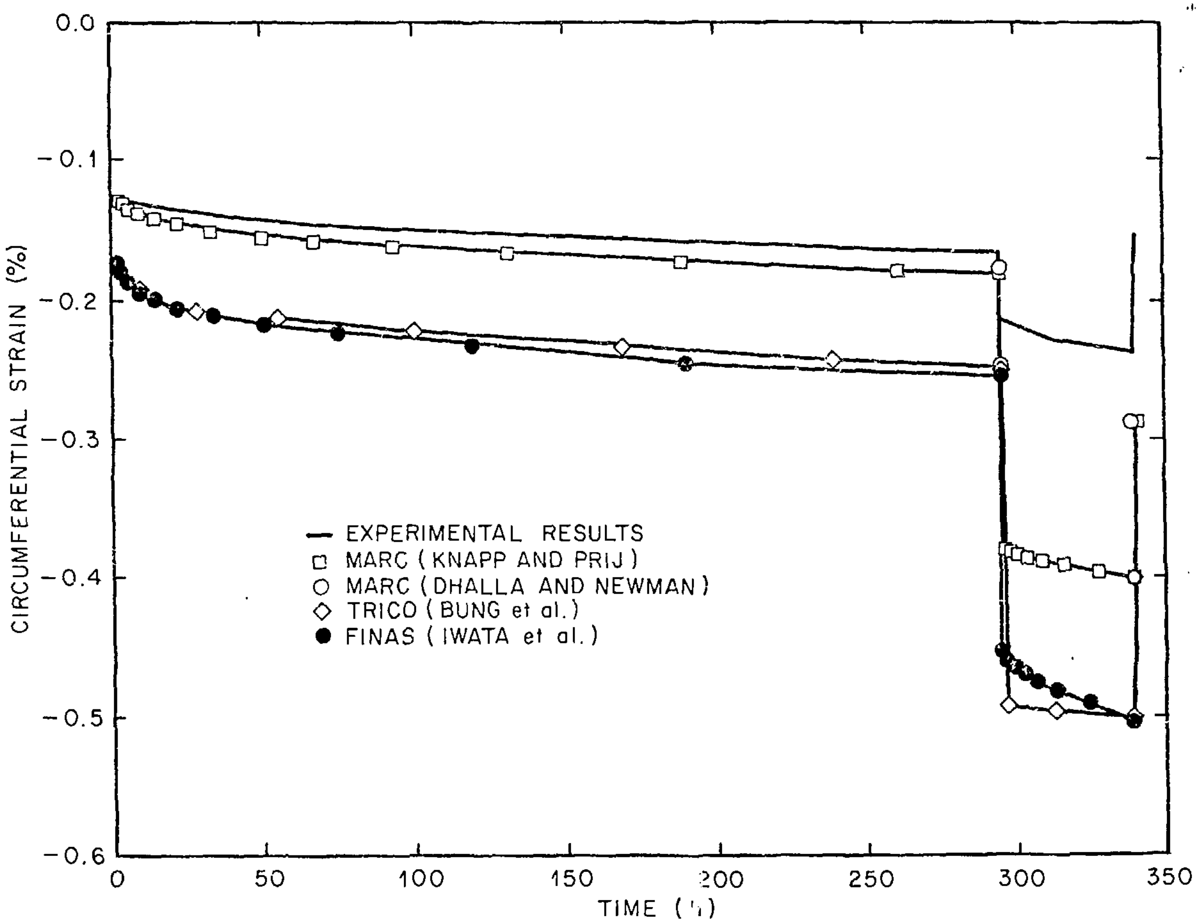
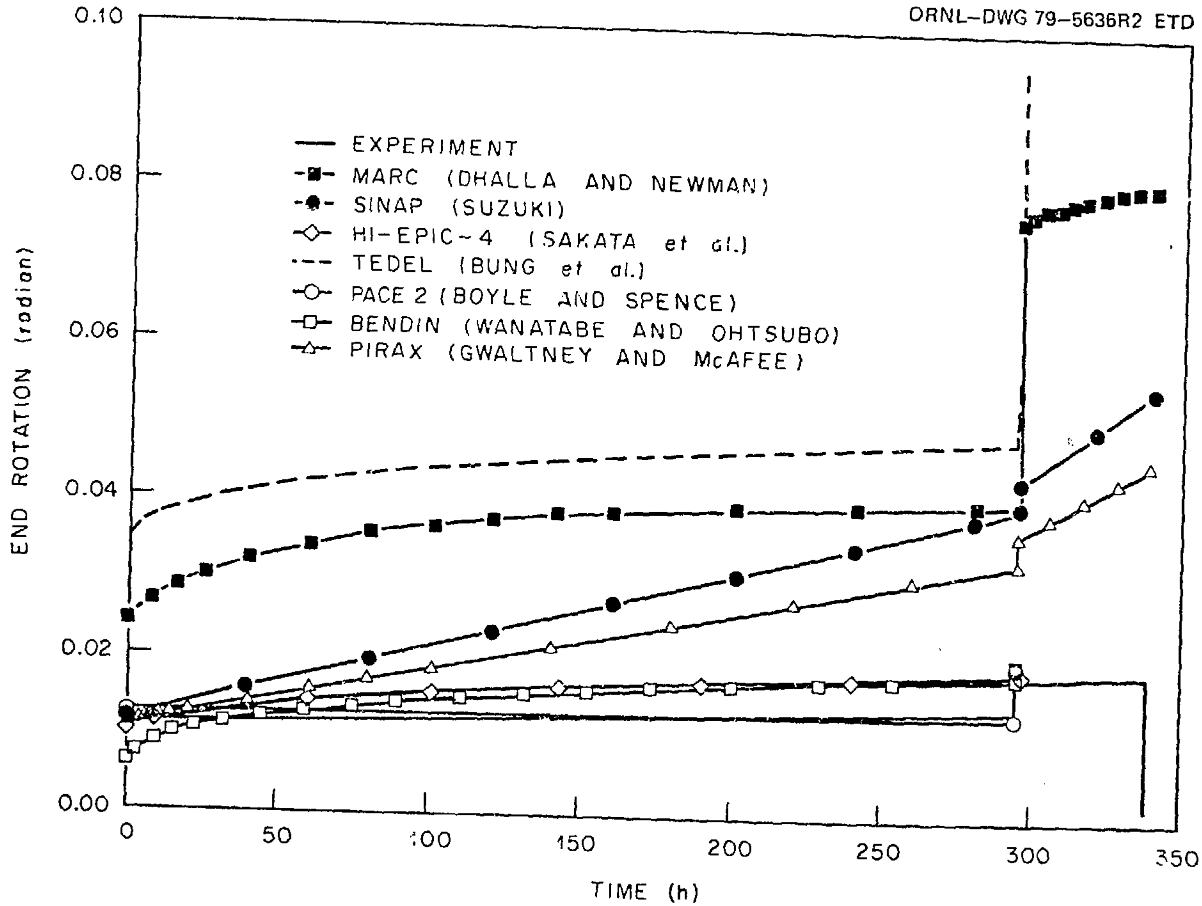


Fig 8



ORNL-DWG 79-5636R2 ETD
EXPERIMENT
MARC (DHALLA AND NEWMAN)
SINAP (SUZUKI)
HI-EPIC-4 (SAKATA et al.)
TEDEL (BUNG et al.)
PACE 2 (BOYLE AND SPENCE)
BENDIN (WANATABE AND OHTSUBO)
PIRAX (GWALTNEY AND McAFEE)
END ROTATION (radian)
0.10
0.08
0.06
0.04
0.02
0.00
0
50
100
150
200
250
300
350
TIME (h)

FIG 9

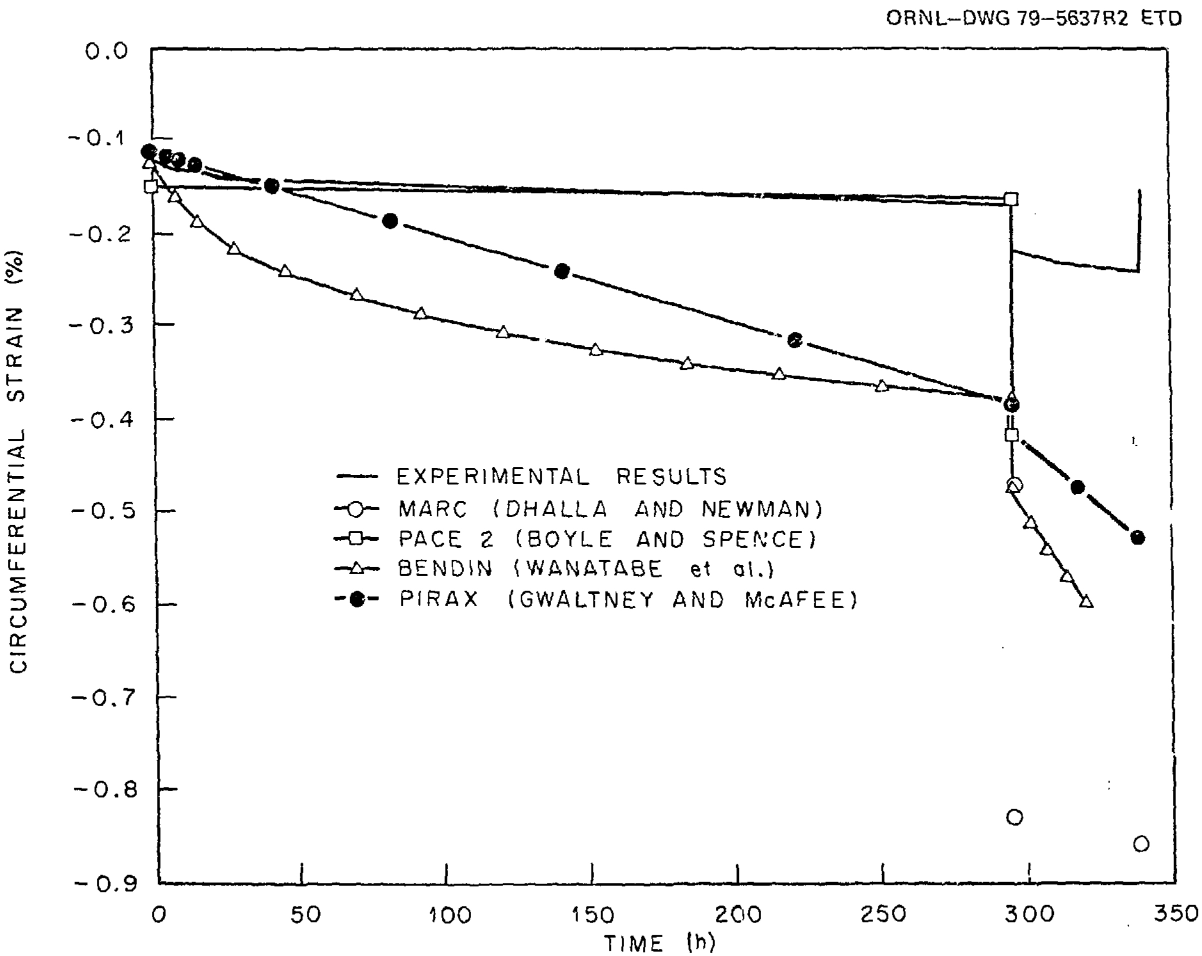

ORNL–DWG 79–5637R2 ETD
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
-0.9
CIRCUMFERENTIAL STRAIN (%)
0
50
100
150
200
250
300
350
TIME (h)
EXPERIMENTAL RESULTS
MARC (DHALLA AND NEWMAN)
PACE 2 (BOYLE AND SPENCE)
BENDIN (WANATABE et al.)
PIRAX (GWALTNEY AND McAFEE)

Fig 10

ORNL-DWG 79-5632 ETD

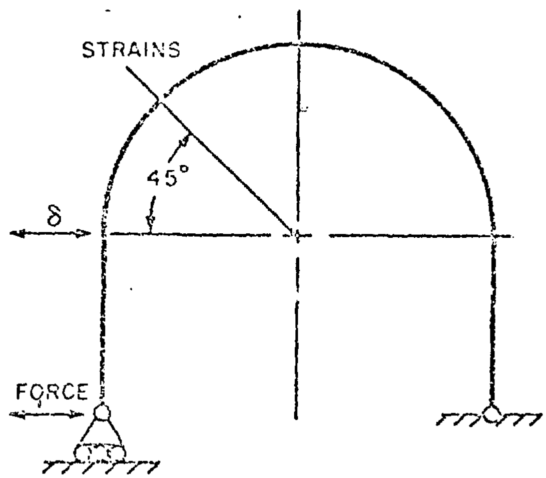


Fig 11 Schematic of test assembly for IPBP-3

79-5632

ORNL–DWG 82–5165 ETD

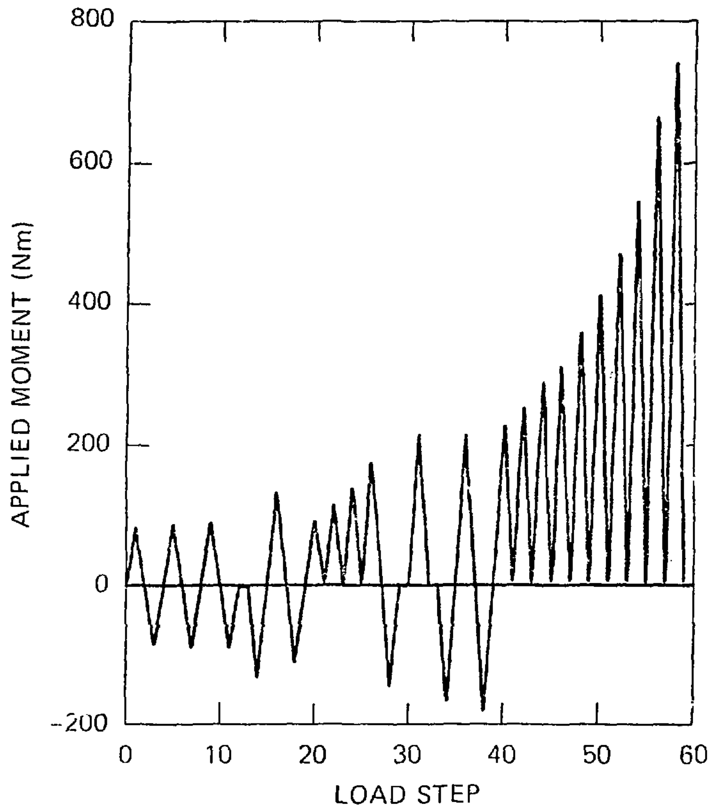


Fig 12

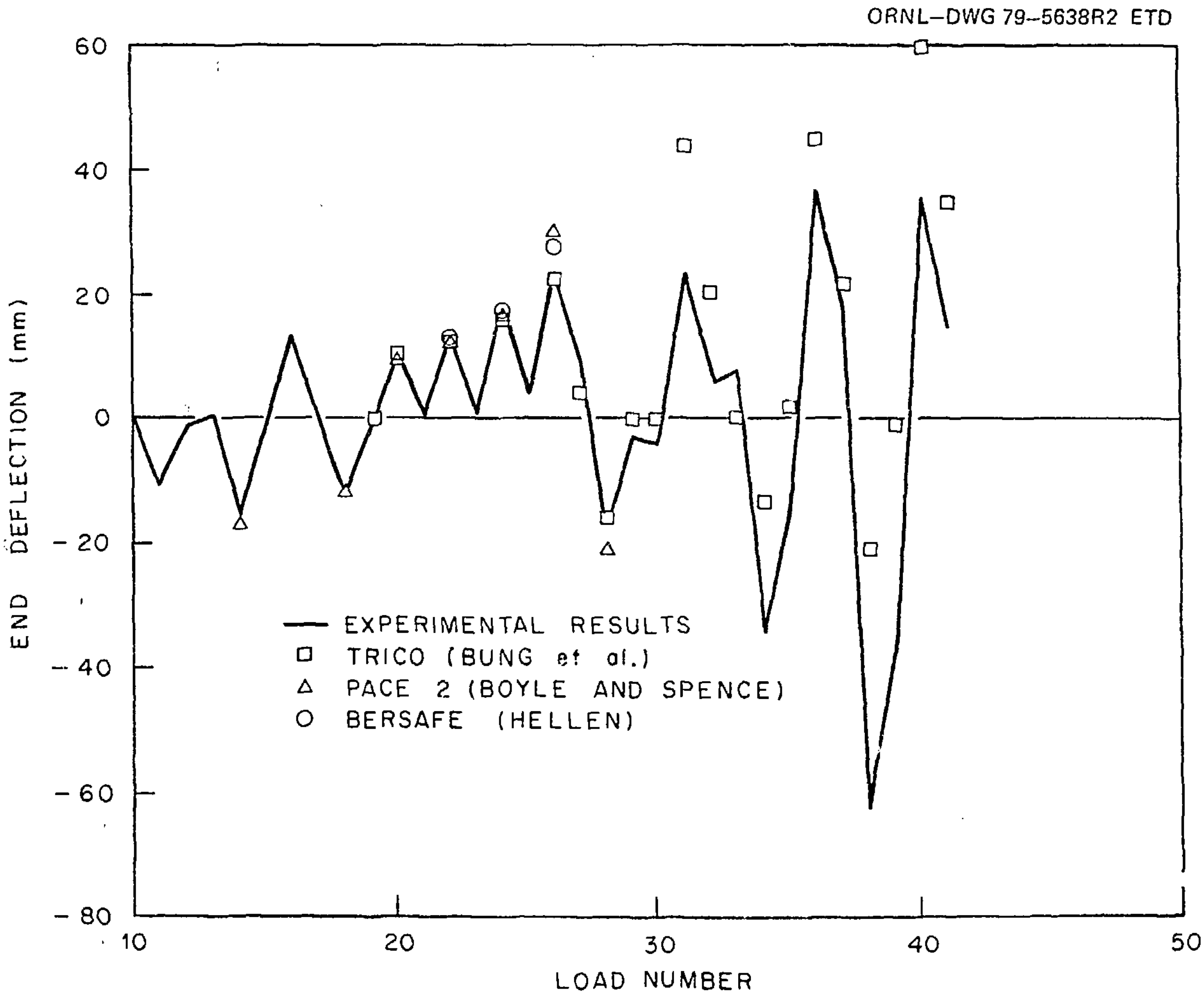

ORNL-DWG 79-5638R2 ETD
60
40
20
0
-20
-40
-60
-80
END DEFLECTION (mm)
10
20
30
40
50
LOAD NUMBER
EXPERIMENTAL RESULTS
TRICO (BUNG et al.)
PACE 2 (BOYLE AND SPENCE)
BERSAFE (HELLEN)

Fig 13

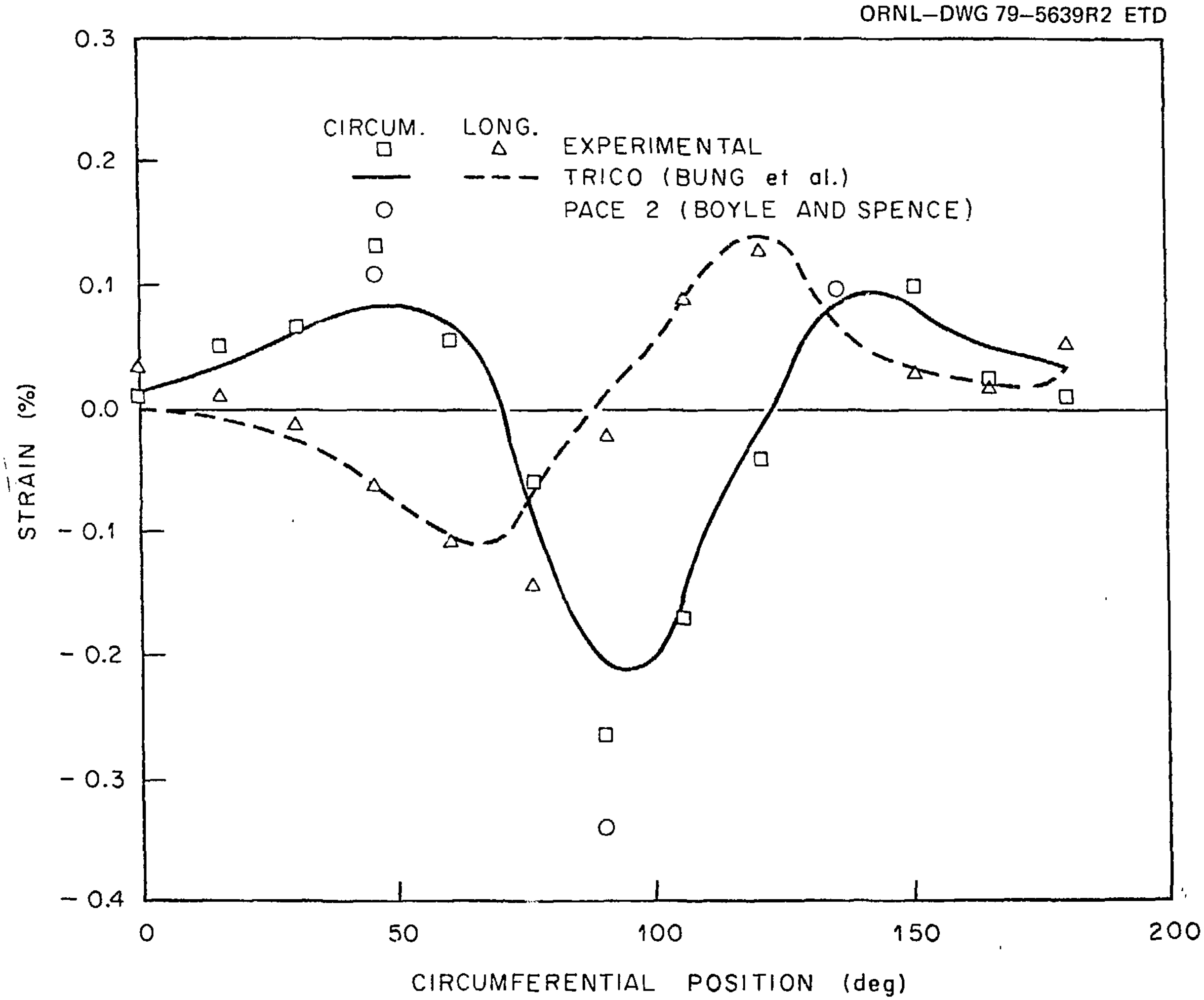
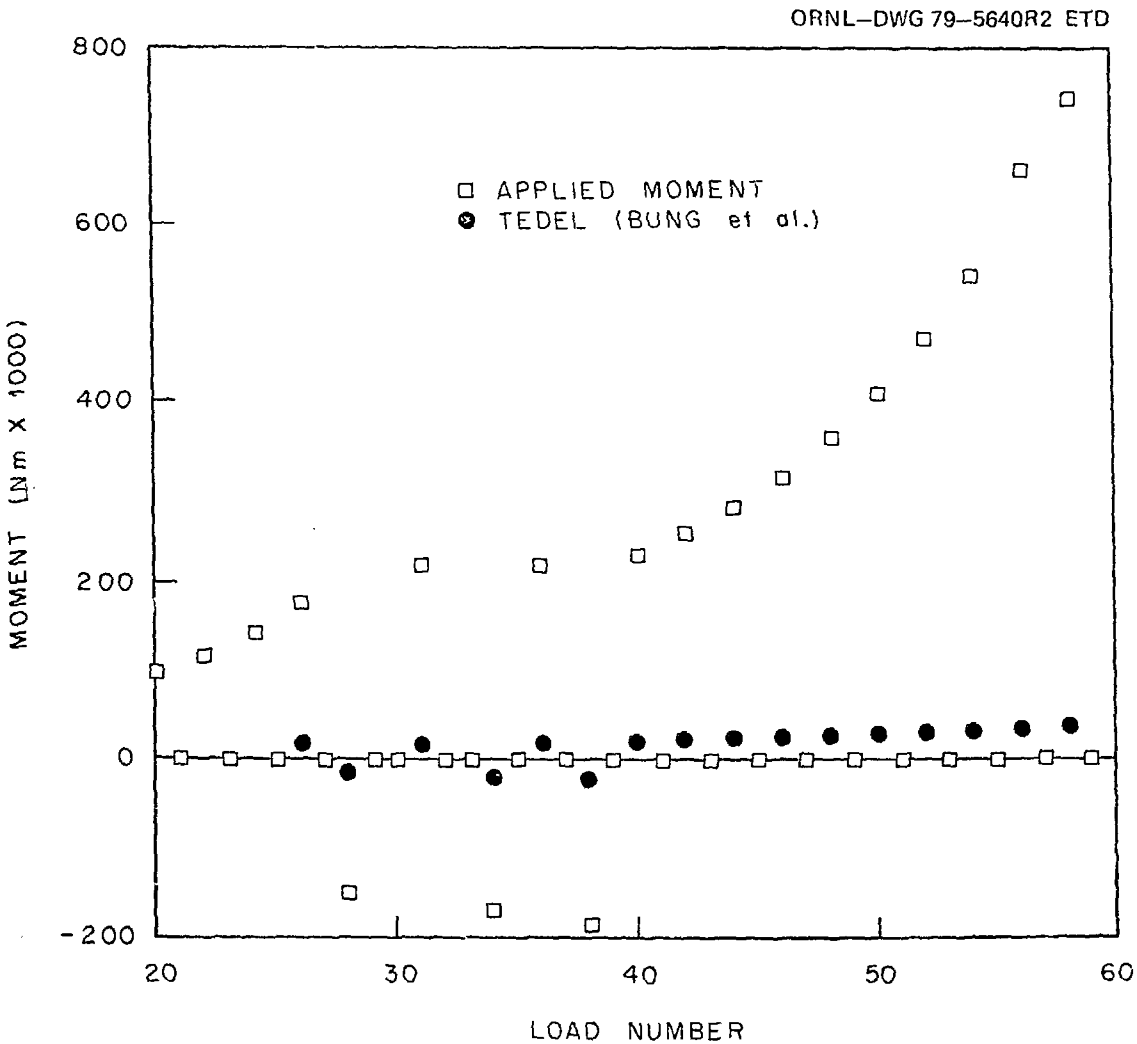

ORNL–DWG 79–5639R2 ETD
CIRCUM.
LONG.
EXPERIMENTAL
TRICO (BUNG et al.)
PACE 2 (BOYLE AND SPENCE)
STRAIN (%)
0.3
0.2
0.1
0.0
– 0.1
– 0.2
– 0.3
– 0.4
0
50
100
150
200
CIRCUMFERENTIAL POSITION (deg)

FIG 14



ORNL–DWG 79–5640R2 ETD
APPLIED MOMENT
TEDEL (BUNG et al.)
MOMENT (Nm X 1000)
800
600
400
200
0
-200
20
30
40
50
60
LOAD NUMBER

FIG. 15