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RESULTS OF THE ROUND ROBIN ON OPENING-LOAD MEASUREMENT

Conducted By

ASTM TASK GROUP E24.04.04 ON CRACK CLOSURE MEASUREMENT AND ANALYSIS

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SUMMARY

An experimental Round Robin on the measurement of the opening load in fatigue crack growth tests has been conducted by the ASTM Task Group E24.04.04 on Crack Closure Measurement and Analysis. The purpose of the Round Robin was to evaluate the current level of consistency of opening load measurements among laboratories and to identify causes for observed inconsistency. Eleven laboratories participated in the testing of compact and middle-crack specimens. Opening-load measurements were made for crack growth at two stress-intensity factor levels, three crack lengths, and following an overload. All opening-load measurements were based on the analysis of specimen compliance data. When all of the results reported (from all participants, all measurement methods, and all data analysis methods) for a given test condition were pooled, the range of opening loads was very large--typically spanning the lower half of the fatigue loading cycle. Part of the large scatter in the reported opening-load results was ascribed to consistent differences in results produced by the various methods used to measure specimen compliance and to evaluate the opening load from the compliance data. Another significant portion of the scatter was ascribed to lab-to-lab differences in producing the compliance data when using nominally the same method of measurement.

INTRODUCTION

Since Elber's paper in 1971 (ref. 1) on the significance of crack closure for the interpretation of fatigue crack growth data, a large number of researchers have published experimental measurements of crack opening or closing loads which they have used in the interpretation of their crack growth results. A variety of experimental techniques including ultrasonics, potential drop, specimen compliance, and photographic methods have been used to characterize the closure behavior. Techniques based on the measurement of compliance have emerged as the most popular approach. However, even for the compliance approach, a number of different compliance measurement and data analysis methods have been used to determine the opening load (ref. 2-4). Considering the number of different approaches being used to determine opening loads, the question arises as to whether all of the approaches produce the same results. Judging from the rather inconsistent body of data on closure behavior in the literature, it appears that either the raw data measurement process is not adequately controlled in the reporting laboratories or that the different experimental techniques and analysis procedures give systematically different results. Admittedly, the actual level of inconsistency is difficult to judge from a review of the literature because data for the same material and test conditions are seldom reported.

This report documents the results of a Round Robin test activity undertaken by the ASTM Task Group E24.04.04 on Crack Closure Measurement and Analysis in an attempt to gain better information on the current level of consistency of opening load measurements among various laboratories (and by inference the consistency of data being reported in the literature) and to identify causes for observed inconsistency. The results will be used to help guide the development of a recommended practice for making opening load measurements that will lead to the production of a more consistent data base in the literature.

ROUND ROBIN TEST PLAN

The intent of the test plan was to specify the test and measurement conditions sufficiently so that opening load measurements would be made by all participants under nominally identical conditions. In addition, the test plan was drawn to provide data for comparisons among measurement and analysis methods as a function of several test parameters such as stress-intensity factor level, crack length, and specimen type. The test plan also called for the measurement of opening loads following a specified overload to provide some insight into the potential utility of the various measurement and analysis methods in interpreting variable-amplitude-loading crack growth results. The detailed Test Plan and instructions for the tests that were sent to all participants are included in this document as Appendix A. The salient features of the tests and analysis methods described in the Test Plan are given below.

The Test Plan defined fatigue crack growth tests on the C(T) and M(T) specimen configurations shown in Figures 1a and 1b respectively. All test specimens were fabricated by the same company from a single plate of 9.5 mm (3/8 inch) thick 2024-T351 aluminum alloy. Specimens were numbered according to their location within the plate and then were allotted to participants by a random draw process. Four tests were defined in the Test Plan -- two using C(T) specimens and two using M(T) specimens. All tests were to be conducted in ambient air at a constant stress ratio (R) of 0.1. One specimen of each type was to be tested at a constant K_{max}=6.6 MPa-$m^{1/2}$ (6 ksi-$in^{1/2}$) and one at K_{max}=22 MPa-$m^{1/2}$ (20 ksi-$in^{1/2}$) for the initial portion of the test. (In the remainder of this report, these tests will be referred to as the low-K and high-K tests respectively.) Crack opening loads were to be measured at three specified crack lengths during the constant K_{max} portion of the tests. After the constant K_{max} portion of the tests, the low-K specimen was to be overloaded to 14.8 MPa-$m^{1/2}$ (13.5 ksi-$in^{1/2}$) and the high-K specimen was to be overloaded to 38.5 MPa-$m^{1/2}$ (35 ksi-$in^{1/2}$). The overloads correspond to overload ratios (OLR) of 2.25 and 1.75 for the low-K and high-K tests respectively. After the single overload, opening loads were to be measured at specified numbers of cycles of the constant-amplitude loading that was being used just before the overload. The opening-load measurement times specified for the tests, either a crack length before the overload or a number of cycles after the overload, are listed in Table 1.

Although the Test Plan did not specify the experimental technique to be used to measure opening loads, it was anticipated that the compliance approach would be used in most of the tests. For participants using the compliance approach, the Test Plan requested that the compliance data be analyzed according to the method of choice of the participant and also according to several other commonly used methods described in the Plan. Of the nine analysis methods and variations of methods identified in the Test Plan, results for only four of the methods are presented in this report. The four methods include three visual, subjective methods--Upper Linear Displacement, Intersection, and Reduced Displacement--and one nonvisual, nonsubjective method identified as Nonvisual(1%). Results for the other five analysis methods cited in the Test Plan are not presented in this report for the following reasons. The Test Plan called for opening-load determinations at the 0.5%, 1%, 2%, and 4% slope-exceedance levels for the Nonvisual method, but the results for only the 1% level are presented because: (1) the trends in differences between the Nonvisual method and the other methods were generally the same at all slope-exceedance levels and (2) including all of the levels would clutter the figures. Data for two of the analysis methods (see Test Plan paragraphs 4.1 and 4.2.3) are not reported simply because too few data were received to be useful.

The four compliance-based opening-load analysis methods that are compared in this report are described below and illustrated in Figures 2a-2d:

(1) Upper Linear Displacement- From a load-displacement plot, determine the load at which the upper portion of the loading curve becomes linear.

(2) Intersection- From a load-displacement plot, determine the load at which a line drawn through the maximum load and tangent to the upper part of the curve intersects with a line drawn through the minimum load and tangent to the lower part of the curve.

(3) Reduced Displacement- From a load-"reduced" displacement plot, determine the load at which the slope of the loading curve becomes equal to the slope of the upper portion of the unloading curve. A "reduced" displacement is the difference between the measured displacement at a given load and the displacement defined by a linear load-displacement relation at the same load.

(4) Nonvisual (1%)- From load-displacement data, evaluate the variation of slope with load and compare the slopes to the average slope for the upper 25% of the load cycle. Determine the maximum load below which the slope is always at least 1% greater than the average slope of the upper portion of the curve. (A more detailed description of the procedure is given in the Test Plan in Appendix A)

It was recognized that the scatter in results that would be reported from the different labs using the compliance approach would have two components--scatter due to differences in collecting the compliance data and scatter due to differences in analyzing the compliance data to evaluate the opening load. It was also recognized that it would be extremely difficult to quantify the two components of scatter based solely on the Round Robin data. To obtain some indication of the scatter in the Round Robin data set due to the analysis methods alone, all participants were provided with identical sets of load-displacement data and asked to determine the opening load using the same analysis methods specified for the experimental Round

Robin. Analysis of the opening load results from the various labs for the same raw data should indicate the differences in mean values and scatter to be expected from the different analysis methods.

ROUND ROBIN DATA SET

One complete set and ten partial sets of test results were received from the participants listed in Table 2. The partial data sets either did not include data for all test conditions or for all analysis methods. All of the participants used measurement of specimen compliance to determine opening loads. Results were reported for measurements made using displacement gages at the crack mouth on C(T) specimens and the specimen centerline on M(T) specimens; strain gages on the back face of C(T) specimens, and an interferometric displacement gage near the crack tip in both C(T) and M(T) specimens.

For analysis purposes, all of the opening-load data were entered in the Round Robin data set as the ratio of the measured opening load to the maximum fatigue load that was being applied just before the opening-load measurement was made. When participants reported multiple measurements for a particular test condition, the mean value of the measurements was entered into the Round Robin data set. The Round Robin data set is tabulated in Appendix B. Participants are identified in the tables by a number assigned to each by a random draw procedure.

Some of the data that were received were not included in the set of data that was analyzed. Data were eliminated if they were not for the test and measurement conditions specified in the Test Plan or if the reported crack growth data indicated that the accuracy of the test loading was suspect. About five percent of the data submitted were discarded for the latter reason.

ANALYSIS OF THE ROUND ROBIN EXPERIMENTAL RESULTS

In this section, the test results from the Round Robin participants are presented: (1) to indicate the current level of consistency in making opening-load measurements among several labs, and (2) to indicate trends in the opening-load results as a function of measurement type, data analysis method, and several test parameters. As expected, the Round Robin data set is too fragmented to support a rigorous statistical analysis of the data. Therefore, an attempt has been made to show trends in the opening-load data by pooling data in various ways and plotting the means and standard deviations of the pooled data sets. The reader is cautioned that inhomogeneous data sets (variables that may influence the comparison are not necessarily held constant in each set) are generally being compared and may indicate trends that are misleading when interpreted alone. Significance should only be attached to those gross trends that are evident across the breadth of the Round Robin data population.

Most of the results are plotted on figures which show the opening-load ratio (ratio of opening load to maximum fatigue load) against test measurement time. Where mean values or standard deviations of opening-load ratios are used, these terms are defined in the usual way as

$$\text{mean value} = \bar{x} = [\sum x_i]/n$$

$$\text{standard deviation} = s = [(\sum(x_i-\bar{x})^2)/(n-1)]^{0.5}$$

where x_i are individual data points and n is the number of data points in the sample.

Overall Consistency

All of the Round Robin opening-load data for the four crack growth tests are shown in Figures 3a-3d. The lines in the figures connect data points representing the same combination of participant, measurement type, and analysis method. With few exceptions, the lines in the figures do not fluctuate up and down very much. This suggests that the large overall scatter shown in the figures is mainly due to systematic differences among labs, measurement types, and analysis methods. It is felt that the large scatter in results shown in these figures represents the potential scatter that might be reported in the literature because data from all of the measurement types and analysis methods represented in the figures are also represented in the literature. Scatter of this magnitude would make it very difficult to develop a clear picture of closure effects and to verify quantitative models of closure effects using data from the literature.

Effect of Compliance Measurement Type

The following types of compliance measurement were used in the Round Robin:
(1)Crack opening displacement (COD) gages at the crack mouth of C(T) specimens and at the centerline of M(T) specimens, (2)strain gages on the back face (BFS) of C(T) specimens, and (3)interferometric displacement gages (IDG) located 0.05-0.08 mm (0.002-0.003 in.) behind the crack tip on both types of specimen. The opening-load data from all participants and all analysis methods were pooled to detect any trends in results due to measurement type. The mean values of the pooled data are shown in Figures 4a-4c for the two C(T) tests and the one M(T) test for which comparative data were available. From these results, it appears that there are no consistent differences in the results from the COD and BFS measurements made on C(T) specimens, but the IDG does appear to give consistently higher values of opening load than the COD approach on both types of specimen. The scatter in opening-load values from each of the measurement types is shown in Figures 5a-5c. These results do not indicate any consistent differences in scatter among the COD, BFS, and IDG methods.

Effect of Data Analysis Method

The opening-load data from all participants and all measurement types were pooled to detect any trends in results due to method of data analysis. The mean values of the pooled data are shown in

Figures 6a-6d. These results indicate that there are systematic differences in the opening-load values determined by the four analysis methods. The Intersection method consistently produced the lowest opening-load values, the Upper Linear Displacement method consistently produced the second-lowest values, while the Reduced Displacement and Nonvisual(1%) methods produced about the same values overall. The scatter in opening-load values from each of the analysis methods is shown in Figures 7a-7d. In the C(T) test results, the Reduced Displacement method appears to show more scatter than the other three methods, which are all about the same. No consistent differences in scatter due to analysis method are discernible in the plots for the M(T) specimen.

Effect of Overload

All of the data in the previously presented figures were examined to determine whether different measurement types and analysis methods showed the same capability to detect the effects of an overload on subsequent opening-load behavior. In both the C(T) and M(T) low-K tests, none of the measurement types or analysis methods showed a systematic change in the opening loads after the overload , even though the crack growth showed a large drop in rate or even arrest in some cases. These results suggest that either the opening-load detection methods were not sufficiently sensitive to detect the changes in closure behavior or that closure mechanisms were not responsible for the drop in growth rates. In both the C(T) and M(T) high-K tests, all of the measurement types for which data were available showed a trend towards higher opening load values following the overload, although the changes in values were not very pronounced in some cases. Three of the four analysis methods showed a trend towards higher values, but the trend was not found by all participants and this is reflected in the higher scatter in the results following the overload. The Intersection method consistently showed no change in results following the overload.

Effects of Other Variables

The Round Robin results were also examined to detect whether there were effects of specimen type, K level, and crack length on the measured opening loads. No consistently large effects were evident for any of these variables but there were hints in the data that small effects might exist. Most notable were the tendencies in the C(T) specimen towards lower opening-load values for higher K levels and towards lower scatter in the results at the longer crack lengths (before overload).

ANALYSIS OF IDENTICAL COMPLIANCE DATA BY SEVERAL PARTICIPANTS

Identical load-displacement data were sent to several labs for evaluation of opening loads by the four analysis methods described earlier in this report. These results should provide a good indication of systematic differences in the mean values and the scatter of opening-load values produced by the different analysis methods. Load-displacement data for seven complete load cycles were selected for analysis. Data for six of the load cycles were taken during the Round Robin and represent a variety of the test conditions specified for opening-load measurements on C(T) specimens. The load-displacement data for one of the load cycles was generated analytically using displacements calculated from the crack closure model in ref. 5. The analytical load-displacement data contain no experimental artifacts that might influence the analyses. Analysts of the data were not told that one of the data sets was generated analytically. Lists of the test conditions for the individual load cycles (data sets) and the participating analysts are given in Tables 3 and 4 respectively.

The mean values of the opening loads evaluated by the four analysis methods are shown in Figure 8a. These results indicate that there are systematic differences in the opening-load values produced by the different analysis methods. The Intersection method produced the lowest values, the Upper Linear Displacement method produced the second-lowest values, and the other two methods (Reduced Displacement and Nonvisual(1%)) produced about the same values. The trends in the results are the same as noted for the Round Robin data set shown in Figures 6a-6d. The analytically-generated load-displacement data (data set 7) had a known, numerically-defined opening load. Therefore, analysis results from data set 7 should give some indication of the relative capability of the various analysis methods to detect the actual opening loads. As indicated in Figure 8a, all four of the Round Robin analysis methods substantially underestimated the opening load -- with the values from the Reduced Displacement method being closest and the Intersection method being farthest from the analytical value.

The standard deviations of the opening loads evaluated by the four analysis methods are shown in Figure 8b. These results indicate that the Reduced Displacement and the Upper Linear Displacement methods produced substantially more scatter in results than the Intersection and Nonvisual(1%) methods. The low scatter in the Intersection results was a bit surprising because it had been expected that all three of the subjective analysis methods would show more scatter than the nonsubjective Nonvisual method. The analysis of the scatter in the Round Robin data set had also shown large scatter for the Reduced Displacement method, but had shown essentially no differences among the other three methods. It is not clear why the results from the Round Robin data set did not show higher scatter for the Upper Linear Displacement method than the Intersection and Nonvisual methods, but the inhomogeneity of the Round Robin data set could have caused the difference to be obscured.

DISCUSSION

As mentioned earlier, an objective of the Task Group is to develop recommended procedures for measuring opening loads and to encourage their use. The motivation for developing the procedures is to improve the consistency of the opening-load data being published in the literature. The current Round Robin serves as the first step towards meeting the Task Group objectives by providing results that document the current level of consistency, indicate some directions for improving the consistency, and identify areas where further work is required.

Considering the differences in results (both mean values and scatter) obtained from the different analyses, an obvious way to improve the consistency beyond that shown in Figures 3a-3d would be to use only one analysis method for all measurements. Also, since the data suggest that the values obtained by the IDG measurements of compliance near the crack tip are different from those obtained by COD and BFS measurements, the consistency could be further improved by segregating the data population into groups representing measurements remote from the crack tip and near the crack tip. The potential improvement in consistency to be gained by using only one analysis method and only remote compliance measurements is indicated in Figures 9a-9b using the data from the Round Robin tests on C(T) specimens. The analysis method chosen for illustration in Figures 9a-9b is the Nonvisual method because common sense would indicate that a nonsubjective analysis should produce the most reproducible results (experimental accuracy being equal) and, indeed the results discussed earlier tend to confirm that. As expected, the standard deviations of opening loads for the restricted data set are consistently less than those for the all-inclusive data set. To give an idea of how much further improvement in consistency might be made if experimental accuracy was the same for all labs, the standard deviations from analysis of the identical data sets (Figure 8b) using the Nonvisual(1%) method are also plotted in Figures 9a-9b. From these results, it appears that recommended procedures for obtaining uniformity in compliance data among labs is necessary to achieve high levels of consistency.

The accuracy of the opening-load measurements reported in the Round Robin cannot be determined at present because an accepted method of establishing the "true" opening load does not exist. Actually, for most cases the crack does not open along the entire crack front at a single load, but rather it opens incrementally over a range of load. Therefore, a question concerning the accuracy of the kind of opening-load measurements made in the Round Robin will always remain. Nevertheless, when considered as an "effective" opening load representing the effects of closure along the entire crack front, the single-load opening characterization may be useful in correlating crack growth data and interpreting phenomenological effects in crack growth tests. That being the case, it would seem worthwhile to identify and promote the use of a well-defined, nonsubjective measurement procedure to assure the production of consistent opening-load values in different laboratories.

CONCLUSIONS

The following conclusions are based on the results from the Round Robin on crack opening-load measurement conducted by ASTM Task Group E24.04.04:

1. When all of the measured opening loads (from all participants, all measurement types, and all analysis methods) for a given test condition (specimen type, K level, and crack length) were pooled,

the range of opening loads was very large--typically spanning the lower half of the range of the fatigue loading.

2. The opening loads measured using certain compliance measurement methods and data analysis methods were systematically different from those measured using the other methods. These systematic differences were largely responsible for the large scatter in the pooled results described in conclusion 1.

3. Of the four analysis methods used to determine the opening load from the load-displacement data, the Intersection method systematically produced the lowest values for opening load, the Upper Linear Displacement method systematically produced the second-lowest values, and the other two methods (Reduced Displacement and Nonvisual(1%)) produced about the same values. This trend was noted in the analysis of the load-displacement data from the various participants in the Round Robin and in the analysis of identical load-displacement data by several participants.

4. The opening loads derived from the Interferometric Displacement Gage compliance measurements made near the crack tip appeared to be higher than the opening loads derived from crack-mouth-opening and back-face-strain compliance measurements made remote from the crack tip.

5. Results of the analysis of identical load-displacement data by several participants indicated that use of the Intersection and Nonvisual(1%) analysis methods resulted in very little scatter in reported opening loads, whereas the Upper Linear Displacement and Reduced Displacement methods produced considerably greater scatter in results.

6. When only those Round Robin opening load results based on compliance data taken remote from the crack tip and analyzed by the Nonvisual(1%) method were pooled, the scatter in the results was substantially less than the scatter for the overall data set described in conclusion 1. This result indicates the potential improvement in consistency of published opening load data that could be achieved by widespread use of a single data analysis method by the research community.

7. Substantial lab-to-lab differences were also noted in the Round Robin results. To achieve a high level of consistency among labs, procedures to assure the generation of acceptably uniform load-displacement data in the various labs must be developed and implemented.

8. The capability to detect changes in opening load behavior following an overload was not consistent among labs--even among those using the same compliance measurement and analysis methods. Among the analysis methods, the Intersection method was the only one that did not show a general trend towards higher opening loads following the overload in the high K test of the C(T) specimen.

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5. Newman, J. C., Jr. : A Crack-Closure Model for Predicting Fatigue Crack Growth under Aircraft Spectrum Loading. Methods and Models for Predicting Fatigue Crack Growth under Random Loading, ASTM STP 748, American Society for Testing and Materials, 1981, pp. 53-84.

Table 1.- Opening-load measurement times specified for the Round Robin tests

	Crack Lengths	
Figure Caption	C(T) a, mm(in.)	M(T) a, mm(in.)
CL1	25.4(1.00)	12.7(0.50)
CL2	27.9(1.10)	15.2(0.60)
CL3	38.1(1.50)	25.4(1.00)

	Cycles After Overload	
Figure Caption	Low-K Test	High-K Test
N0	0	0
N1	2.5×10^4	2.5×10^2
N2	5.0×10^4	5.0×10^2
N3	1.0×10^5	1.0×10^3
N4	2.0×10^5	2.0×10^3
N5	4.0×10^5	4.0×10^3

Table 2.- Participants in Round Robin

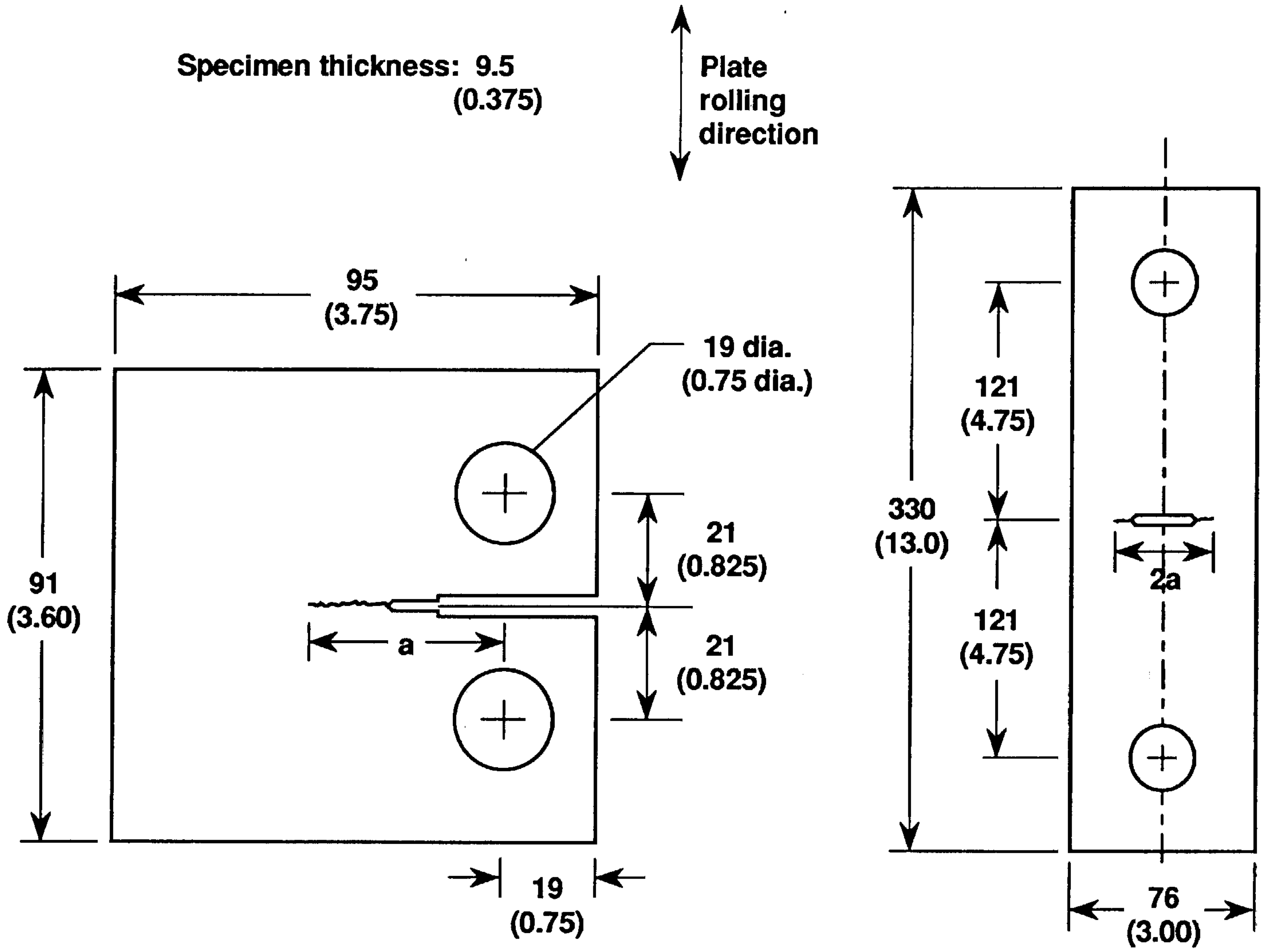
Participants	Affiliations
Noel Ashbaugh	University of Dayton Research Institute
Anders Blom	FFA (Sweden)
Keith Donald	Fracture Technology Associates
Alten Grandt	Purdue University
Linda Link	David Taylor Research Center
George Miller	PSG, Inc.
Matt Miller	Boeing Commercial Airplane Company
Ed Phillips	NASA Langley Research Center
Bill Sharpe	Johns Hopkins University
Ralph Stephens	University of Iowa
Dale Wilson	Tennessee Technological University

Table 3.- Round Robin test conditions represented in load-displacement data analyzed by several participants

Data Set	Test Condition
1	Low K, CL3, BFS
2	Low K, CL3, COD
3	High K, N4, BFS
4	High K, CL1, COD
5	High K, NO, BFS
6	Low K, N4, BFS
7	(Analytically generated)

Table 4.- Analysts of identical load-displacement data

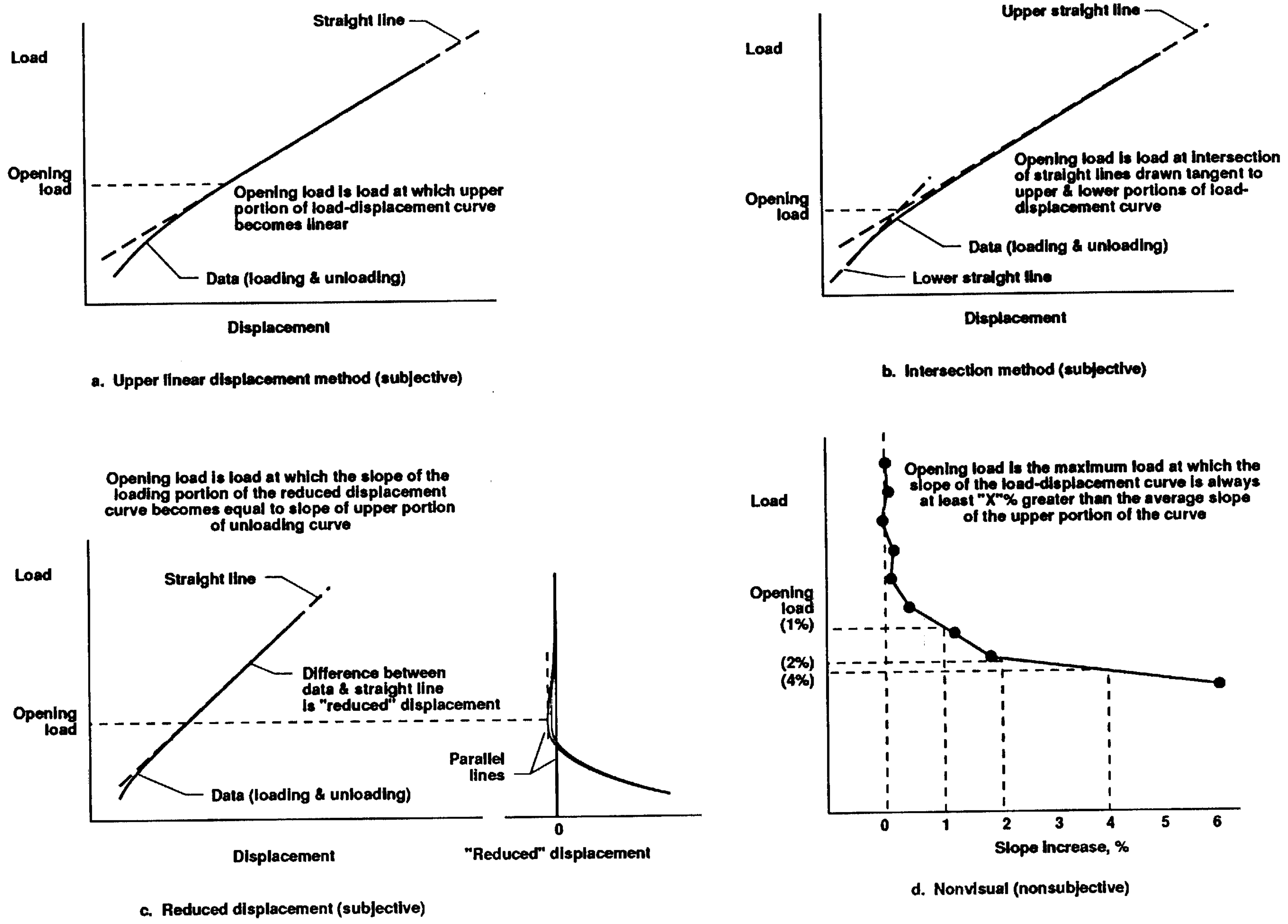
Participant	Affiliation
Noel Ashbaugh	University of Dayton Research Institute
Linda Link	David Taylor Research Center
Matt Miller	Boeing Commercial Airplane Company
Ed Phillips	NASA Langley Research Center
Bill Sharpe	Johns Hopkins University



a. C(T) specimen

b. M(T) specimen

Figure 1.- Specimen configurations used in the Round Robin. (dimensions in millimeters (inches))



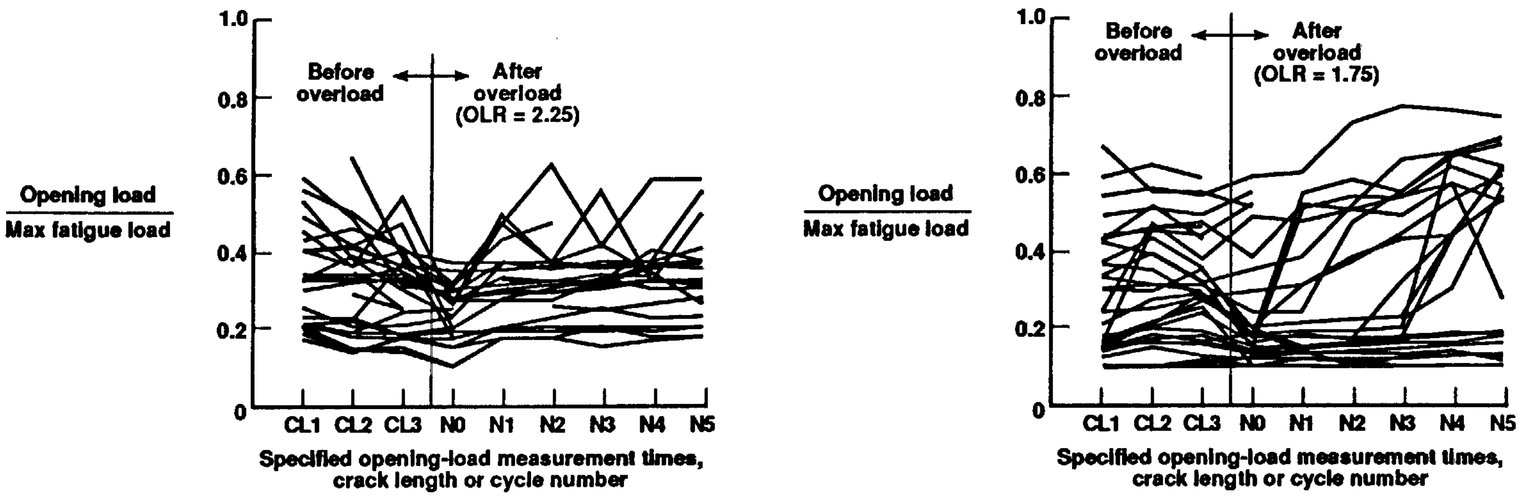
a. Upper linear displacement method (subjective)

b. Intersection method (subjective)

c. Reduced displacement (subjective)

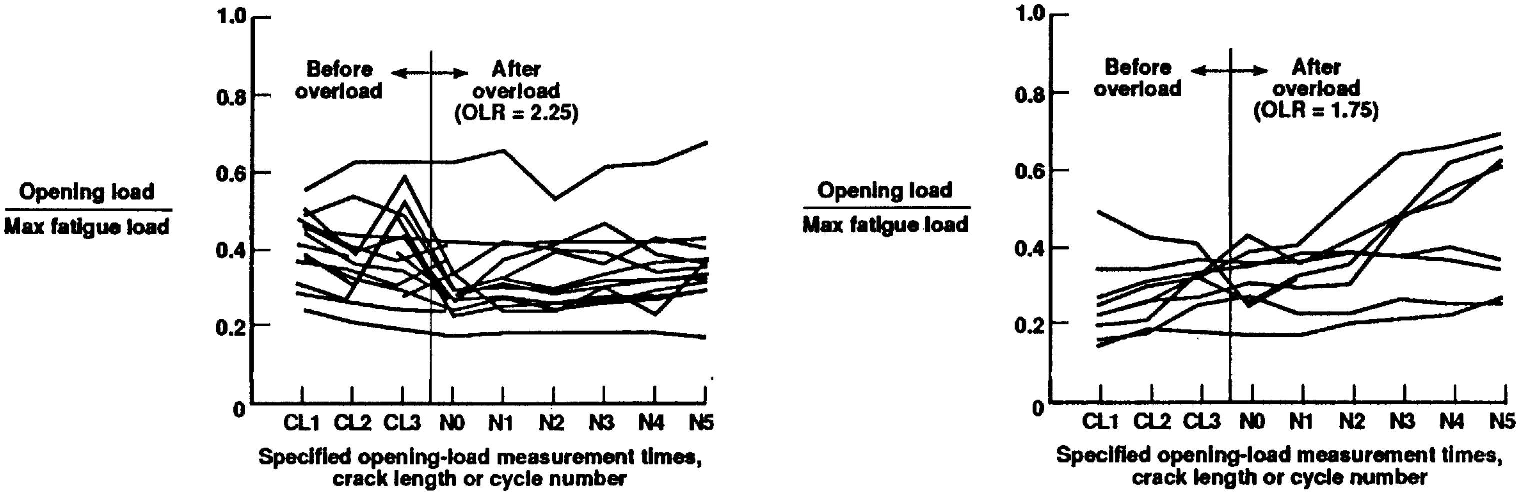
d. Nonvisual (nonsubjective)

Figure 2.- Illustrations of the four methods used in the Round Robin to evaluate the opening load from load-displacement data.



a. Low-K test of C(T) specimen

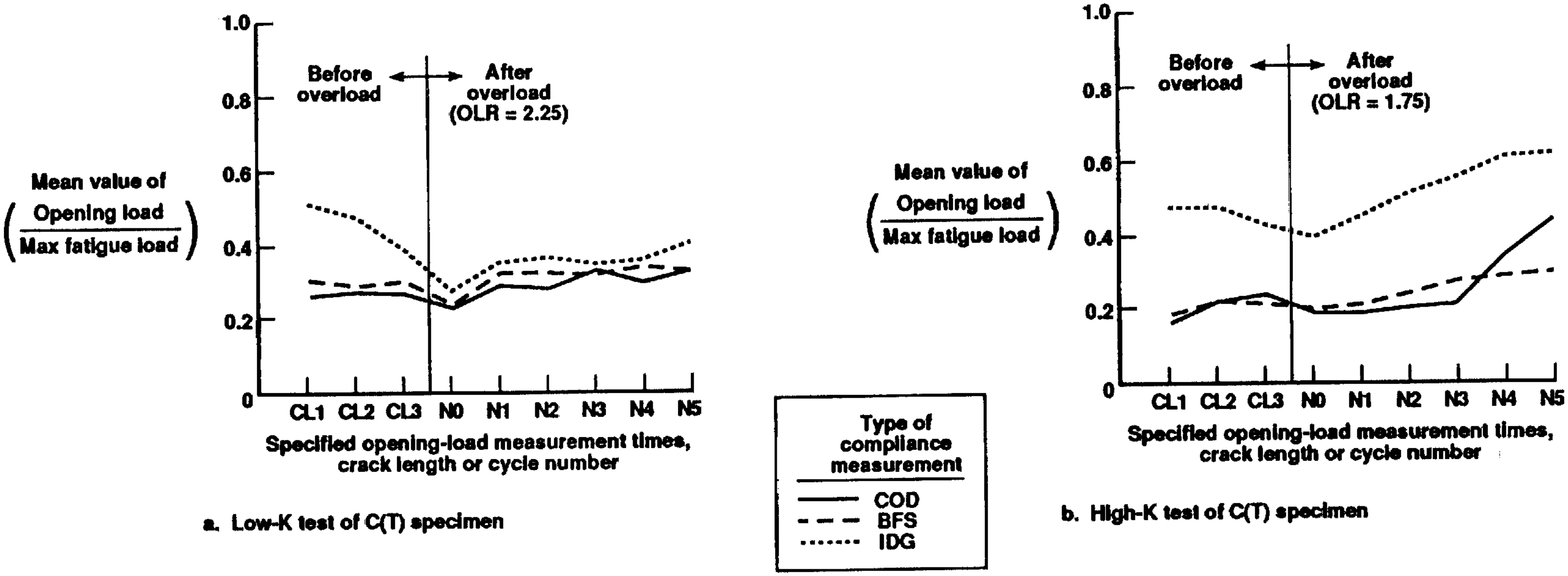
b. High-K test of C(T) specimen



c. Low-K test of M(T) specimen

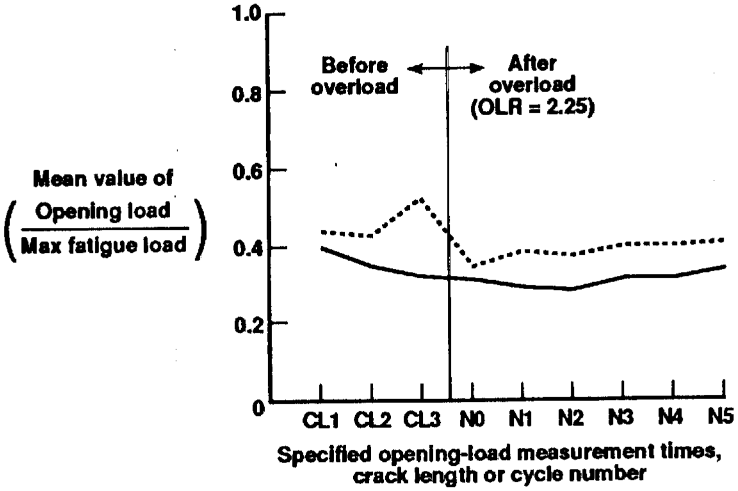
d. High-K test of M(T) specimen

Figure 3.- All opening load data received for each of the Round Robin tests. (lines connect data from same combination of participant, measurement type, and analysis method)



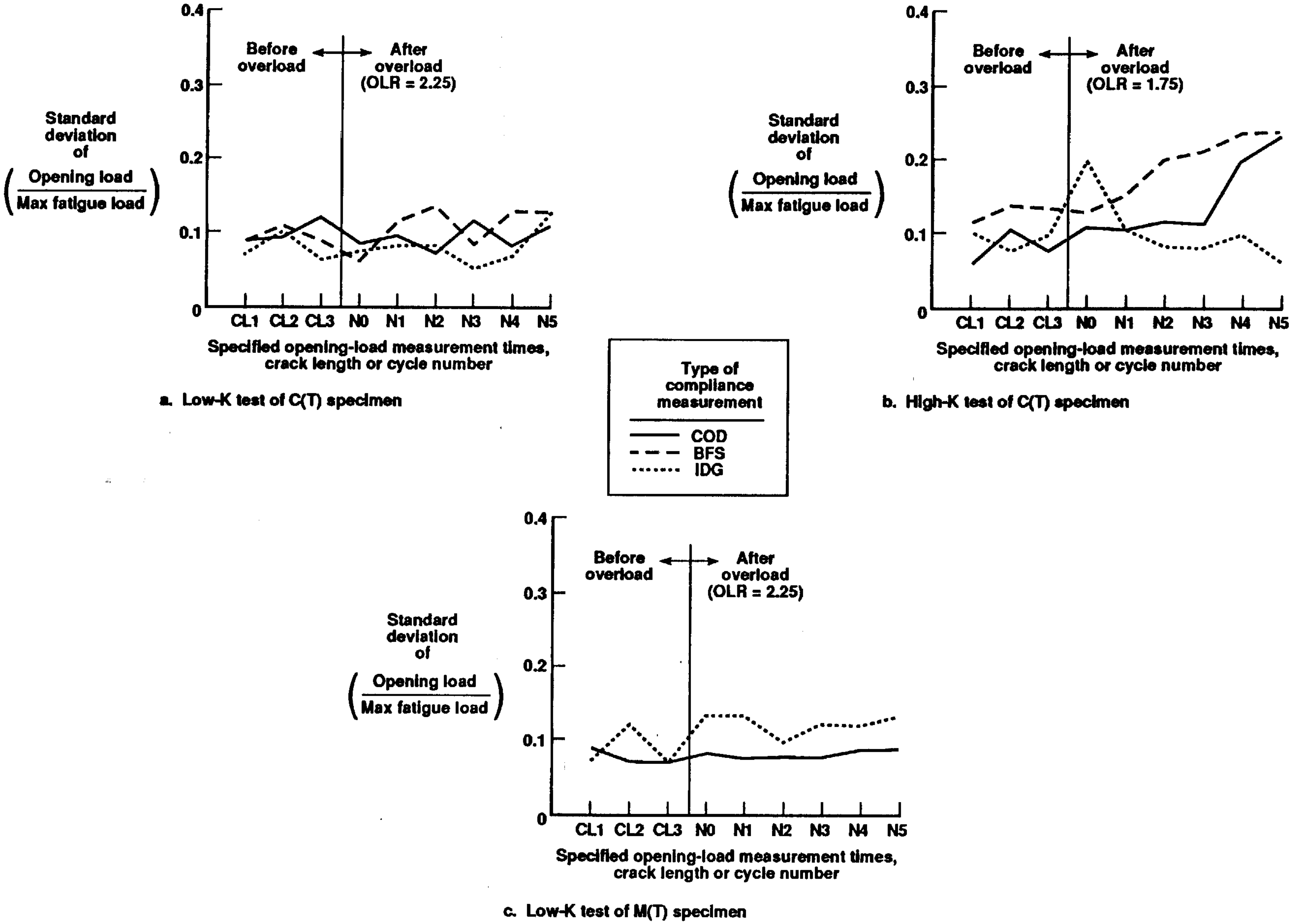
a. Low-K test of C(T) specimen

b. High-K test of C(T) specimen



c. Low-K test of M(T) specimen

Figure 4.- Effect of type of compliance measurement on opening load results. (pooled data from all participants and analysis methods)

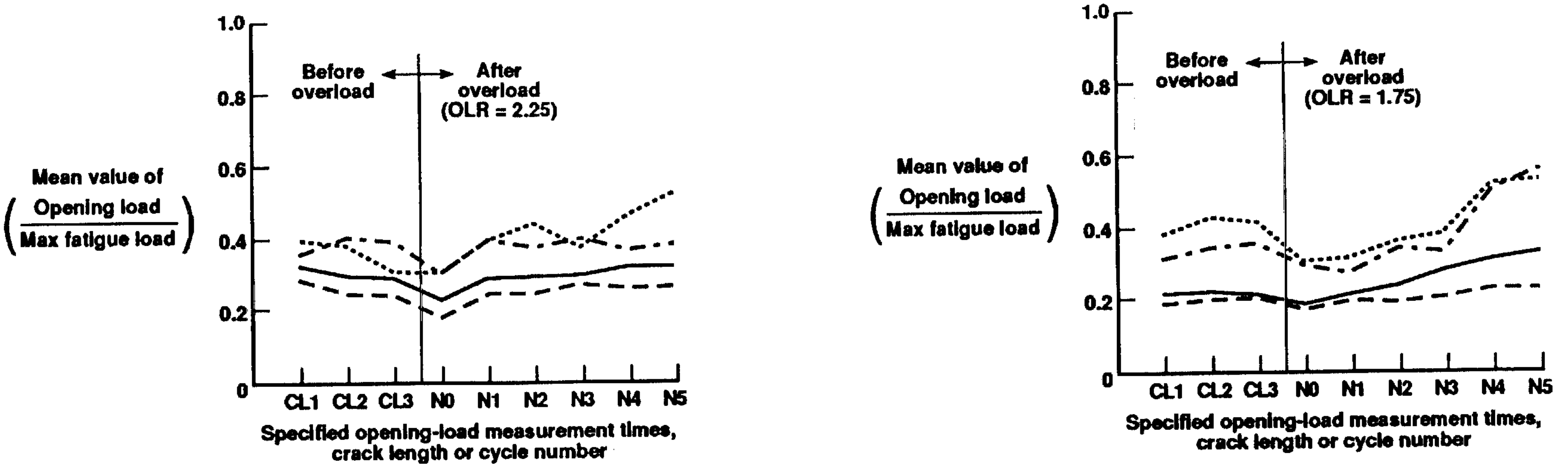


a. Low-K test of C(T) specimen

b. High-K test of C(T) specimen

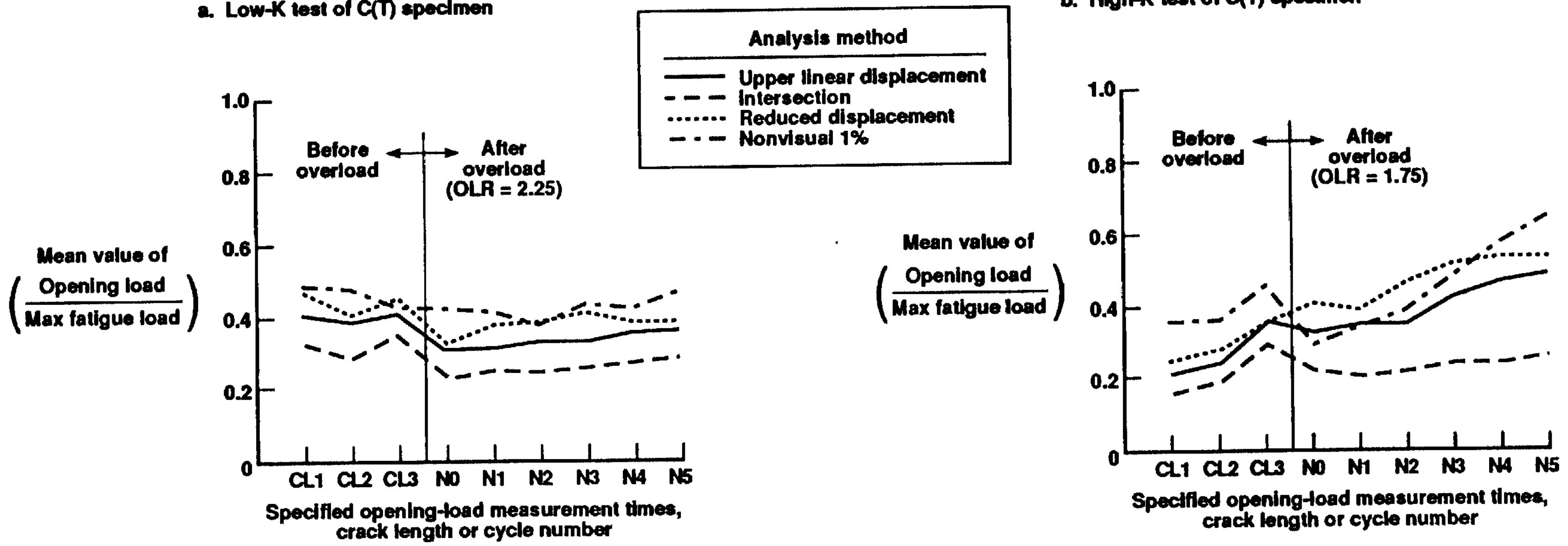
c. Low-K test of M(T) specimen

Figure 5.- Effect of type of compliance measurement on the scatter in the opening load results. (pooled data from all participants and analysis methods)



a. Low-K test of C(T) specimen

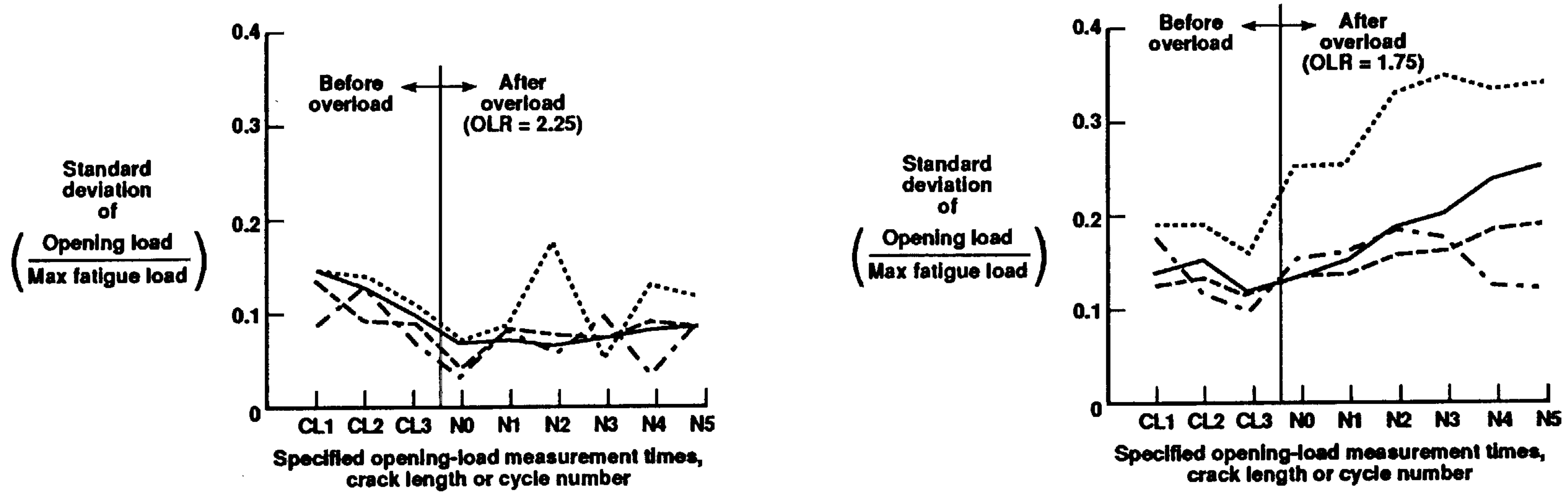
b. High-K test of C(T) specimen



c. Low-K test of M(T) specimen

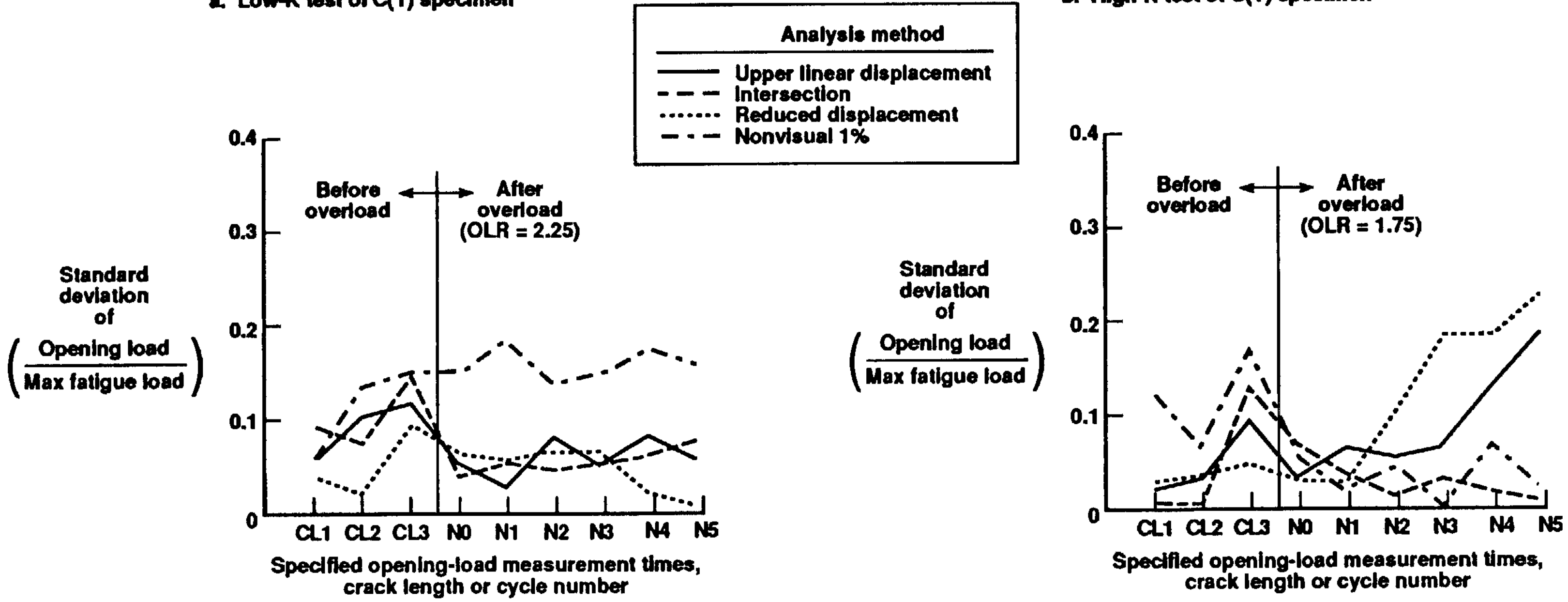
d. High-K test of M(T) specimen

Figure 6.- Effect of data analysis method on opening-load results. (pooled data from all participants and types of compliance measurement)



a. Low-K test of C(T) specimen

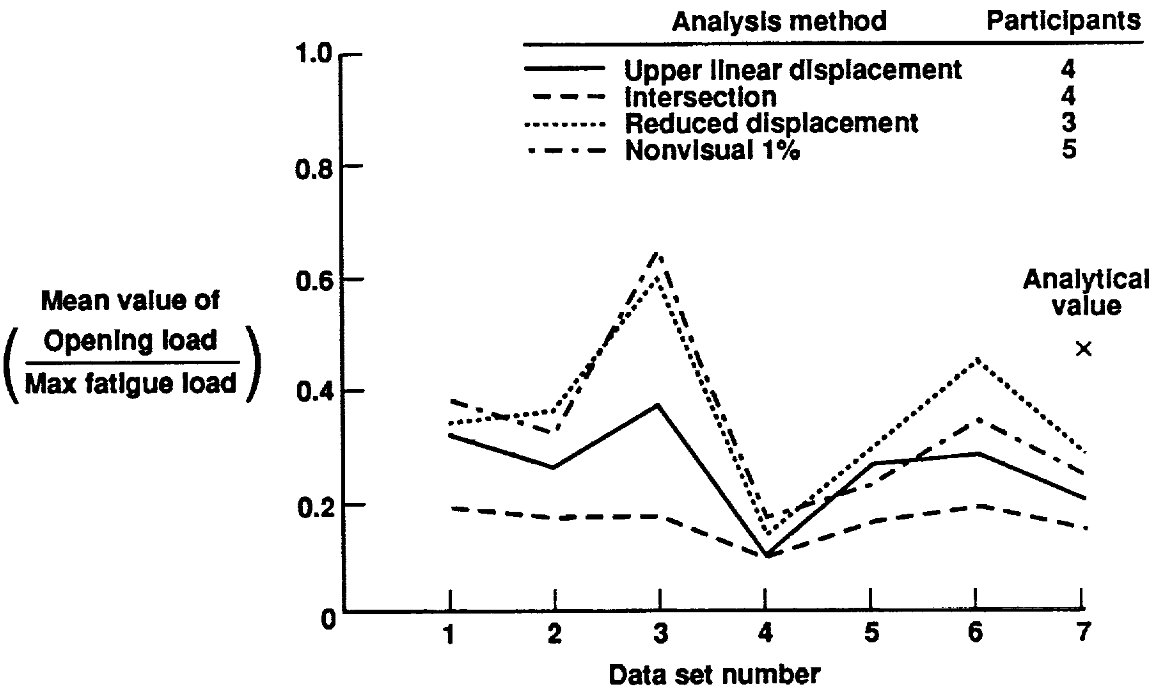
b. High-K test of C(T) specimen



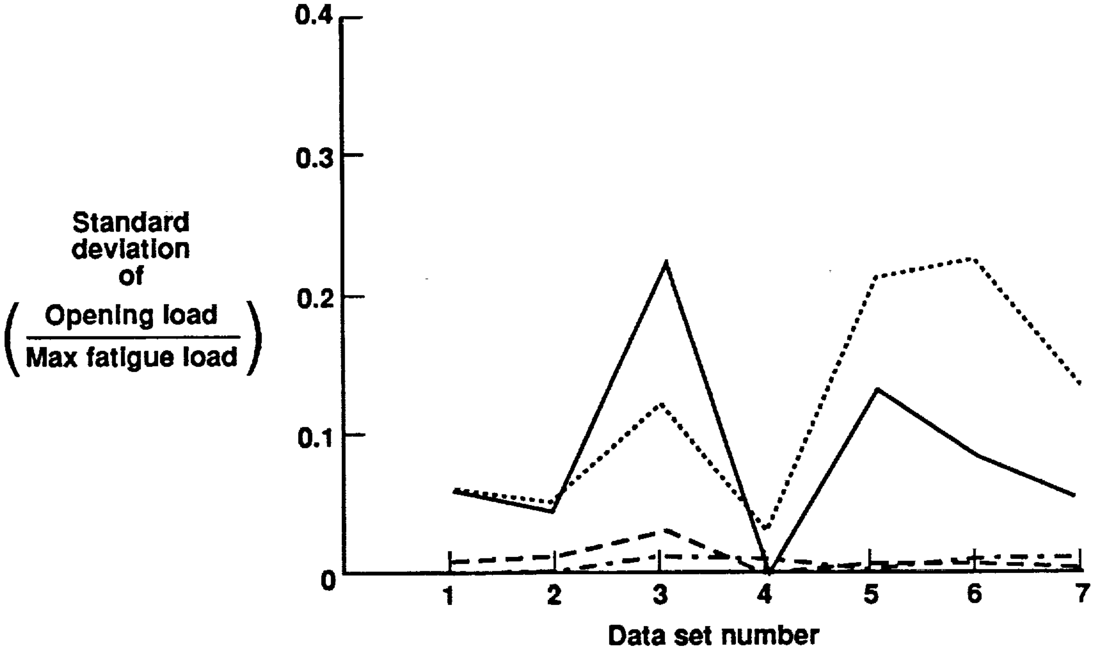
c. Low-K test of M(T) specimen

d. High-K test of M(T) specimen

Figure 7.- Effect of data analysis method on the scatter in the opening load results. (pooled data from all participants and types of compliance measurement)

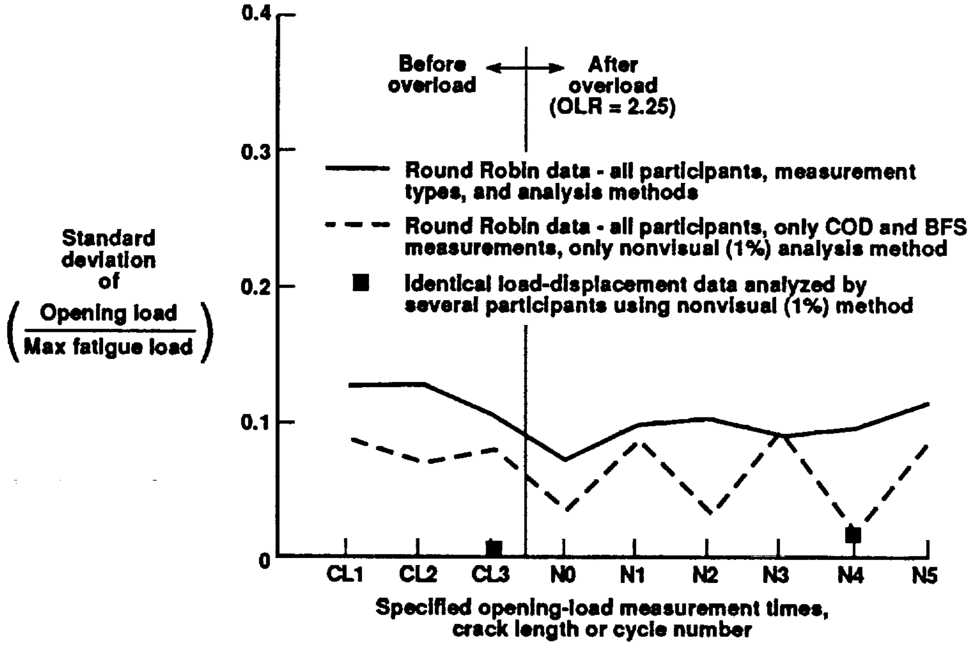


a. Effect on mean values

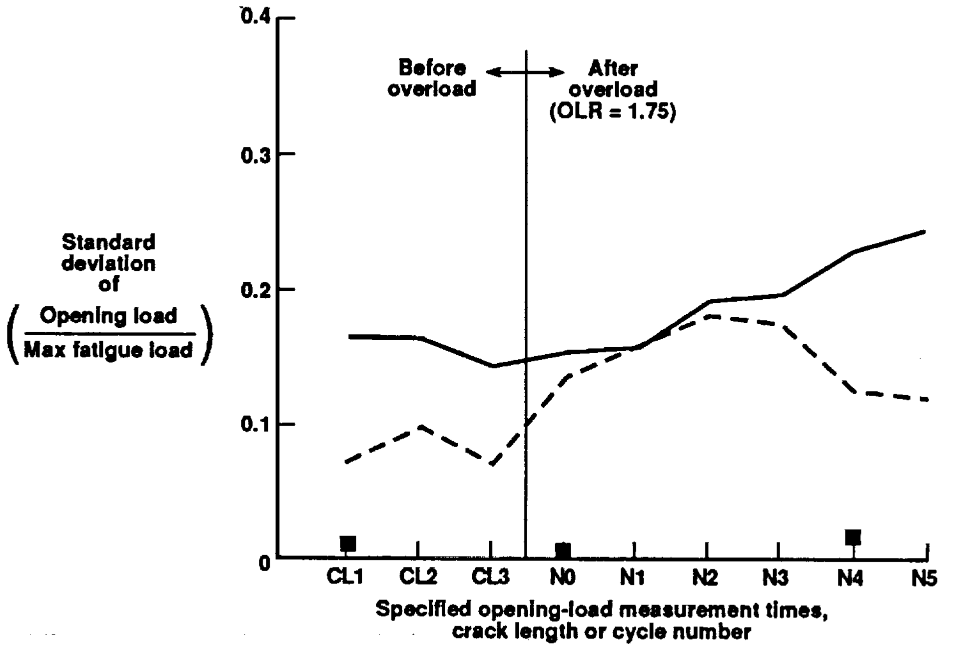


b. Effect on scatter

Figure 8.- Effect of data analysis method on the mean values and scatter of opening loads determined from evaluation of identical load-displacement data sets by several participants.



a. Low-K test of C(T) specimen



b. High-K test of C(T) specimen

Figure 9.- Scatter in measured opening loads for all Round Robin data, for a subset of Round Robin data, and for identical load-displacement data sets analyzed by several participants using the Nonvisual (1%) method

APPENDIX A

Test Plan and Instructions for E24.04.04 Round Robin on Crack Opening Load Measurement

General Description

This experimental Round Robin program is being conducted to determine the current level of consistency of crack opening load measurement among laboratories and to obtain data to guide development of a recommended practice for opening load measurements. The test program consists of tests on two C(T) and two M(T) specimens that are being provided to the participants. Stress intensity histories have been specified for each specimen such that one specimen will exhibit a nearly-constant, low growth rate and the other specimen will exhibit a nearly-constant, high growth rate for most of the test. Crack opening loads are to be measured at three specified crack lengths during the constant-rate portion of the test. After the constant-rate portion of the test, a specified overload is to be applied and then opening loads are to be measured at specified cyclic intervals following the overload. Participants using load-displacement data to determine the opening load are to determine the opening load using several specified data analysis methods.

Detailed Description

1. Material and Specimens

   1.1 Material - Single plate of 3/8 inch thick 2024-T351 aluminum alloy.

   1.2 Specimens - C(T) and M(T) (See Figures A1 and A2).

   Note 1: The initial crack starter configuration may be modified to accommodate a participant's particular measurement apparatus as long as the length of the notch is not increased and the configuration remains consistent with the guidelines of ASTM Standard E647.

   Note 2: The M(T) specimen can be tested by using either clamping-type grips or a pin/clevis arrangement.

2. Displacement Measurement Methods

   All methods with which the participant has experience (COD gages, CMOD gages, back-face strain gages, laser interferometry, strain gages across crack, scribe marks, etc.)

3. Displacement Measurement Locations

3.1 C(T) specimen - Crack mouth, back face and as many other locations as possible.

3.2 M(T) specimen - Specimen centerline and as many other locations as possible.

4. Procedures for Evaluation of Opening Load from Displacement Data

4.1 Customary method

Evaluate opening loads using the method you would use if you published a report today.

4.2 Visual (subjective) methods

4.2.1 From a load-displacement plot, determine the load at which the upper portion of the loading curve becomes linear. (See Figure A3)

4.2.2 From a load-displacement plot, determine the load at which a line drawn through maximum load tangent to the upper part of the curve intersects with a line drawn through the minimum load tangent to the lower part of the curve. (See Figure A4)

4.2.3 From a load-displacement plot, determine the load at which the slope of the loading curve becomes equal to the slope of the upper portion of the unloading curve. (See Figure A5)

4.2.4 From a load-"reduced" displacement plot, make the same determination as in 4.2.3. A "reduced" displacement is the difference between the measured displacement at a load and the displacement defined by a linear load-displacement relation at the same load. (See Figure A6)

4.3 Nonvisual (nonsubjective) method

1. Collect load-displacement digitized data for a complete load cycle. At least 100, preferably more, data pairs should be taken to describe the load-displacement curve.

2. Starting with the first data sample below maximum load on the unloading curve, fit a least-squares straight line to a segment of the curve spanning approximately the uppermost 25 percent of the cyclic load range. The slope of this line is assumed to correspond to the fully-open crack configuration.

3. Starting with the first data sample below maximum load on the loading curve, fit least-squares straight lines to

segments of the curve that span approximately 10 percent of the cyclic load range and that overlap each other by approximately 5 percent of range (See Figure A7). Store the slope and corresponding mean load for each segment in an array.

4. Starting with the first (highest load) slope in the array, compare the slopes to the open-crack slope and identify the location in the array beyond which the slopes always exceed the open-crack slope by at least a specified percentage.

5. Starting at the array location identified in Step 4, find the nearest, higher-load array location beyond which the slope is always less than the criterion level in Step 4.

6. Determine the opening load corresponding to the specified exceedance criterion by interpolating between the two slope-load points identified in Steps 4 and 5. (See Figure A8)

For the Task Group test program, opening loads should be evaluated for several exceedance level criteria. I suggest levels of 0.5, 1, 2, and 4 percent.

5. Methods of Opening Load Determination Not Based on Displacement Data

Participants are encouraged to make measurements by all methods that they feel are viable approaches.

6. Test and Measurement Conditions

6.1 Ambient laboratory environment

6.2 Test loads

The K_{max} and R values are to be maintained constant at the specified values during the initial part of the test by shedding load either by manual or computer control. If manual control is used, the increment of crack growth at each crack tip between adjustments to the load should be nominally 0.02 inches and should not exceed 0.03 inches. Stress intensity factors should be calculated according to the equations and methods given in Standard E647. Determine the initial loads for the test by using the specified constant-K_{max} value with assumed crack lengths of: a=0.90 inches for the C(T) specimen, and 2a=0.80 inches for the M(T) specimen. Maintain the initial loads until cracks are detected on both surfaces at the end(s) of the EDM slot. Load shedding should begin at this point and continue until: a=1.50 inches for the C(T) specimen and 2a=2.00 inches for the M(T) specimen.

6.2.1 R=0.1 for all fatigue loading.

6.2.2 Low growth rate specimen

- o Constant-K_{max} = 6.0 ksi-in$^{1/2}$
- o Overload-K_{max} = 13.5 ksi-in$^{1/2}$
  Apply a single load cycle such that the stress intensity factor cycles from 0.6 to 13.5 to 0.6 ksi-in$^{1/2}$.
- o After overload
  After the overload, the fatigue loading should be R=0.1, constant-amplitude loading such that K_{max} = 6.0 ksi-in$^{1/2}$ for the crack length immediately after the overload.

6.2.3 High growth rate specimen

- o Constant-K_{max} = 20.0 ksi-in$^{1/2}$
- o Overload-K_{max} = 35.0 ksi-in$^{1/2}$
  Apply a single load cycle such that the stress intensity factor cycles from 2.0 to 35.0 to 2.0 ksi-in$^{1/2}$
- o After overload
  After the overload, the fatigue loading should be R=0.1, constant-amplitude loading such that K_{max}= 20.0 ksi-in$^{1/2}$ for the crack length immediately after the overload.

6.3 Opening load measurements

6.3.1 Low growth rate specimen

- o At crack length no.1- C(T): a=1.00 +or- 0.01 inches
  M(T): 2a=1.00 +or- 0.01 inches
  Make multiple, independent crack opening load measurements (preferably as many as 10). If the measuring apparatus does not normally remain in place during the fatigue loading, then it should be removed and remounted for each measurement. If load-displacement data are taken, make recordings during load cycles that have max. load = 40, 70, and 100 percent of the max. load for the last increment of fatigue crack growth before the opening load measurements. The min. load in the recording cycles should not go below the min. fatigue load for the last growth increment.

- o At crack length no.2 - C(T): a=1.10 +or- 0.01 inches
  M(T): 2a=1.20 +or- 0.01 inches

  (Same instructions as at length no.1)

- o At crack length no.3 - C(T): a=1.50 +or- 0.01 inches
  M(T): 2a=2.00 +or- 0.01 inches

  (Same instructions as at length no.1)

- o At the overload length-C(T): a=1.50 +or- 0.01 inches
  M(T): 2a=2.00 +or- 0.01 inches

  After making the opening load measurements at length no.3, apply the specified single overload cycle. Then at 0, 2.5×10^4, 5×10^4, 1×10^5, 2×10^5, and 4×10^5 total fatigue cycles after the overload, make opening load measurements during load cycles that go to 100 percent of the post-overload max. fatigue load.

6.3.2 High growth rate specimen

- o At crack length no.1 - C(T): a=1.00 +or- 0.01 inches
  M(T): 2a=1.00 +or- 0.01 inches

  (Same instructions as for crack length no.1 for low growth rate specimen except only record load-displacement data during load cycles to the 100 percent fatigue load level.)

- o At crack length no.2 - C(T): a=1.10 +or- 0.01 inches
  M(T): 2a=1.20 +or- 0.01 inches

  (Same instructions as at crack length no.1)

- o At crack length no.3 - C(T): a=1.50 +or- 0.01 inches
  M(T): 2a=2.00 +or- 0.01 inches

  (Same instructions as at crack length no.1)

- o At the overload length-C(T): a=1.50 +or- 0.01 inches
  M(T): 2a=2.00 +or- 0.01 inches

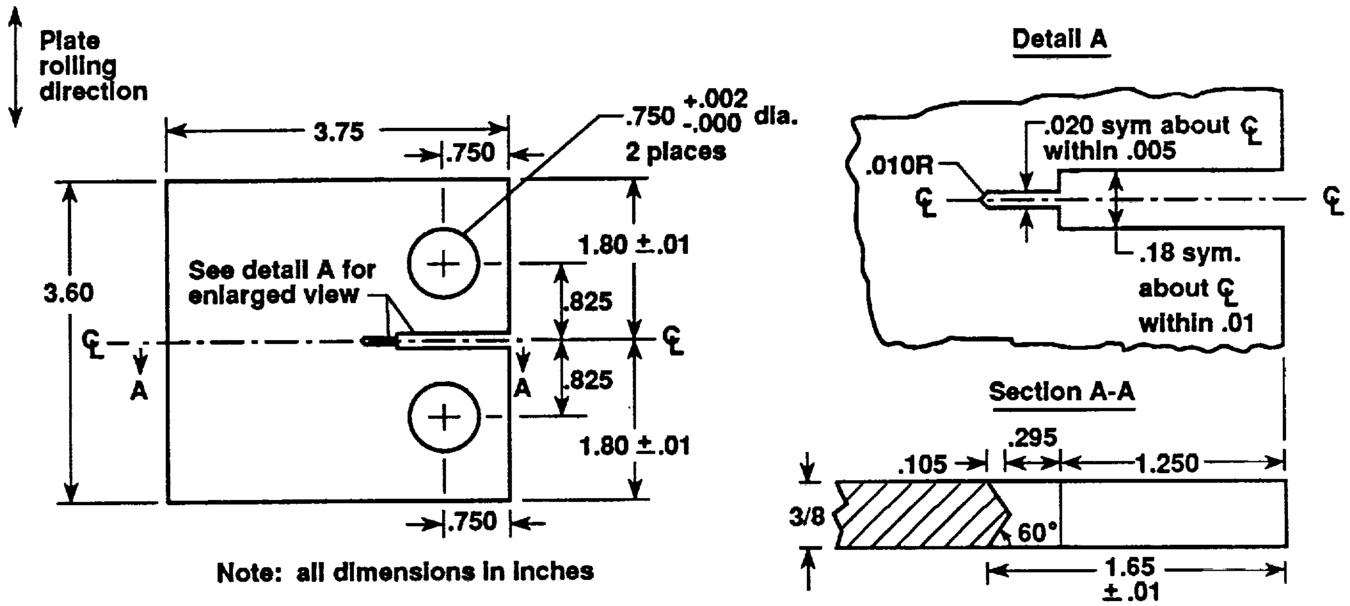
  After making the opening load measurements at length no.3, apply the specified single overload cycle. Then at 0, 2.5×10^2, 5×10^2, 1×10^3, 2×10^3, and 4×10^3 total fatigue cycles after the overload, make opening load measurements during load cycles that go to 100 percent of the post-overload max. fatigue load.

7. Documentation of Tests and Results

Participants should thoroughly document their experimental apparatus and procedures. All details will not be required in the initial reporting of the results, but the need to investigate the effects of differences in experimental procedure may become evident after an initial analysis of the results. Raw data should be stored so that they can be easily retrieved for further analysis.

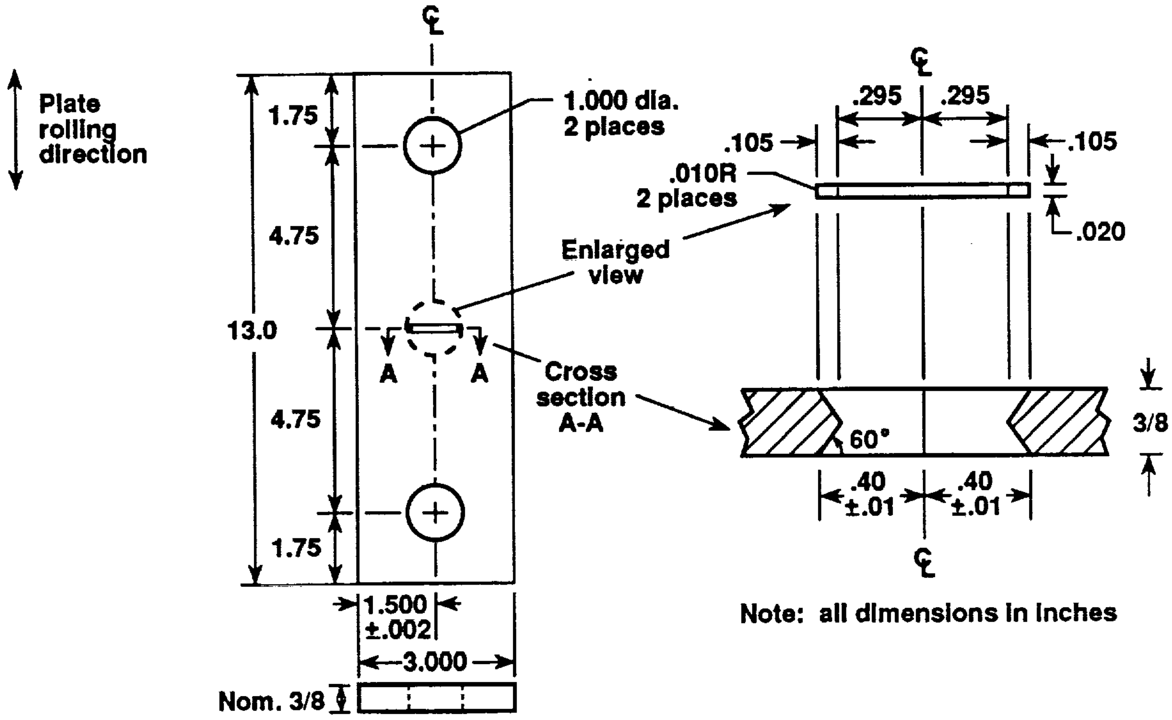
The following should be included in the initial report of results for each specimen:

- o Specimen number that is scribed on the specimen
- o Plot of growth rate vs. crack length
- o Experimental approach - load-displacement, potential drop, ultrasonics, etc.
  - If load-displacement approach is used, indicate type of displacement measurement apparatus (COD gages, strain gages, interferometry, etc.) and measurement location on the specimen.
- o Crack length at measurement and, after overload, the cycle number
- o Maximum load in recording cycle
- o Opening loads reported in chronological order of determination
  - If load-displacement approach is used, then opening loads should be reported for all the analysis methods listed in paragraph 4.



Note: all dimensions in inches

Figure A1.- C(T) specimen to be used in the Round Robin



Note: all dimensions in inches

Figure A2.- M(T) specimen to be used in the Round Robin

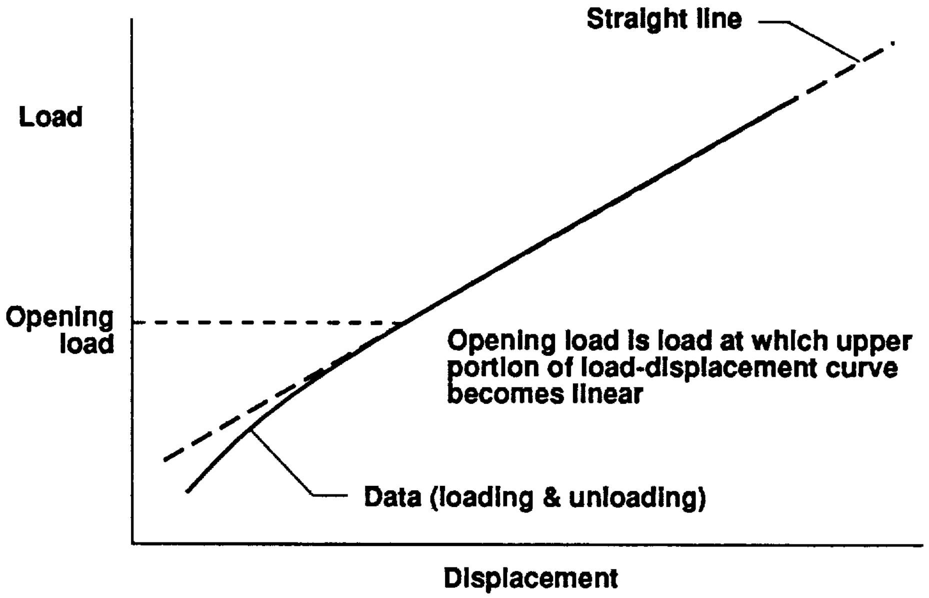


Figure A3.- Determination of opening load from load-displacement data according to method of Test Plan paragraph 4.2.1

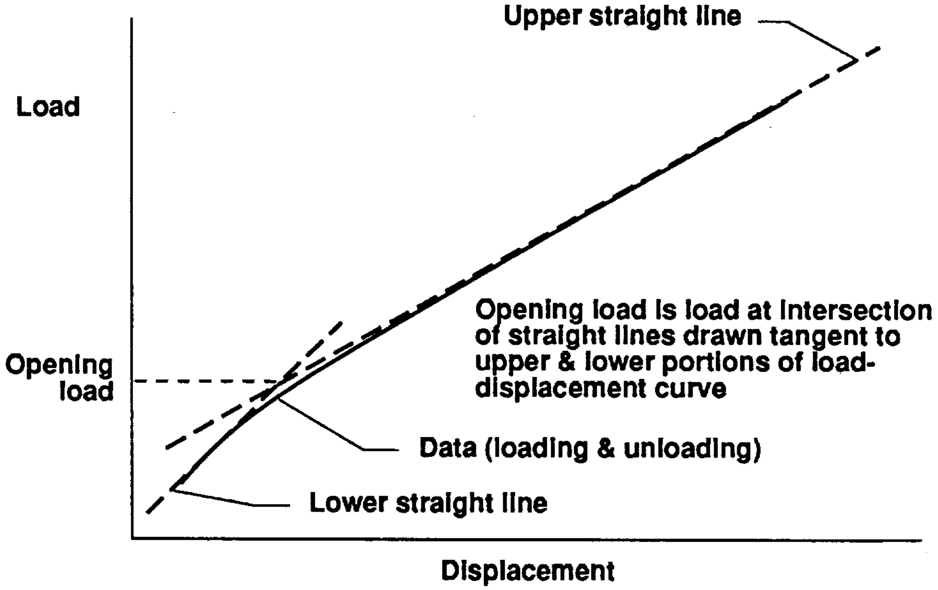


Figure A4.- Determination of opening load from load-displacement data according to method of Test Plan paragraph 4.2.2

Opening load is load at which the slope of the loading portion of the load-displacement curve becomes equal to slope of upper portion of unloading curve

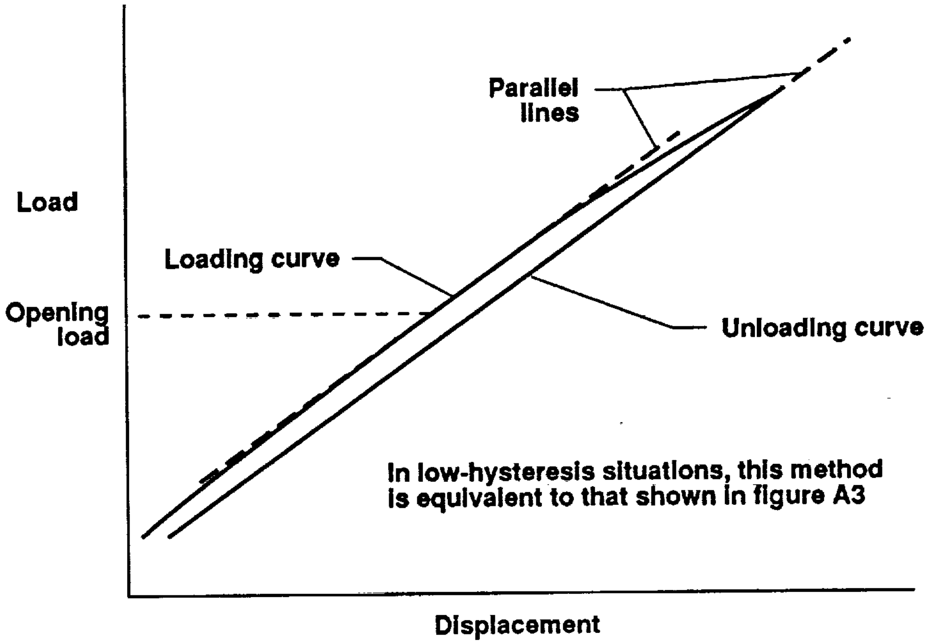


Figure A5.- Determination of opening load from load-displacement data according to method of Test Plan paragraph 4.2.3

Opening load is load at which the slope of the loading portion of the reduced displacement curve becomes equal to slope of upper portion of unloading curve

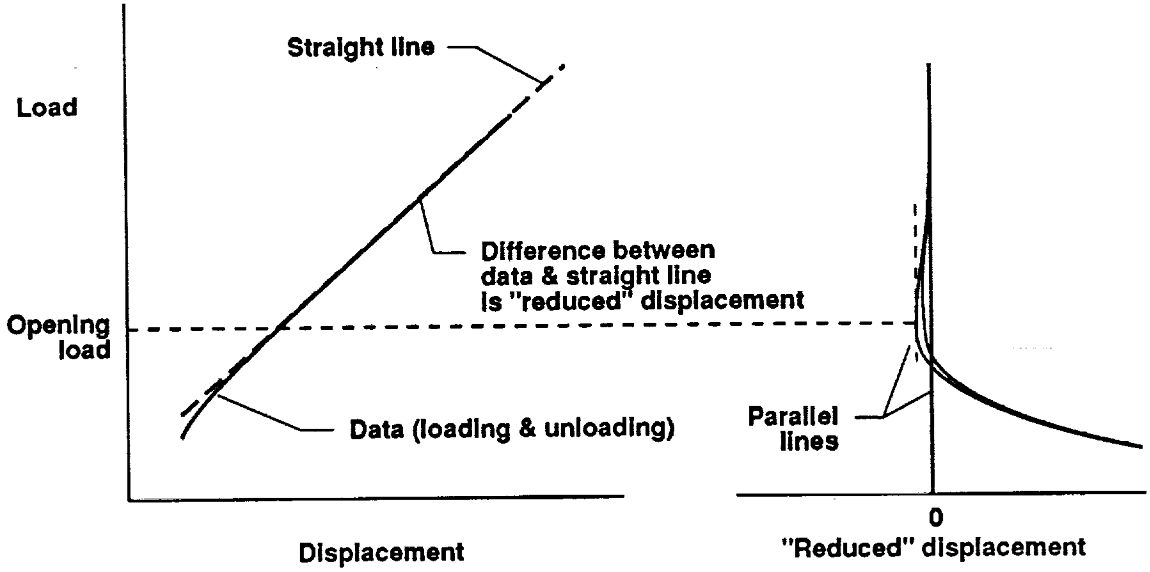


Figure A6.- Determination of opening load from load-displacement data according to method of Test Plan paragraph 4.2.4

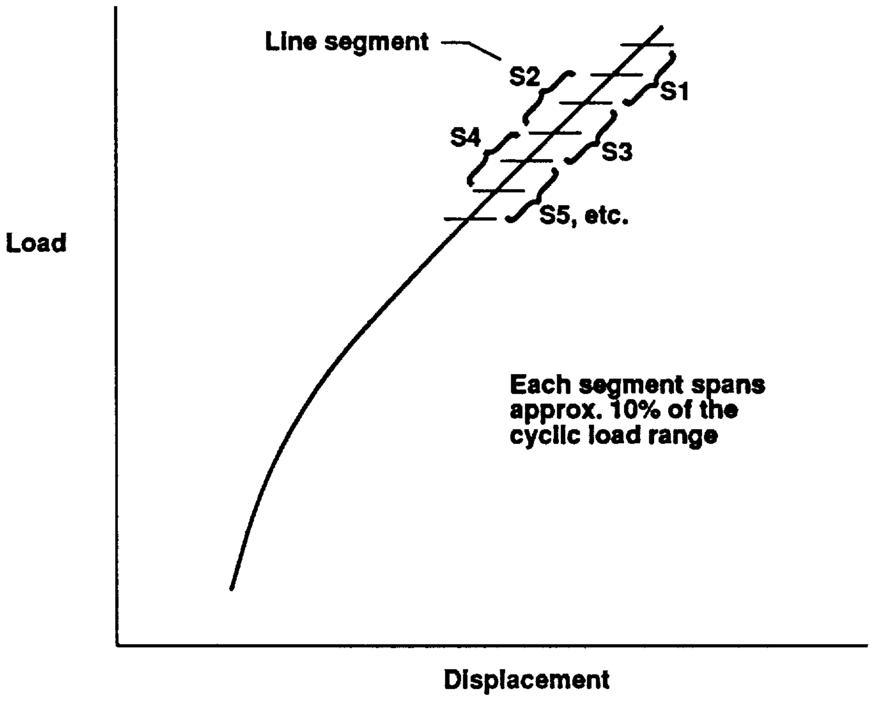


Figure A7.- Evaluation of slopes of load-displacement curve for use in evaluating the opening load according to method of Test Plan paragraph 4.3

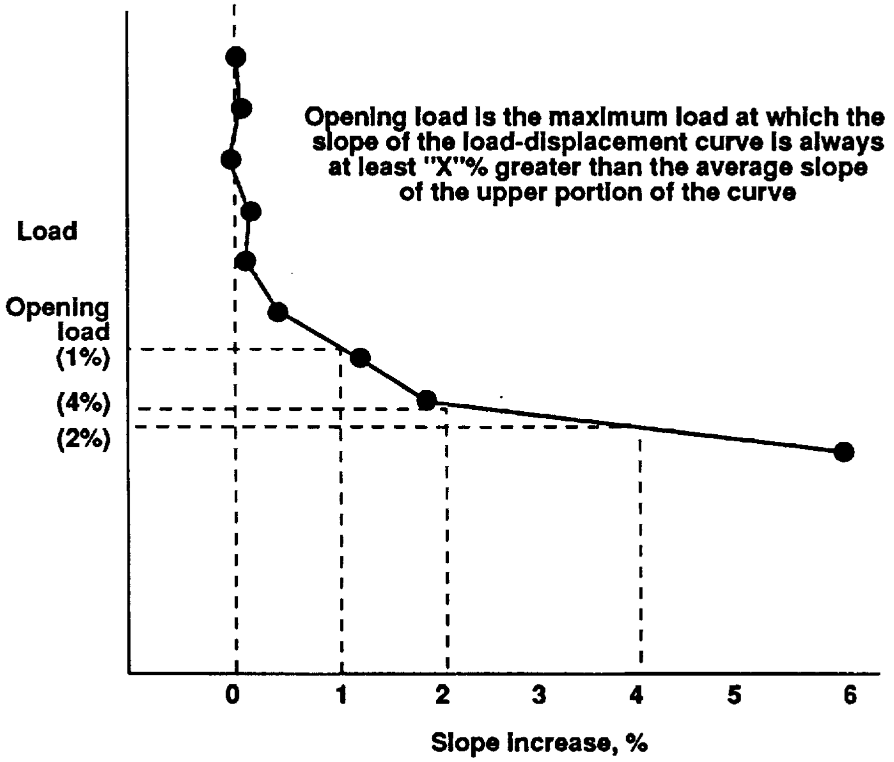


Figure A8.- Determination of opening load from slopes of load-displacement curve according to method of Test Plan paragraph 4.3

APPENDIX B

Round Robin Opening-Load Data Set

Table B1.- Opening-load ratios for low-K test of C(T) specimen.

Participant number	Measurement time								
	CL1	CL2	CL3	N0	N1	N2	N3	N4	N5
(A) COD compliance measurement									
Upper Linear Displacement									
7	0.20	0.19	0.24	0.25	--	0.26	0.24	0.26	0.28
8	0.30	0.32	0.33	0.27	0.27	0.27	0.32	0.36	0.35
11	0.21	0.15	0.15	0.10	0.18	0.18	0.15	0.16	0.18
Intersection									
8	0.21	0.22	0.18	0.19	0.19	0.19	0.19	0.20	0.20
11	0.21	0.15	0.14	0.10	0.18	0.18	--	0.16	0.18
Reduced Displacement									
8	0.34	0.34	0.34	0.28	0.30	0.29	0.31	0.36	0.37
9	--	--	0.19	--	--	--	--	--	--
Nonvisual (1%)									
1	0.45	0.36	0.54	0.27	0.47	0.37	0.55	0.32	0.49
6	0.40	0.42	0.36	0.35	0.35	0.36	0.36	0.36	0.36
8	0.33	0.33	0.32	0.28	0.29	0.29	0.30	0.32	0.32
10	0.33	0.33	0.36	--	0.32	0.32	0.34	0.33	--
(B) BFS compliance measurement									
Upper Linear Displacement									
5	--	0.35	0.25	--	0.30	0.31	0.31	0.32	0.31
8	0.33	0.39	0.35	0.27	0.33	0.32	0.32	0.40	0.37
9	0.26	0.21	0.21	0.23	--	--	--	--	--
11	0.19	0.14	0.18	0.15	0.20	0.20	0.20	0.19	0.20
Intersection									
5	--	0.29	0.25	--	0.30	0.31	0.31	0.32	0.31
8	0.23	0.23	0.18	0.19	0.19	0.19	0.20	0.20	0.20
9	0.21	0.18	0.18	0.17	--	--	--	--	--
11	0.17	0.14	0.18	0.15	0.18	0.18	0.20	0.18	0.18
Reduced Displacement									
8	0.43	0.46	0.41	0.32	0.47	0.62	0.41	0.58	0.58
9	0.21	0.19	0.19	0.20	--	--	--	--	--
Nonvisual (1%)									
1	0.21	0.23	0.37	0.27	0.49	0.37	0.41	0.34	0.26
8	0.40	0.41	0.36	0.30	0.31	0.32	0.32	0.35	0.37

Table B1.- Opening load ratios for low K test of C(T) specimen

Participant	Measurement time								
number	CL1	CL2	CL3	N0	N1	N2	N3	N4	N5
(C) IDG compliance measurement									
			Upper Linear Displacement						
5	0.59	0.49	0.31	0.29	0.37	0.37	0.36	0.37	0.40
11	0.49	0.42	0.47	0.20	0.28	0.30	0.33	0.30	0.30
			Intersection						
5	0.53	0.38	0.30	0.23	0.37	0.37	0.36	0.37	0.40
11	0.40	0.37	0.40	0.18	0.20	0.23	0.25	0.23	0.23
			Reduced Displacement						
5	0.56	0.50	0.40	0.37	0.37	0.35	0.37	0.37	0.55
			Nonvisual (1%)						
5	--	0.64	0.38	0.31	0.43	0.47	--	0.41	--

Table B2.- Opening load ratios for high K test of C(T) specimen

Participant number	Measurement time								
	CL1	CL2	CL3	N0	N1	N2	N3	N4	N5
(A) COD compliance measurement									
			Upper Linear Displacement						
2	--	--	0.14	--	--	--	--	--	--
7	0.15	--	0.16	0.14	0.13	0.14	0.15	0.15	0.16
8	0.17	0.20	0.24	0.16	0.18	0.17	0.32	0.44	0.53
11	0.10	0.10	--	--	--	--	--	--	--
11	0.10	0.10	0.12	0.10	0.10	0.10	0.10	0.10	0.10
			Intersection						
8	0.14	0.17	0.18	0.14	0.15	0.15	0.16	0.16	0.18
11	0.10	0.10	--	--	--	--	--	--	--
11	0.10	0.10	0.12	0.10	0.10	0.10	0.10	0.10	0.10
			Reduced Displacement						
8	0.15	0.21	0.29	0.18	0.19	0.19	0.20	0.65	0.69
			Nonvisual (1%)						
1	0.25	0.47	0.38	0.49	0.47	0.50	0.49	0.57	0.52
3	0.17	0.22	0.26	0.10	0.12	0.11	0.10	--	0.57
6	0.21	0.28	0.29	0.17	0.18	0.17	0.17	0.44	0.61
8	0.16	0.21	0.27	0.20	0.21	0.22	0.23	0.43	0.62
10	0.33	0.31	0.30	--	--	--	0.22	0.30	0.56
(B) BFS compliance measurement									
			Upper Linear Displacement						
2	--	--	0.15	--	--	--	--	--	--
5	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
8	0.24	0.25	0.28	0.20	0.31	0.37	0.44	0.53	0.59
9	0.15	0.18	0.16	0.19	0.14	0.16	0.18	0.19	0.19
11	0.10	0.10	0.11	0.12	0.14	0.10	0.12	0.14	0.12
11	0.10	0.10	0.12	0.10	0.10	0.10	0.10	0.10	0.10
			Intersection						
5	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
8	0.18	0.20	0.19	0.15	0.15	0.16	0.17	0.18	0.19
9	0.13	0.15	0.13	0.12	0.12	0.12	0.12	0.13	0.13
11	0.10	0.10	0.11	0.12	0.14	0.10	0.12	0.14	0.12
11	0.10	0.10	0.12	0.10	0.10	0.10	0.10	0.10	0.10
			Reduced Displacement						
8	0.54	0.56	0.54	0.59	0.60	0.73	0.77	0.76	0.74
9	0.15	0.16	0.16	0.13	0.13	0.13	0.13	0.13	0.13
			Nonvisual (1%)						
1	0.16	0.46	0.47	0.38	0.52	0.50	0.54	0.57	0.28
3	0.30	0.29	0.35	0.20	0.15	--	0.29	--	0.59
8	0.30	0.31	0.31	0.24	0.24	0.47	0.55	0.64	0.67

Table B2.- Opening load ratios for high K test of C(T) specimen

Participant number	Measurement time								
	CL1	CL2	CL3	N0	N1	N2	N3	N4	N5
(C) IDG compliance measurement									
			Upper Linear Displacement						
5	0.49	0.51	0.49	0.55	--	--	--	--	--
11	0.37	0.43	0.36	0.17	0.54	0.58	0.55	0.65	0.62
11	0.42	0.39	0.32	--	0.38	0.52	0.63	0.65	0.69
			Intersection						
5	0.44	0.45	0.44	0.52	--	--	--	--	--
11	0.34	0.39	0.32	0.15	0.51	0.54	0.53	0.61	0.57
11	0.37	0.35	0.28	--	0.31	0.38	0.43	0.44	0.53
			Reduced Displacement						
5	0.43	0.46	0.46	--	--	--	--	--	--
11	0.43	0.52	0.43	--	--	--	--	--	--
11	0.59	0.62	0.59	--	--	--	--	--	--
			Nonvisual (1%)						
5	0.67	0.55	0.55	0.51	--	--	--	--	--
11	0.59	--	--	--	--	--	--	--	--

Table B3.- Opening load ratios for low K test of M(T) specimen

Participant number	Measurement time								
	CL1	CL2	CL3	N0	N1	N2	N3	N4	N5
(A) COD compliance measurement									
Upper Linear Displacement									
8	0.38	0.32	0.29	0.24	0.27	0.24	0.26	0.27	0.29
9	0.37	0.35	0.30	0.37	--	--	--	--	--
Intersection									
8	0.24	0.21	0.19	0.17	0.18	0.18	0.18	0.18	0.17
9	0.28	0.26	0.24	0.24	--	--	--	--	--
Reduced Displacement									
8	0.50	0.39	0.39	0.29	0.30	0.29	0.33	0.36	0.37
9	0.48	0.41	0.37	0.41	--	--	--	--	--
Nonvisual (1%)									
3	--	--	0.28	0.33	0.24	0.23	0.30	0.23	0.37
6	0.45	0.44	0.43	0.42	0.41	0.41	0.41	0.41	0.42
8	0.44	0.36	0.34	0.28	0.31	0.28	0.30	0.32	0.32
(B) IDG compliance measurement									
Upper Linear Displacement									
5	0.49	0.53	0.48	0.29	0.32	0.39	0.36	0.42	0.40
11	0.38	0.31	0.52	0.30	0.32	0.29	0.32	0.31	0.33
Intersection									
5	0.45	0.39	0.43	0.22	0.25	0.26	0.26	0.29	0.31
11	0.31	0.27	0.49	0.27	0.28	0.26	0.28	0.28	0.29
Reduced Displacement									
5	0.45	0.43	0.43	0.26	0.37	0.41	0.46	0.38	0.36
11	0.41	0.38	0.58	0.34	0.41	0.40	0.39	0.34	0.35
Nonvisual (1%)									
5	0.55	0.62	0.62	0.62	0.65	0.53	0.61	0.62	0.67

Table B4.- Opening load ratios for high K test of M(T) specimen

Participant number	Measurement time								
	CL1	CL2	CL3	N0	N1	N2	N3	N4	N5
(A) COD compliance measurement									
			Upper Linear Displacement						
8	0.23	0.26	0.27	0.30	0.29	0.30	0.46	0.54	0.60
9	0.20	0.21	0.33	0.35	0.38	0.38	0.37	0.36	0.34
			Intersection						
8	0.15	0.19	0.18	0.17	0.17	0.20	0.21	0.22	0.26
9	0.16	0.18	0.25	0.27	0.22	0.22	0.26	0.25	0.25
			Reduced Displacement						
8	0.27	0.31	0.33	0.38	0.40	0.52	0.63	0.65	0.68
9	0.23	0.26	0.32	0.43	0.36	0.38	0.37	0.39	0.36
			Nonvisual (1%)						
3	0.49	0.43	0.41	0.25	0.31	--	--	--	--
6	0.34	0.35	0.37	0.36	0.36	0.41	0.47	0.51	0.61
8	0.25	0.30	0.32	0.26	0.32	0.35	0.47	0.61	0.65
(B) IDG compliance measurement									
			Upper Linear Displacement						
5	--	--	0.46	--	--	--	--	--	--
			Intersection						
5	--	--	0.43	--	--	--	--	--	--
			Reduced Displacement						
5	--	--	0.41	--	--	--	--	--	--
			Nonvisual (1%)						
5	--	--	0.69	--	--	--	--	--	--

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16. Abstract
An experimental Round Robin on the measurement of the opening load in fatigue crack growth tests has been conducted by the ASTM Task Group E24.04.04 on Crack Closure Measurement and Analysis. The purpose of the Round Robin was to evaluate the current level of consistency of opening load measurements among laboratories and to identify causes for observed inconsistency. Eleven laboratories participated in the testing of compact and middle-crack specimens. Opening-load measurements were made for crack growth at two stress-intensity factor levels, three crack lengths, and following an overload. All opening-load measurements were based on the analysis of specimen compliance data. When all of the results reported (from all participants, all measurement methods, and all data analysis methods) for a given test condition were pooled, the range of opening loads was very large--typically spanning the lower half of the fatigue loading cycle. Part of the large scatter in the reported opening-load results was ascribed to consistent differences in results produced by the various methods used to measure specimen compliance and to evaluate the opening load from the compliance data. Another significant portion of the scatter was ascribed to lab-to-lab differences in producing the compliance data when using nominally the same method of measurement.

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