NASA TECHNICAL MEMORANDUM 109032

RESULTS OF THE SECOND ROUND ROBIN ON OPENING-LOAD MEASUREMENT CONDUCTED BY ASTM TASK GROUP E24.04.04 ON CRACK CLOSURE MEASUREMENT AND ANALYSIS

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NOVEMBER 1993

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SUMMARY

A second experimental Round Robin on the measurement of the crack opening load in fatigue crack growth tests has been completed by the ASTM Task Group E24.04.04 on Crack Closure Measurement and Analysis. Fourteen laboratories participated in the testing of aluminum alloy compact tension specimens. Opening-load measurements were made at three crack lengths during constant ΔK, constant stress ratio tests by most of the participants. Four participants made opening-load measurements during threshold tests. All opening-load measurements were based on the analysis of specimen compliance behavior, where the displacement/strain was measured either at the crack mouth or the mid-height back face location. Several measures of the "quality" of the raw load and displacement/strain data were evaluated as possible bases for judging acceptability of the data for use in opening load analyses. The Round Robin data were analyzed for opening load using two non-subjective analysis methods -- the compliance offset and the correlation coefficient methods. The quality of the raw data had an effect on the opening load results from both analysis methods. The scatter in the opening load results was significantly reduced when some of the results were excluded from the analysis population based on an accept/reject criterion for raw data quality. The compliance offset and correlation coefficient opening load analysis methods produced similar results for data populations that had been screened to eliminate poor quality data. However, for overall ease of use, the compliance offset method was found to be preferable to the correlation coefficient method.

INTRODUCTION

In the first Round Robin on fatigue crack opening load measurement conducted by ASTM (ref.1), all of the participating laboratories determined the opening load by analyzing specimen compliance behavior, but several different methods of measurement and analysis were used. The results of the first Round Robin indicated that there were significant differences among laboratories using the same analysis method and also systematic differences produced by different analysis methods applied to the same raw load and displacement/strain data. Taken together as a group without qualification, the Round Robin test results showed a large dispersion in measured opening loads. It was clear that to achieve more consistent results among laboratories, some standardized procedures for determining opening load would be required.

This report documents the results of the second Round Robin test program on opening load measurement undertaken by the ASTM Task Group on Crack Closure Measurement and Analysis. The objectives of the second Round Robin were to generate specimen compliance data in several laboratories for the same test conditions and to use the data to evaluate: (1) procedures for establishing the acceptability of the raw load and displacement/strain data, and (2) non-subjective methods of analyzing the compliance data to determine the opening load. The results of this effort were to serve as the basis for proposing a recommended procedure for determining opening load from specimen compliance data.

ROUND ROBIN TEST PLAN

The intent of the test plan was to specify the test and measurement conditions sufficiently so that the opening load measurements would be made by all participants under nominally identical conditions. The salient features of the tests and analyses described in the Test Plan document sent to participants are given below.

The Test Plan defined fatigue crack growth tests on the compact tension (C(T)) specimen configuration shown in Figure 1. 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. All tests were to be conducted in ambient air at a constant stress ratio (R) of 0.1. Two types of tests were defined -- a "basic program" constant K_{max} test and an "optional program" threshold test. Participants were asked to conduct two tests of each type to provide information on repeatability of results at each laboratory. The basic-program tests were to be conducted at a constant K_{max} of 6.6 MPa(m)$^{1/2}$ (6 ksi(in.)$^{1/2}$) and crack opening loads were to be measured at the following three crack lengths: a = 25.4, 27.9, and 38.1 mm (1.00, 1.10, and 1.50 inches). For the optional-program threshold tests, a crack was to be grown to a length of 25.4 mm (1.00 inches) using the same procedure and K level as in the basic-program tests, and then the load-shedding threshold test was to proceed using the method of ASTM Standard

E647. Crack opening loads were to be measured after approximately every 1.5 mm (0.06 inches) of crack growth. The Test Plan did not restrict the participants as to the type of displacement or strain measuring device, but the location of the measurement was specified to be either at the crack mouth, back face, or near-crack-tip.

Participants were asked to submit a magnetic diskette containing a complete load cycle of digitized load versus displacement/strain data taken at the start of each test (uncracked specimen) and at each crack length for which an opening load was determined. Also, participants were asked to determine and report opening loads for their tests using a prescribed data analysis method -- the compliance offset method (described in a subsequent section of this report).

ROUND ROBIN DATA SET

Test results were received from the participants listed in Table 1. However, not all of the test results received were included in the analyses of this report. The opening load results reported by the participants were not used because there were questions as to whether all participants had applied the prescribed opening load analysis method correctly. Therefore, to be consistent, only the analyses of the digitized load versus displacement/strain data submitted on magnetic diskette are included in this report. Results submitted without raw data on magnetic diskette were not used. Also, a small amount of data obtained for an unusual strain measurement location (different from that specified in the Test Plan) were excluded in the interest of obtaining a more homogenous data population.

Table 2 lists the tests that were included in the final data set for analysis. Data were received for 17 constant ΔK tests and 6 threshold tests. Since data were received for only a small number of threshold tests, most of the evaluations in this report used only the data from the constant ΔK tests. The final analysis data set contained only results for displacement measurements at the crack mouth (CMOD) and for strain measurements at the mid-height, back-face (BFS) locations. The crack growth data submitted for all tests listed in Table 2 looked reasonable. That is, there were no indications that the accuracy of any of the test results should be questioned. Participants are identified in the table by a number assigned to each by a random draw procedure.

OPENING LOAD ANALYSIS METHODS

Two methods of determining opening load from compliance information were evaluated using the Round Robin data set. The two methods were the compliance offset method and the correlation coefficient method. Both methods are based on the following characteristic compliance behavior. When a cracked specimen is loaded up to the load at which the crack becomes fully open, the compliance (slope of the strain or displacement against load curve) attains a characteristic value and remains essentially constant upon further load increase until the load is increased enough to cause large-scale yielding near the crack. Upon unloading from the maximum load in a cycle, the compliance again has the characteristic value for the fully-open crack regardless of whether large-scale yielding occurred before maximum load was achieved. Conceptually, the experimental task is very simple -- determine the load at which the strain or displacement against load curve becomes linear. In practice, however, this task is very difficult due to the gradual change in compliance as it approaches the open-crack value and to the variability in the compliance data. To be consistent in evaluating opening load from such data, non-subjective analysis methods such as the two methods evaluated in this report are required.

Compliance Offset Method

The compliance offset method used in the Round Robin is a modified version of a method proposed and described in reference 2. In general, this method defines opening load by finding the load on the ascending portion of the load cycle at which the compliance reaches a value that is less than (offset from) the compliance for a fully open crack by some specified percentage (the offset criterion) of the open-crack value. Offset criteria of 1, 2, 4, and 8 percent were used in the Round Robin. Because there are several ways this might be accomplished, the following detailed seven-step procedure was defined for use in the Round Robin.

Step 1.- Collect digitized strain/displacement and load data for a complete load cycle. The data sampling rate should be high enough to assure that at least one data pair (displacement and load) is taken in every two percent interval of the cyclic load range.

Step 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 the compliance value that corresponds to the fully-open crack configuration.

Step 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 2). Store the compliance (slope) and the corresponding mean load for each segment in a vertical array with the highest-load location at the top.

Step 4.- Replace the compliance stored in each location in the array with the corresponding compliance offset, which is computed as a percentage of the "open-crack" compliance and is given by:

$$(\text{Compliance offset}) = \frac{[(\text{"open-crack" compliance}) - (\text{compliance})](100)}{(\text{"open-crack" compliance})}$$

where the "open-crack" value is taken from Step 2.
Step 5.- Identify the highest-load-location in the array which: (1) has a compliance offset greater than the selected offset criterion, and (2) all array locations below it have compliance offsets greater than the offset criterion.
Step 6.- Starting at the array location identified in Step 5, identify the nearest, higher-load location which: (1) has a compliance offset less than the selected offset criterion, and (2) all array locations above it have compliance offsets less than the offset criterion.
Step 7.- Determine the opening load corresponding to the selected offset criterion by linear interpolation between the two (compliance offset,load) points identified in Steps 5 and 6. (see Figure 3)

The example given in Figure 3 represents a raw data set with low "noise" or variability, and for cases like that the determination of an opening load is rather straightforward. If, however, the raw data has high noise, the analysis procedure given above can produce an unreasonably high value of opening load. That case is illustrated in Figure 4. In Figure 4, the analysis method produces an opening load of 0.69 of maximum fatigue load, which is much higher than the value that a visual evaluation of the data would suggest. In some cases, the high variability in the raw data near maximum load prevented the analysis from producing an opening load result at all. The effect of high noise on opening load results is discussed further in subsequent sections.

Correlation Coefficient Method

The correlation coefficient method used to analyze the Round Robin data is a slightly modified version of the procedure described in reference 3. The correlation coefficient method is based on the fact that the correlation coefficient, defined as

$$r=[n\Sigma(x_i y_i)-\Sigma x_i \Sigma y_i]/[(n\Sigma x_i^2-(\Sigma x_i)^2)(n\Sigma y_i^2-(\Sigma y_i)^2)]^{1/2}$$

where, x_i are individual load data samples,
y_i are individual displacement data samples,
n is the number of data pairs,
Σ denotes the summation from $i=1$ to n

can be interpreted as a measure of the strength of the linear relationship between two variables. Therefore, if it is assumed that the relationship between displacement and load is linear when the crack is fully open and that the maximum load is not high enough to cause large-scale yielding, the opening load can be evaluated in the following way. First, the points in the upper 25 percent of the cyclic load range on the ascending load portion of the cycle are used to calculate a baseline correlation coefficient. Then, starting at the lowest load used in the baseline calculation and progressing towards lower loads, points are added one by one to the calculation set and the correlation coefficient is recalculated each time. Since the correlation coefficient will increase if added points are still part of a linear relation and decrease if they are deviating from a linear relation, the opening load is defined as the load at which the coefficient has the highest value. Determination of opening load using the correlation coefficient method is illustrated in Figure 5 using the same raw data that was analyzed by the compliance offset method in Figure 3.

MEASURES OF RAW DATA QUALITY

One of the conclusions from the first Round Robin (ref. 1) was that a significant portion of the scatter in measured opening loads among different labs was probably due to differences in the quality of the raw load and displacement/strain data. So to assure the generation of a consistent body of opening load measurements among labs, some method of assessing the acceptability of the raw data quality is required. As used here, quality can be defined in terms of two attributes of the measurement system: (1) the linearity of the system, and (2) the "noise" or variability in the system. Since both the methods of determining opening load evaluated in this report are based on detecting deviations from linear relationships in the data, the importance of the linearity of the measurement system seems obvious. Any nonlinearity in the measurement system could introduce an error in the evaluation of the opening load. The effect of noise on the opening load results is not so obvious and may be highly dependent on the method of evaluating opening load.

To assess the quality of the raw data being generated in the current Round Robin, each participant was asked to record load and displacement/strain data for a complete load cycle at the start of each test before a crack was generated at the notch. The recordings were made at the same loading frequency at which data would be acquired during the test and at the load level specified for the start of the crack growth test. Since the specimen was uncracked, the load and displacement/strain should be linearly related and deviations from linearity should represent the nonlinearity of the measurement system. It was assumed that measures of data quality taken at the start of the test were representative of the entire test.

Three measures of the raw data quality were evaluated using the data from the basic-program (constant ΔK) tests: (1) the average of the squares of the residuals (ASR) about a straight line fit to the data (2) the correlation coefficient computed from the data, and (3) the means and standard deviations of the compliance offsets computed from the data. The procedures for computing these measures of data quality are given in the following paragraphs.

Average of the Squares of Residuals

A least-squares best-fit straight line was established for the increasing load portion of the displacement/strain against load raw data from the uncracked specimen for each test. The average square of the residuals (ASR) about that line was calculated as:

$$ASR = [\Sigma(y_i - y_l)^2]/n$$

where, y_i are the experimental raw data displacement/strain values

y_l are the displacement/strain values computed from the best-fit line using the raw data load values corresponding to the y_i values

n is the number of data points

Correlation Coefficient

A correlation coefficient was calculated for all raw data from the increasing load portion of the load cycle recorded for the uncracked specimen for each test. The correlation coefficient was calculated using the same formula as given earlier in the section on calculating opening loads using the correlation coefficient method.

Means and Standard Deviations of Compliance Offsets

The displacement/strain and load raw data from the increasing load portion of the load cycle for each test were analyzed using the same procedure described earlier for the compliance offset method of evaluating opening load. For a perfectly-linear noise-free system, all of the computed compliance offsets for a specimen without a crack should be zero. For imperfect systems, the compliance offsets will not be zero and the degree to which they differ from zero should be a measure of the quality of the data. Because the differences from zero may be due to either nonlinearity or noise in the system, a measure of each attribute was adopted. The mean of the compliance offsets was taken as a measure of the linearity and the standard deviation of the offsets about the mean was taken as a measure of noise.

RESULTS FROM CONSTANT ΔK TESTS

The data from the constant ΔK tests were analyzed using both the compliance offset and correlation coefficient methods. Initially, opening loads were determined for all tests regardless of the quality of the raw load and displacement/strain data. Then, several proposed measures of raw data quality were evaluated to determine if the measure of quality correlated with the values of opening load. Next, an accept/reject criterion based on a selected measure of data quality was applied to all tests to determine the effect of screening out poor quality raw data on the scatter in the opening load values. Finally, the results from the two opening load analysis methods were compared to determine whether one method was preferable over the other. Details of these analyses and the results are given in the following sections. Numerical results from opening load analyses are tabulated in Table 3 and from data-quality-measure analyses in Table 4.

Results of Opening Load Analyses of Unscreened Raw Data

Compliance Offset Method

The opening load results from all tests are plotted in Figure 6 for an offset criterion of 2 percent. The lines in the figure connect opening loads determined at the three specified crack lengths in the same test using the same displacement/strain measurement type. Plotted points not connected by lines are from tests in which opening loads were only determined for a single crack length. Taken as a whole, the opening loads in the figure show a large scatter, but it is apparent that some test results are very different from the majority. However, it is also apparent that even if the "outliers" were eliminated, there would still be a sizable scatter band ranging from about 0.25 to 0.50 of the maximum fatigue load. The opening load results for the other offset criteria (1, 4, and 8 percent) present a similar picture to that in Figure 6 although there is a trend towards lower scatter as the offset criterion progresses from 1 percent to 8 percent.

The results in Figure 6 are replotted in Figures 7(a) and 7(b), but in Figure 7(a) the results for the CMOD and the BFS measurements are differentiated as solid and dashed lines respectively, and in Figure 7(b) the results for computer-controlled and manually-controlled tests are differentiated as solid and dashed lines respectively. It is evident from the figures that neither the measurement type nor the test control method had a significant effect on the results. In all subsequent discussions and analyses, all results will be pooled together regardless of measurement type or test control method.

Correlation Coefficient Method

The opening load results from the correlation coefficient method are plotted in Figure 8 in the same format as that for the compliance offset method results in Figure 6. Results for the correlation coefficient method show fewer "outliers" than did the compliance offset method, but ignoring the outliers, the main group of data cover about the same scatter band as did the compliance offset method.

Evaluation of Measures of Raw Data Quality

Average of the Squares of Residuals

To assess the value of the ASR as a measure of quality, the opening loads determined by the compliance offset and correlation coefficient methods for a crack length of 25.4 mm were plotted against the ASR values from the uncracked specimens in Figures 9(a) and 9(b) respectively. No relationship between the ASR and opening loads is evident in Figure 9(a), but a trend of lower opening load with higher ASR does appear to exist in Figure 9(b) for the opening loads determined by the correlation coefficient method. In both Figures 9(a) and 9(b), scatter in opening loads appears higher for the higher values of ASR.

Correlation Coefficient

The correlation coefficient results from the uncracked specimens are plotted against the opening loads from the compliance offset and correlation coefficient methods in Figures 10(a) and 10(b) respectively. No strong relationship between the correlation coefficient and opening loads is evident in the figures, but there appears to be a weak trend for the compliance offset opening loads to decrease with increasing uncracked-specimen correlation coefficient. In both Figures 10(a) and 10(b), scatter in opening loads appears higher for the lower values of correlation coefficient.

Means and Standard Deviations of Compliance Offsets

The opening loads from the compliance offset and correlation coefficient methods are plotted against the means of the compliance offsets for the uncracked specimens in Figures 11(a) and 11(b) respectively. In the figures, the numbers written next to the points are the standard deviations of the offsets for those points. Only the points with high standard deviations (>2%) are identified. Considering the results for the compliance offset method in Figure 11(a), no trend of opening load with the mean of the offsets is apparent, but it appears that tests with high standard deviations tend to have high opening loads. This characteristic of the compliance offset method was mentioned earlier. Sometimes the opening load from a high standard deviation test agreed with low standard deviation tests at some single crack length (for example, the test labelled 4.45 in Figure 11(a)), but generally showed high opening loads at the other crack lengths. Considering the results for the correlation coefficient method in Figure 11(b), again there is no apparent trend of opening load with the mean of the offsets but it appears that tests with the high standard deviations tend to have lower opening loads than the average. That is, the trend is in the opposite direction from that noted for the compliance offset method.

Since the results from both opening load analysis methods seem to be biased by the tests with the high standard deviations of compliance offsets, the results of Figure 11(a) and 11(b) are replotted in Figures 12(a) and 12(b) without the high standard deviation tests. Now, the results in Figure 12(a) for the compliance offset method show an obvious trend of opening load with the mean of the offsets. This trend should be expected if the mean of the offsets is a measure of system linearity. The results in Figure 12(b) for the correlation coefficient method show the same trend as in Figure 12(a), but the trend is not as strong mainly due to the single point at the highest mean of the offsets.

Discussion of Results From the Measures of Data Quality

All three of the measures of data quality that were evaluated based on data from uncracked specimens support the same general conclusion that data quality does affect opening load results. However, the trends of opening load with the ASR and correlation coefficient measures were not as strong as was noted for the measure based on the mean and standard deviation of the compliance offsets. One explanation for the above observation is that both nonlinearity and noise affect single-parameter measures such as the ASR and the correlation coefficient in the same way, but nonlinearity and noise can have offsetting effects on opening load. Hence, the single-parameter measures may not correlate well with opening load. By using a two-parameter measure of quality such as the mean and standard deviation of compliance offsets, the effects of nonlinearity and noise can be treated explicitly and separate acceptance criteria set for each. Separate measures of linearity and noise also give the experimenter more information which can be used to guide efforts to improve quality.

Effect of Data Quality Screening on Opening Load Results

All three of the measures of data quality evaluated in the previous section showed at least some correlation with opening loads, and therefore could possibly be used as the basis for an accept/reject criterion for raw data quality. However, for the reasons cited in the previous section, the means and standard deviations of the compliance offsets determined from an uncracked specimen was deemed to be the most promising measure, and therefore was the measure of quality used to determine the effect of data-quality screening on the opening load results. Data meeting the quality criterion were analyzed by both the compliance offset and correlation coefficient opening load analysis methods.

Two sets of accept/reject criteria representing two levels of quality were evaluated. The two criteria were: (1) absolute value of the mean of the offsets less than 1%, and the standard deviation of the offsets less than 2% ($|m|<1, SD<2$), and (2) absolute value of the mean of the offsets less than 0.5%, and the standard deviation of the offsets less than 1% (|m|<0.5,SD<1). The levels of the criteria were chosen rather arbitrarily, although the standard deviation level of 2% was about the level at which the compliance offset method began to produce opening load values much higher than those from the low standard deviation tests.

The means and standard deviations of the opening load results from the unscreened data population and from the data populations meeting the two screening criteria are shown in Figure 13. Note that the first screening level eliminated about half of the original data set and the most stringent screening level halved the data set again. For the compliance offset method, the effect of applying more stringent data acceptance criteria was to decrease the mean and the standard deviation of the opening loads from the Round Robin data set. For the correlation coefficient method, the effect was to increase the mean and decrease the standard deviation. For both analysis methods, the screening had the desirable effect of reducing the scatter in the opening load results. The reduction in scatter due to screening can also be seen in Figures 14(a) and 14(b) where the opening load results from tests that met the |m|<1,SD<2 screening criterion are shown in the same format used to present results from the unscreened data in Figures 5 and 7. Scatter in the results from the current Round Robin can be compared to that from the first Round Robin in Figure 15. In Figure 15, results from the current Round Robin for the compliance offset method (2% offset criterion) applied to tests that met the |m|<1,SD<2 criterion show a significant reduction in scatter from that achieved in the first Round Robin.

Comparison of Opening Load Analysis Methods

Since one of the purposes of the current Round Robin was to provide the basis for a recommended procedure for determining opening load, the two analysis methods were compared to determine whether one method was more desirable than the other. The first point to consider in a comparison is that the correlation coefficient method gives a single result, whereas the compliance offset method gives a result that is dependent on the offset criterion selected. Before making numerical comparisons between the methods, the effects of the offset criterion on the results from the compliance offset method are considered and a single offset criterion selected for making comparisons.

The mean opening loads produced by the compliance offset method for offset criteria of 1,2,4,and 8% are shown in Figure 16. The results in Figure 16 are for tests that met the |m<1|,SD<2 quality criterion. It is clear from Figure 16 that the results for the different offset criteria are consistently and significantly different. The choice of a suitable offset criterion will be somewhat arbitrary, although the amount of scatter for each criterion and the capability of the method to consolidate fatigue crack growth data at different stress ratios are factors to be considered in the choice. Figure 17 shows the scatter in results obtained for the different offset criteria. The scatter for the 1% criterion is greater than for the other criteria, but the scatter at the 2,4, and 8% criteria is about the same. That is, in terms of lower scatter, there is no apparent gain in going lower than a 2% offset level. Figure 18 shows crack growth rates plotted against ΔK for a test with a stress ratio of 0.7. Also in the figure are points plotted at the mean growth rate and ΔK reported for each crack length at which opening load measurements were made. Using the mean opening loads from the analyzed data set, the ΔK_{eff} values ($\Delta K_{eff} = K_{max} - K_{opening}$) associated with each mean ΔK,rate point from the Round Robin are plotted for offset criteria of 1,2, and 4%. No closure was detected at the stress ratio of 0.7, so the points for that test represent both ΔK and ΔK_{eff}. From Figure 18 it appears that an offset criterion of about 2% would be about right to consolidate the results onto a single rate against ΔK_{eff} curve. The scatter in ΔK_{eff} values of the individual data points (caused by scatter in measured opening load) for the 2% offset criterion covers about the same range as that shown for the mean opening load values for the 1% and 4% offset criteria. Considering all of the results for the compliance offset method, a 2% offset criterion seems to be the most reasonable choice.

The mean values and scatter in opening load results from the two opening load analysis methods can be compared in Figure 13 for a 2% offset criterion for the compliance offset method. The two methods give different results for both mean values and scatter for the unscreened data population, but give similar results when the raw data are screened for quality. Since screening the data for quality reduces the scatter in results, any recommended procedure for determining opening load will likely include an accept/reject criterion for data quality. Therefore, the data in Figure 13 do not indicate that one method is clearly more desirable than the other. The choice of one analysis method over the other would then seem to depend on other factors. Since a quality criterion based on the compliance offset method was selected as the best approach in an earlier section, it would seem simpler overall to use the compliance offset method as the recommended procedure.

RESULTS FROM THRESHOLD TESTS

Based on the results and analyses of the constant ΔK tests, the data from the optional-program threshold tests were analyzed for opening load using only the compliance offset method with the 2% offset criterion. All of the raw data submitted for the threshold tests met the compliance-offset-based quality criterion of $|m<1|$,SD<2.

The opening load results for the threshold tests are shown in Figure 19. In the figure, solid lines connect the opening loads measured at different crack lengths for the same test and the same measurement type. Most of the results show a trend of increasing opening load as the crack length increased and the crack growth rate decreased towards threshold, but one test result showed almost no change in opening load during the test. No test or data anomaly was found to explain the behavior of the "odd" test.

Figure 20 shows the opening loads measured at threshold plotted against the threshold ΔK values from the tests. Again, one test point appears to be different from the others. When all points are considered, the standard deviation of the opening loads at threshold is substantially greater than that obtained in the constant ΔK tests, but if the one "outlier" is excluded, the standard deviation is about the same as that in the constant ΔK tests. If no points in the figure are excluded, there appears to be some correlation between opening load at threshold and the ΔK at threshold. Accordingly, when the opening load is used to calculate ΔK_{eff} for each of the threshold tests, the scatter in the ΔK_{eff} values is somewhat lower than that of the ΔK values. The ΔK_{eff} values at threshold ranged from 1.3 to 2.1 MPa(m)$^{1/2}$ and had a mean value of 1.6 MPa(m)$^{1/2}$. For comparison, a value of ΔK_{th} of 1.8 MPa(m)$^{1/2}$ was obtained at an R=0.74 in a threshold test conducted on a Round Robin specimen using the constant K_{max}, increasing K_{min} test method.

CONCLUSIONS

A second Round Robin on the experimental measurement of fatigue crack opening load was conducted by ASTM Task Group E24.04.04 to provide the data necessary for evaluations that would lead to a recommended procedure for determining opening load from specimen compliance information. Most of the evaluations were accomplished on data from constant ΔK, constant R tests on C(T) specimens made of 2024-T351 aluminum alloy. A smaller amount of data were available from threshold tests. Measurements of specimen displacement or strain were taken at either the crack mouth or the back face locations. The following conclusions are based on the evaluations of the test data.

1. The quality of the raw load and displacement/strain data had an effect on the opening load results from both analysis methods that were evaluated -- the compliance offset and the correlation coefficient methods. Quality of the raw data was defined in terms

of the linearity and variability of data taken on the uncracked specimen at the start of each test.

2. Several measures of data quality showed correlations with the opening load results. Of the measures of quality evaluated, a measure using both the means and standard deviations of the compliance offsets was selected as the best overall approach.

3. The scatter in the opening load results was reduced by more than 50 percent when some of the test results were excluded from the analysis population based on an accept/reject criterion for raw data quality.

4. The compliance offset and correlation coefficient opening load analysis methods gave similar results for data populations that had been screened to eliminate poor quality data. For overall ease of use, the compliance offset method was found to be preferable to the correlation coefficient method.

5. The use of a 2% offset criterion in the compliance offset opening load analysis method produced relatively low scatter in opening load values and mean values of opening load that seemed reasonable in terms of collapsing low-R and high-R crack growth results onto a single ΔK_{eff}, rate curve.

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Table 1.- Participants in Round Robin.

Participants	Affiliations
N.Ashbaugh/J.Jira	University of Dayton Research Institute/ USAF-Wright Research and Development Center
J.G.Blauel	Fraunhofer-Institut fur Werkstoffmechanik (Germany)
J.Bogren/A.Blom	Aeronautical Research Institute (Sweden)
R.W.Bush	ALCOA
R.Cervay/S.Thompson	University of Dayton Research Institute/ USAF-Wright Research and Development Center
J.K.Donald	Fracture Technology Associates
D.Jablonski	Instron Corporation
L.Link	David Taylor Research Center
A.McEvily	University of Connecticut
D. Murphy	Pratt&Whitney
E.P.Phillips	NASA-Langley Research Center
G.C.Salivar	Florida Atlantic University
R.Sunder	National Aeronautical Laboratory (India)
J.B.Terrell	Reynolds Metals

Table 2.- Data set analyzed in this report.

Participant number	Number of tests	Measurement type	Test control
		Constant ΔK Tests	
1	2	CMOD	Computer
2	3	CMOD	Computer
3	2	CMOD	Computer
4	1	BFS	Manual
5	1	BFS	Manual
6	1	BFS	Computer
7	1	BFS&CMOD	Manual
8	1	CMOD	Computer
9	2	BFS&CMOD	Computer
10	3	BFS&CMOD	Computer
		Threshold Tests	
1	1	CMOD	Computer
3	2	CMOD	Computer
5	1	BFS	Manual
9	2	BFS&CMOD	Computer

Table 3. - Results of opening load analyses performed on all constant ΔK tests in the Round Robin data set. Opening loads are expressed as a fraction of the maximum fatigue load.

Participant number	Test number	Compliance offset method 1%offset		2%offset		4%offset		8%offset		Correlation coefficient method	
		CMOD	BFS	CMOD	BFS	CMOD	BFS	CMOD	BFS	CMOD	BFS
(A) Crack length = 25.4 mm											
1	1	0.45	--	0.43	--	0.37	--	0.30	--	0.44	--
	2	0.40	--	0.36	--	0.28	--	0.17	--	0.38	--
2	1	(a)	--	(a)	--	(a)	--	0.70	--	0.10	--
	2	0.67	--	0.37	--	0.37	--	0.28	--	0.30	--
	3	0.56	--	0.69	--	0.34	--	0.26	--	0.33	--
3	1	0.60	--	0.47	--	0.38	--	0.29	--	0.47	--
	2	0.31	--	0.27	--	0.24	--	(a)	--	0.42	--
4	1	--	(a)	--	(a)	--	(a)	--	0.23	--	0.26
5	1	--	--	--	--	--	--	--	--	--	--
6	1	--	0.46	--	0.42	--	0.34	--	0.28	--	0.30
7	1	(a)	0.72	(a)	0.63	0.48	0.44	0.34	0.21	0.42	0.36
8	1	0.80	--	0.76	--	0.67	--	0.24	--	0.33	--
9	1	0.43	0.51	0.38	0.42	0.32	0.36	0.18	0.27	0.40	0.48
	2	0.38	0.44	0.34	0.39	0.30	0.34	0.23	0.28	0.42	0.47
10	1	0.54	0.63	0.35	0.45	0.31	0.45	0.24	0.26	0.30	0.28
	2	0.44	--	0.31	--	0.28	--	0.24	--	0.33	--
	3	0.36	(a)	0.26	(a)	0.25	0.54	0.23	0.26	0.30	0.25
(B) Crack length = 27.9 mm											
1	1	0.46	--	0.43	--	0.40	--	0.35	--	0.50	--
	2	0.42	--	0.38	--	0.33	--	0.24	--	0.44	--
2	1	0.62	--	0.46	--	0.51	--	0.23	--	0.60	--
	2	0.81	--	0.74	--	0.29	--	0.20	--	0.29	--
	3	0.54	--	0.49	--	0.39	--	0.27	--	0.28	--
3	1	0.58	--	0.46	--	0.39	--	0.35	--	0.46	--
	2	0.29	--	0.28	--	0.23	--	0.18	--	0.30	--
4	1	--	0.84	--	0.33	--	0.29	--	0.22	--	0.30
5	1	--	0.50	--	0.44	--	0.40	--	0.33	--	0.49
6	1	--	0.45	--	0.42	--	0.37	--	0.29	--	0.34
7	1	(a)	(a)	(a)	(a)	0.42	0.48	0.37	0.32	0.36	0.33
8	1	(a)	--	(a)	--	0.32	--	0.28	--	0.31	--
9	1	0.41	0.46	0.36	0.42	0.32	0.35	0.25	0.29	0.36	0.41
	2	0.41	0.44	0.37	0.40	0.31	0.34	0.26	0.29	0.42	0.43
10	1	--	0.28	--	0.24	--	0.23	--	0.21	--	0.35
	2	0.36	--	0.35	--	0.33	--	0.27	--	0.32	--
	3	0.28	(a)	0.28	(a)	0.26	(a)	0.24	0.24	0.26	0.21

(a) Analysis failed to produce an opening load result

Table 3. - Concluded.

Participant number	Test number	Compliance offset method 1%offset		2%offset		4%offset		8%offset		Correlation coefficient method	
		CMOD	BFS	CMOD	BFS	CMOD	BFS	CMOD	BFS	CMOD	BFS
(C) Crack length = 38.1 mm											
1	1	0.53	--	0.51	--	0.48	--	0.45	--	0.50	--
	2	0.36	--	0.33	--	0.29	--	0.26	--	0.35	--
2	1	(a)	--	(a)	--	0.36	--	0.30	--	0.69	--
	2	--	--	--	--	--	--	--	--	--	--
	3	0.77	--	0.66	--	0.62	--	0.53	--	0.29	--
3	1	0.43	--	0.48	--	0.40	--	0.35	--	0.45	--
	2	0.58	--	0.35	--	0.32	--	0.26	--	0.35	--
4	1	--	(a)	--	0.36	--	0.28	--	0.25	--	0.27
5	1	--	0.66	--	0.51	--	0.40	--	0.30	--	0.36
6	1	--	0.48	--	0.41	--	0.37	--	0.33	--	0.35
7	1	(a)	(a)	(a)	(a)	0.63	0.64	0.37	0.34	0.42	0.32
8	1	(a)	--	0.75	--	0.46	--	0.35	--	0.39	--
9	1	0.39	0.47	0.37	0.40	0.30	0.34	0.26	0.27	0.40	0.46
	2	0.41	0.46	0.36	0.41	0.33	0.35	0.29	0.30	0.42	0.42
10	1	--	0.32	--	0.30	--	0.26	--	0.22	--	0.29
	2	(a)	--	(a)	--	0.36	--	0.32	--	0.33	--
	3	0.34	(a)	0.28	0.67	0.26	0.44	0.23	0.26	0.37	0.26

(a) Analysis failed to produce an opening load result

Table 4. - Results of data-quality-measure analyses performed on data taken before cracks initiated in the specimens used in the constant ΔK tests.

Part. no.	Test no.	Compliance offsets Mean CMOD	Compliance offsets Mean BFS	Stand.Dev. CMOD	Stand.Dev. BFS	Correlation coefficient CMOD	Correlation coefficient BFS	Average of squared residuals CMOD	Average of squared residuals BFS
1	1	-0.89	--	0.20	--	0.9999994	--	1.33E-7	--
	2	-0.19	--	0.29	--	0.9999994	--	1.01E-7	--
2	1	-0.48	--	4.50	--	0.9999636	--	8.79E-6	--
	2	-1.76	--	4.45	--	0.9999417	--	8.08E-6	--
	3	-0.31	--	4.43	--	0.9999727	--	5.86E-6	--
3	1	0.26	--	1.05	--	0.9999926	--	1.63E-6	--
	2	-1.01	--	1.19	--	0.9999967	--	7.45E-6	--
4	1	--	1.06	--	1.36	--	0.9999933	--	1.32E-6
5	1	--	-0.40	--	0.37	--	0.9999975	--	3.64E-7
6	1	--	0.93	--	0.94	--	0.9999780	--	2.89E-6
7	1	0.38	-1.53	2.67	2.03	0.9999542	0.9999623	7.57E-6	5.94E-6
8	1	0.17	--	3.31	--	0.9999688	--	8.28E-6	--
9	1	-0.33	0.43	0.29	0.29	0.9999994	0.9999996	7.92E-8	5.83E-8
	2	-0.48	0.25	0.28	0.23	0.9999997	0.9999998	4.50E-8	3.03E-8
10	1	-1.16	-4.12	2.22	11.62	0.9999892	0.9997935	2.21E-6	4.96E-5
	2	-2.22	--	1.82	--	0.9999881	--	2.59E-6	--
	3	-1.52	0.30	1.79	4.21	0.9999942	0.9999678	1.22E-6	6.26E-6

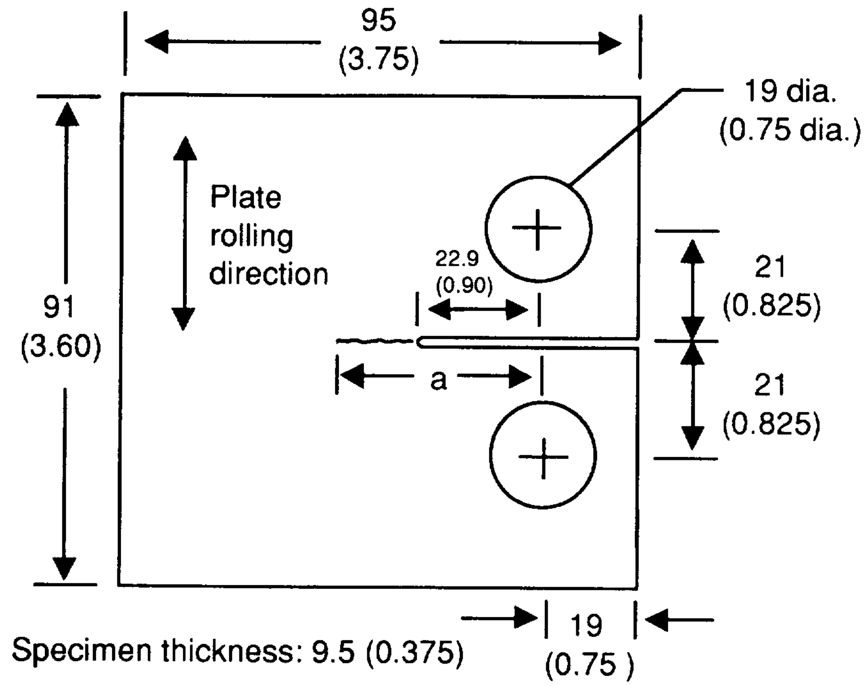


Figure 1.- C(T) specimen configuration used in the Round Robin (dimensions in millimeters(inches)).

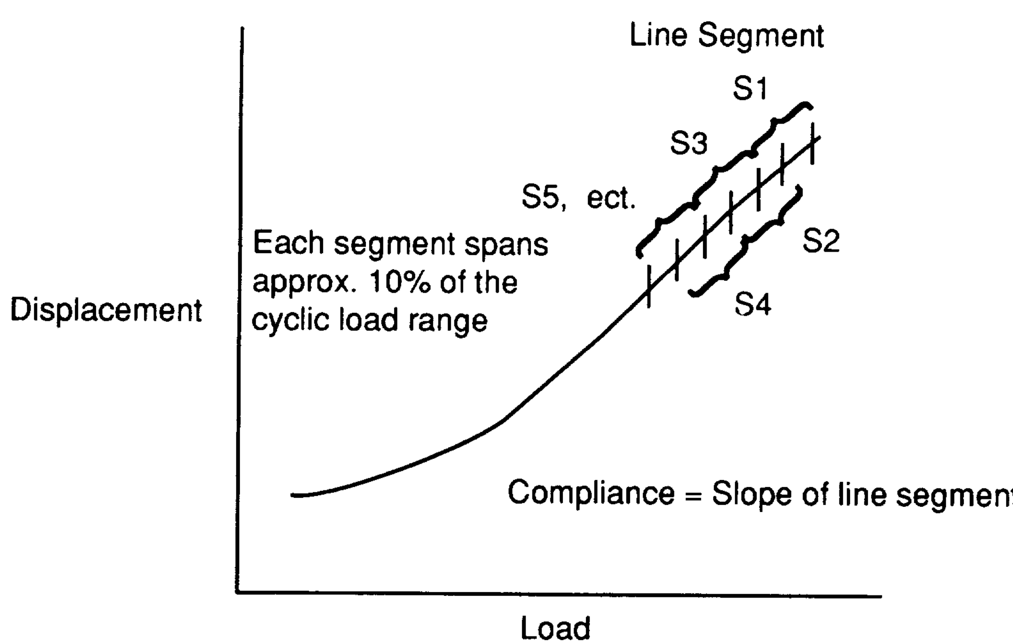


Figure 2. - Evaluation of the variation of compliance with load for use in determination of opening load.

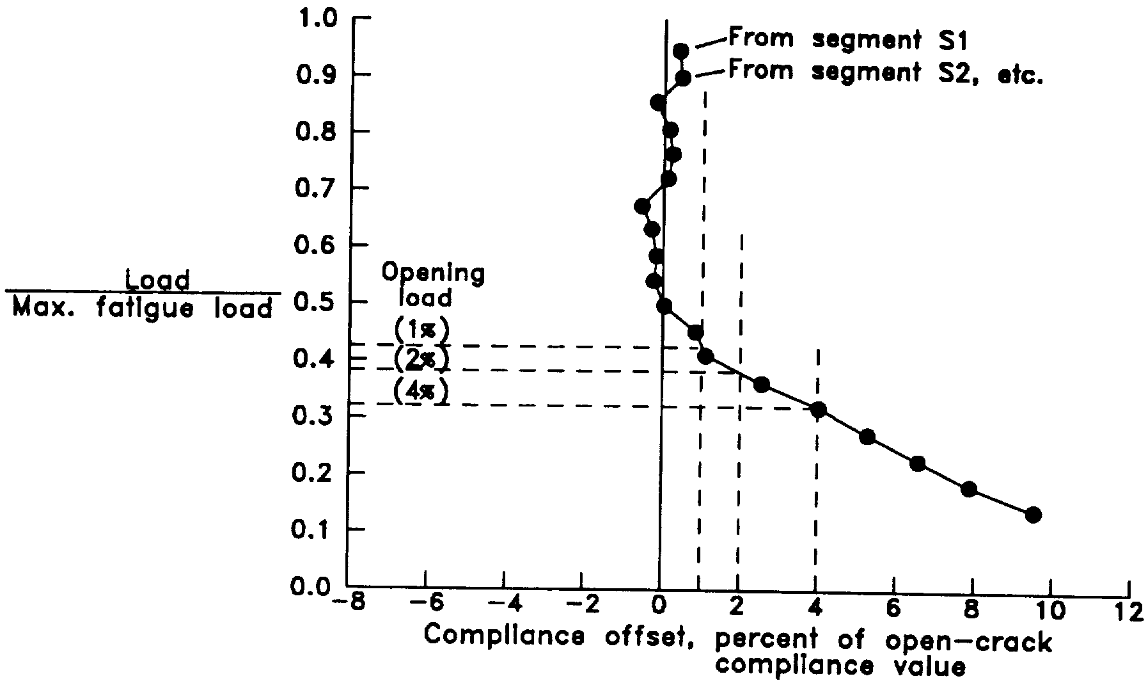


Figure 3.– Example of determination of opening load using the compliance offset method.

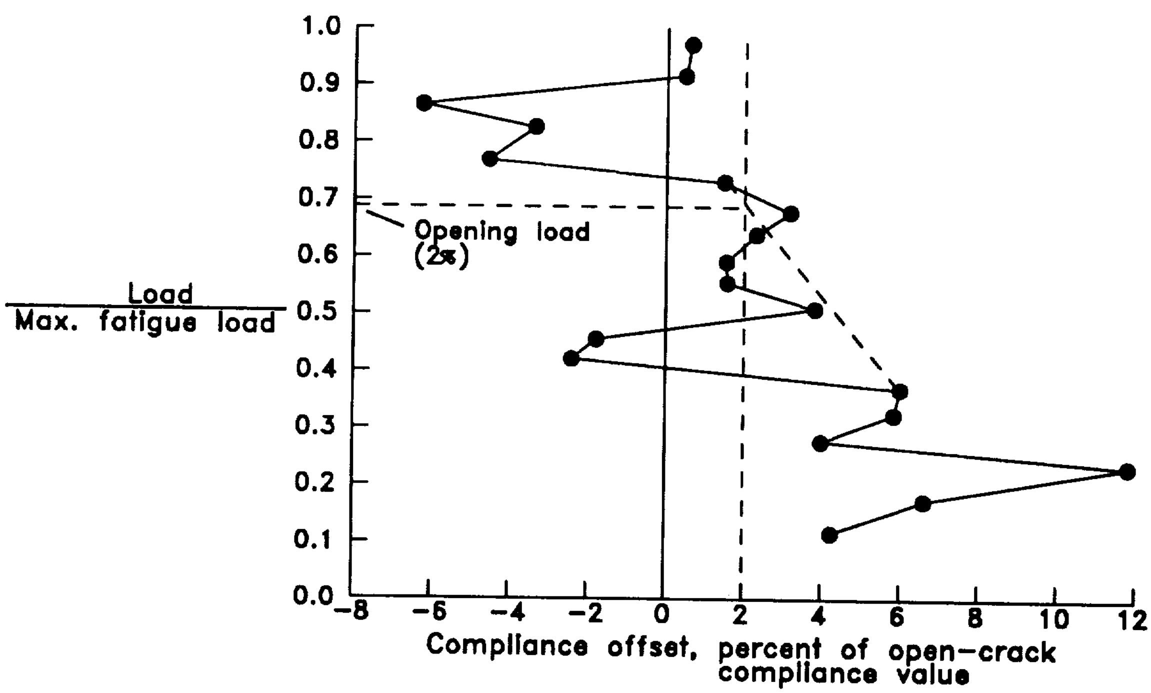


Figure 4.– Example of high opening load result from compliance offset analysis method caused by high variability in compliance data.

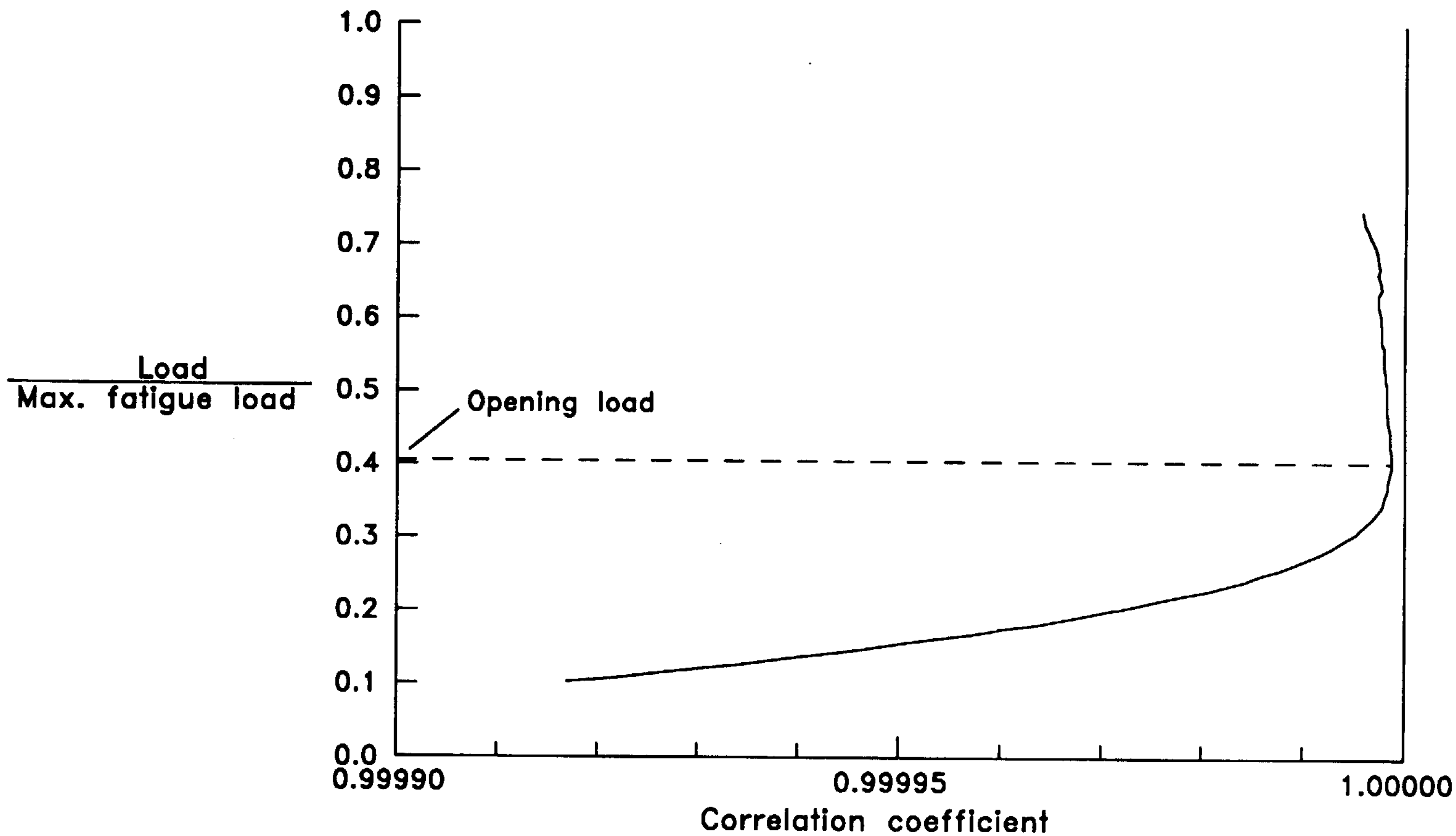


Figure 5.– Example of determination of opening load using the correlation coefficient method.

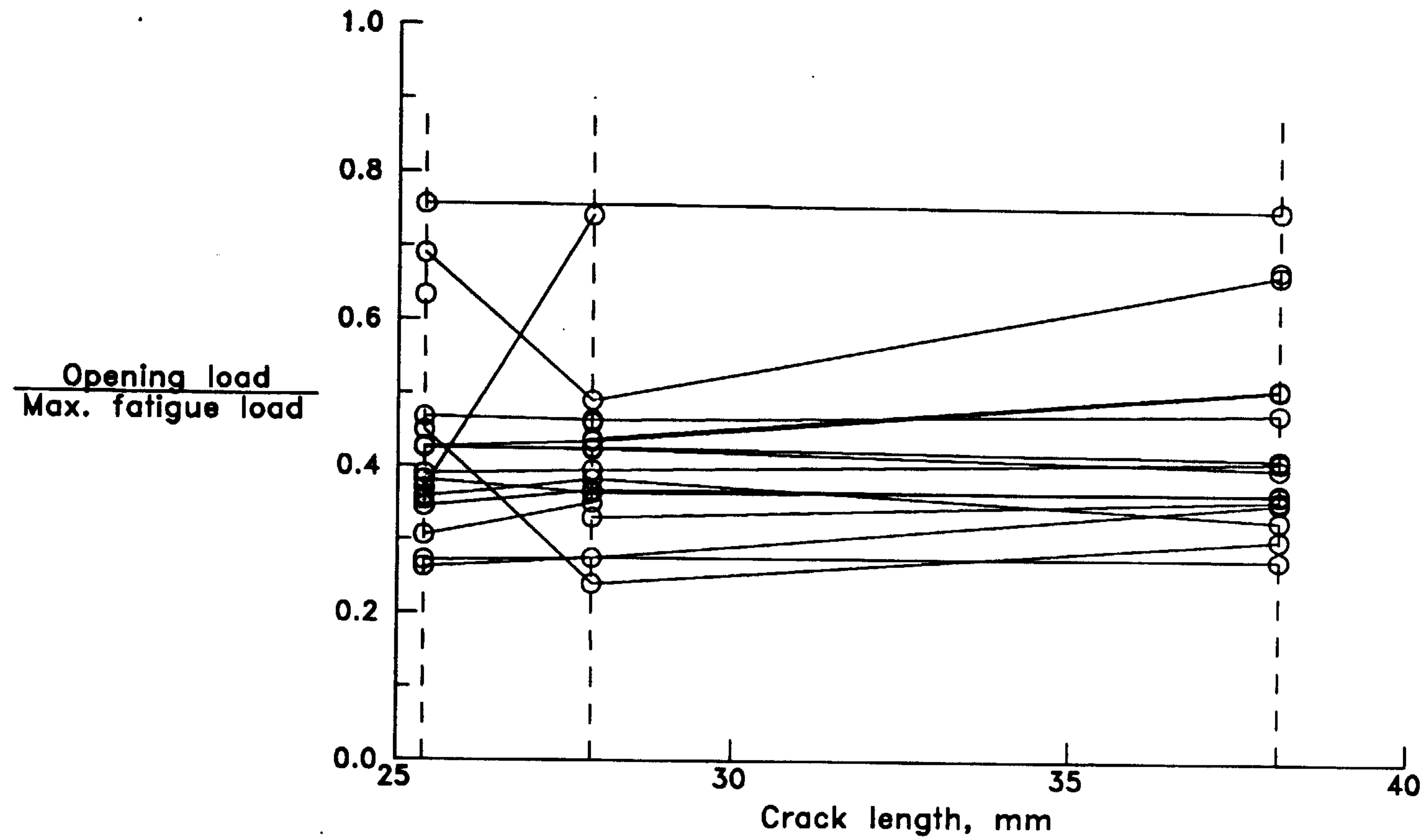
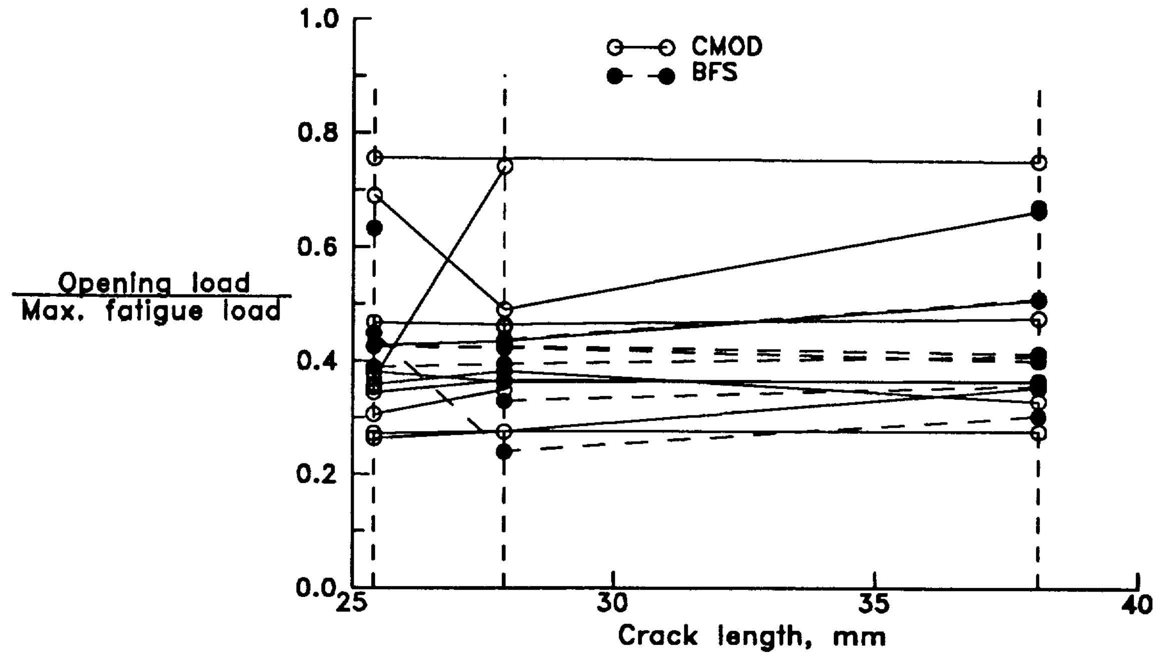
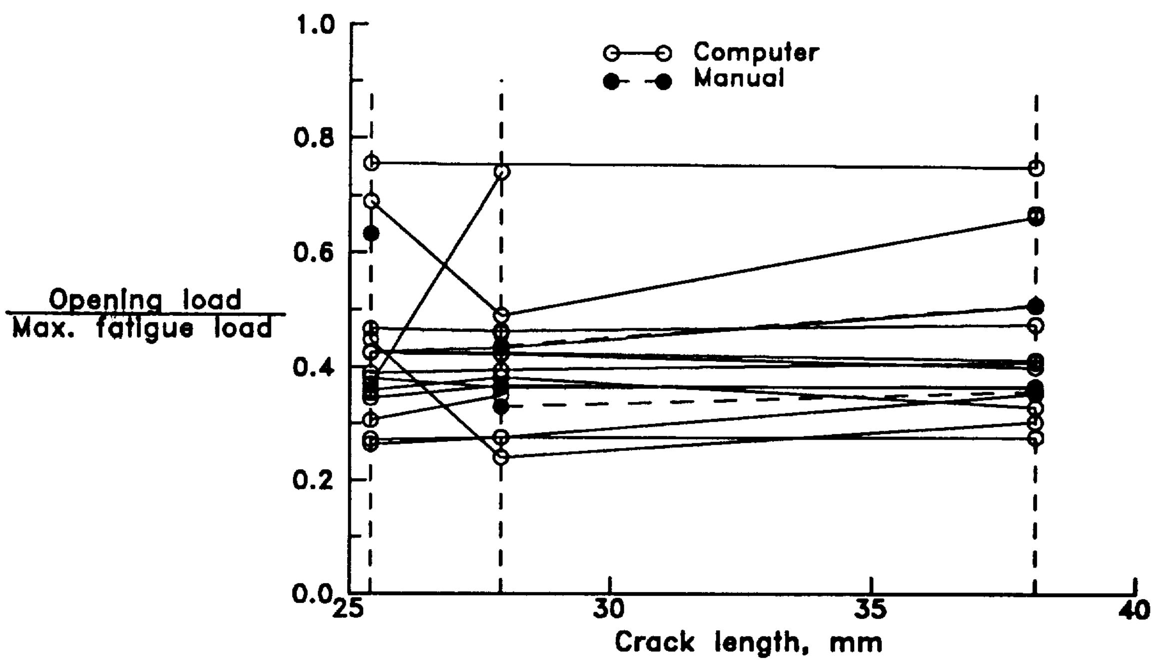


Figure 6.– Opening load values determined by the compliance offset method for all of the constant ΔK tests. (Compliance offset criterion = 2%)



(a) CMOD versus BFS measurement locations



(b) Computer versus manual test control

Figure 7.– Effects of displacement or strain measurement location and of test control method on opening load results.

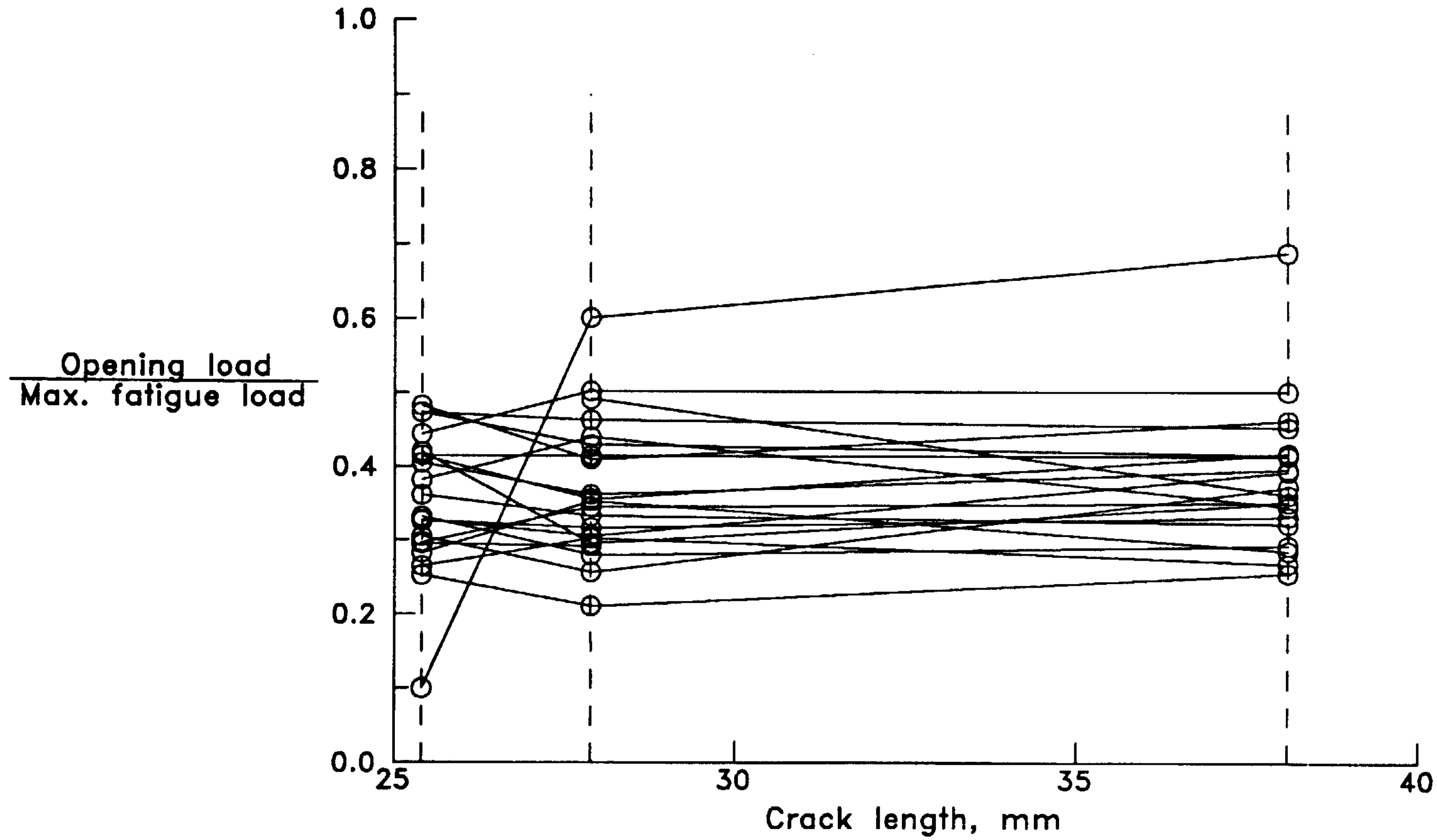
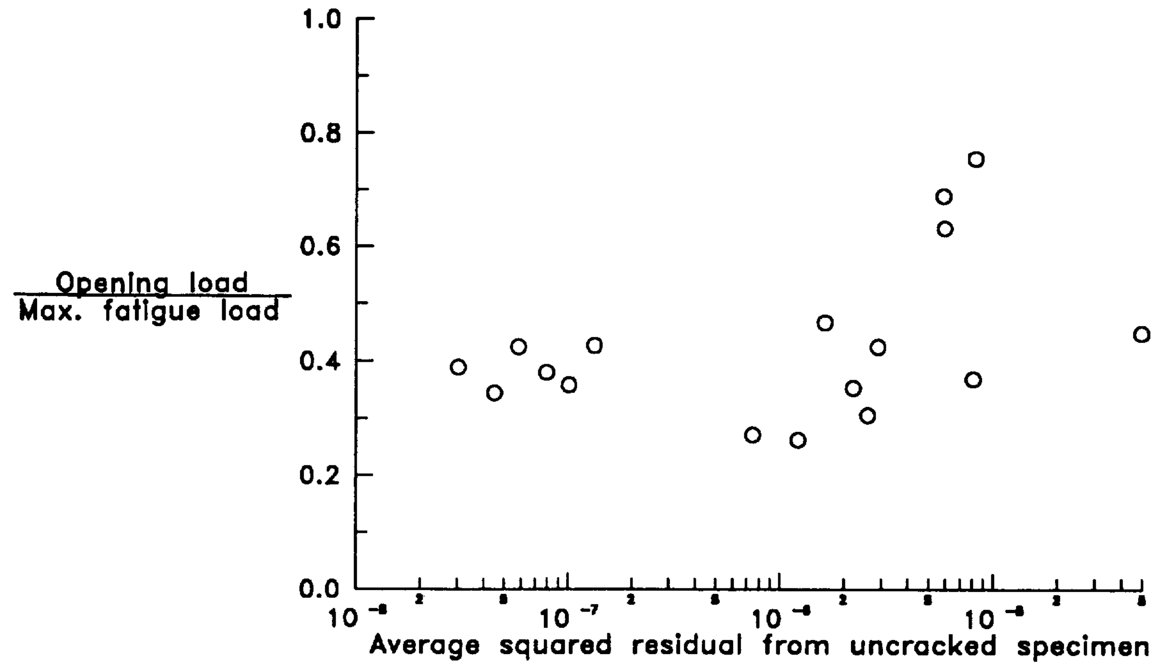
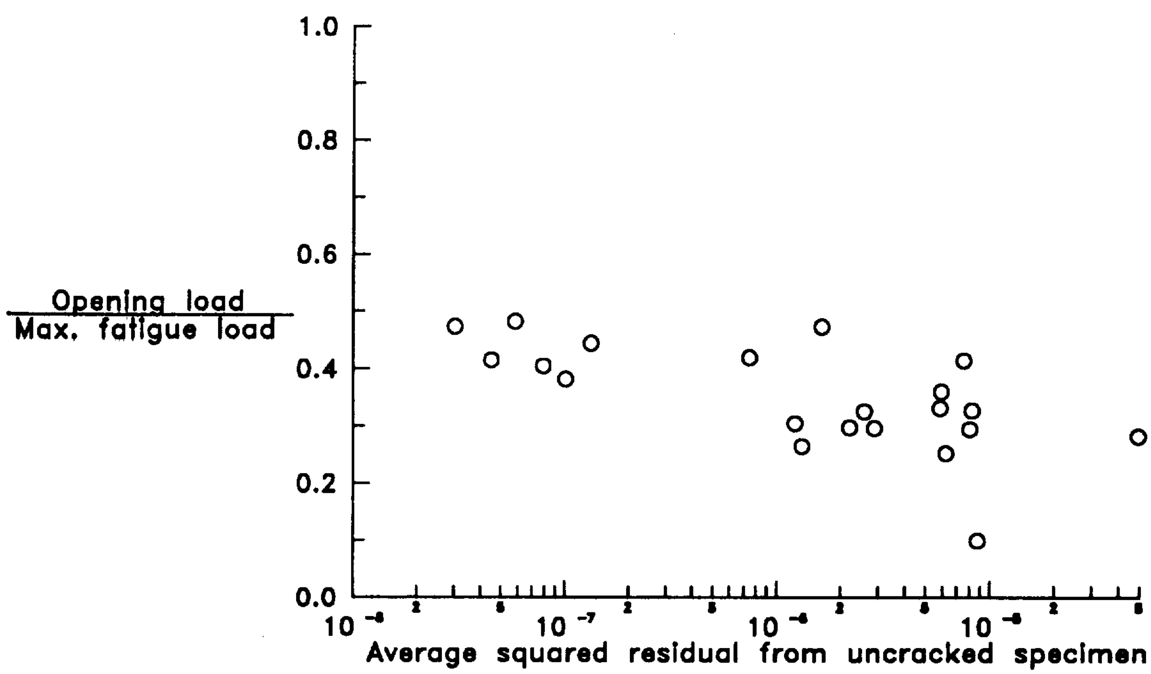


Figure 8.– Opening load values determined by the correlation coefficient method for all of the constant ΔK tests.

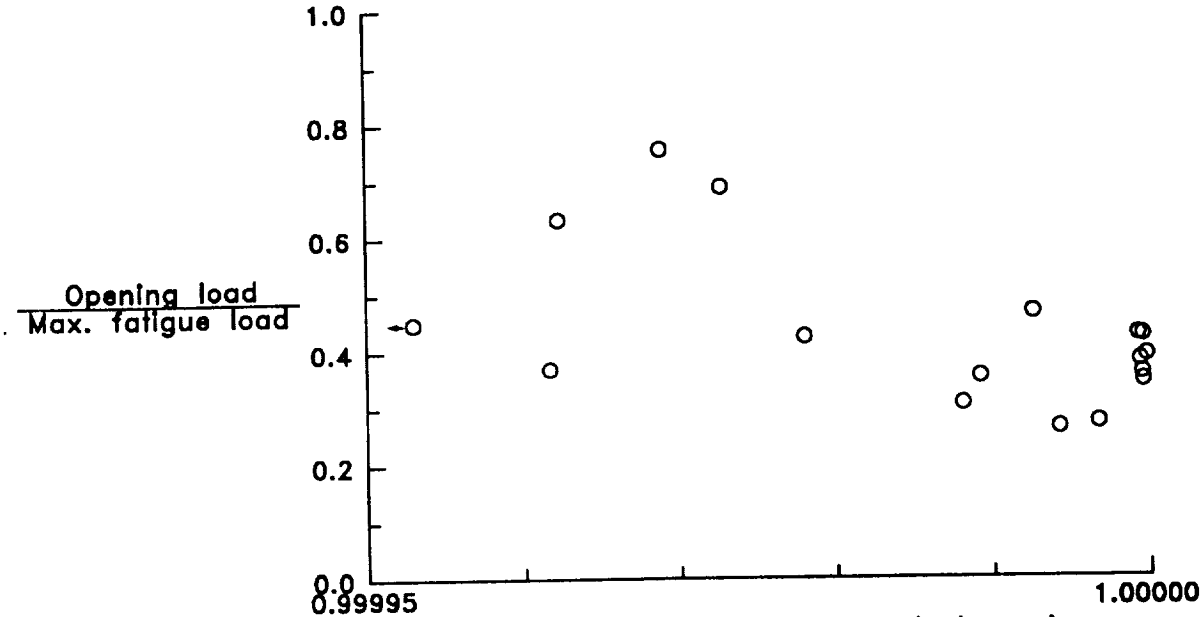


(a) Compliance offset method (Compliance offset criterion=2%)

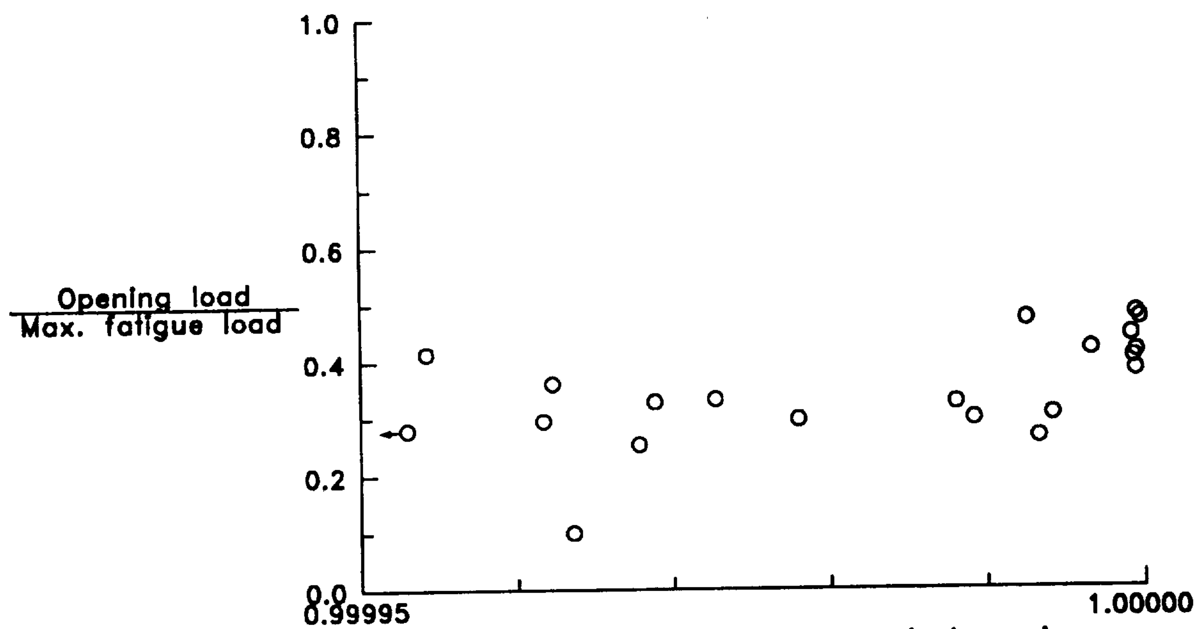


(b) Correlation coefficient method

Figure 9.– Correlation between the average of the squares of residuals (ASR) data quality measure and the opening loads determined by the compliance offset and correlation coefficient methods at a crack length of 25.4 mm.

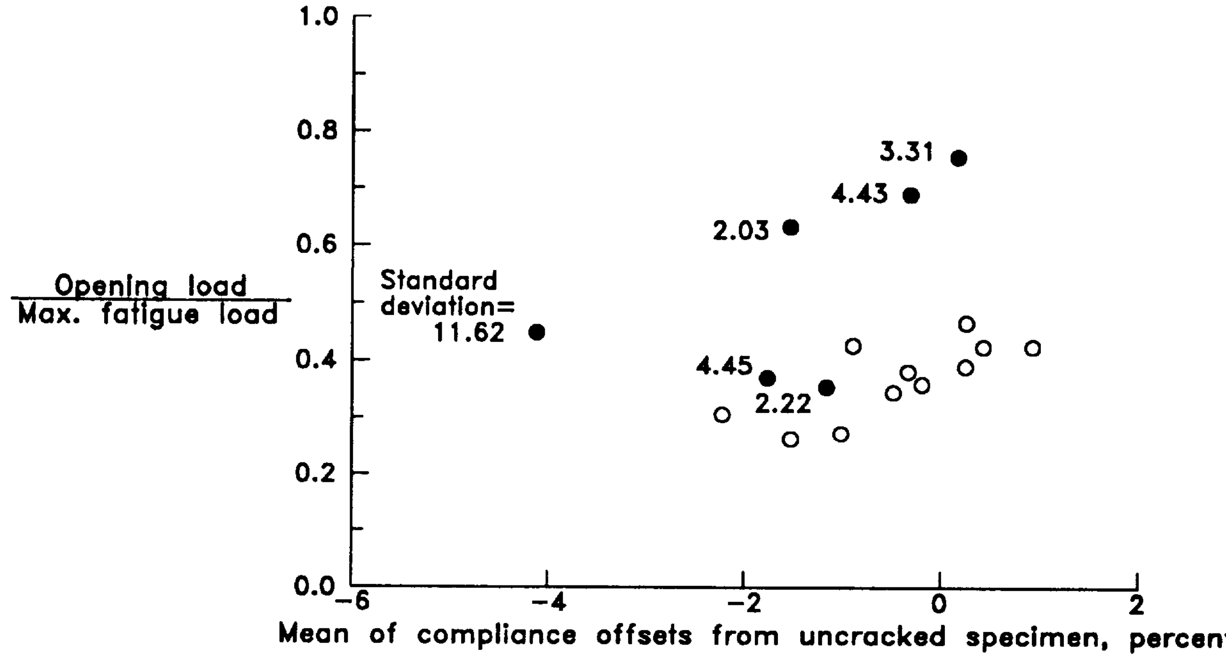


(a) Compliance offset method (Compliance offset criterion=2%)

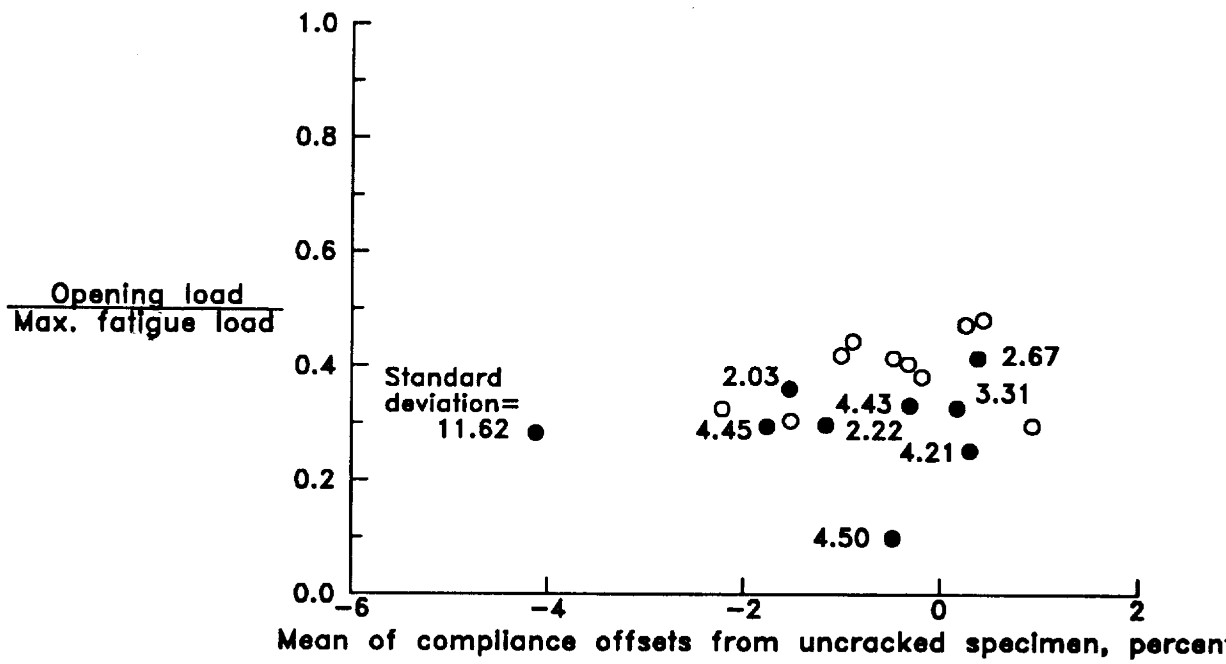


(b) Correlation coefficient method

Figure 10.– Correlation between the correlation coefficient data quality measure and the opening loads determined by the compliance offset and correlation coefficient methods at a crack length of 25.4 mm.

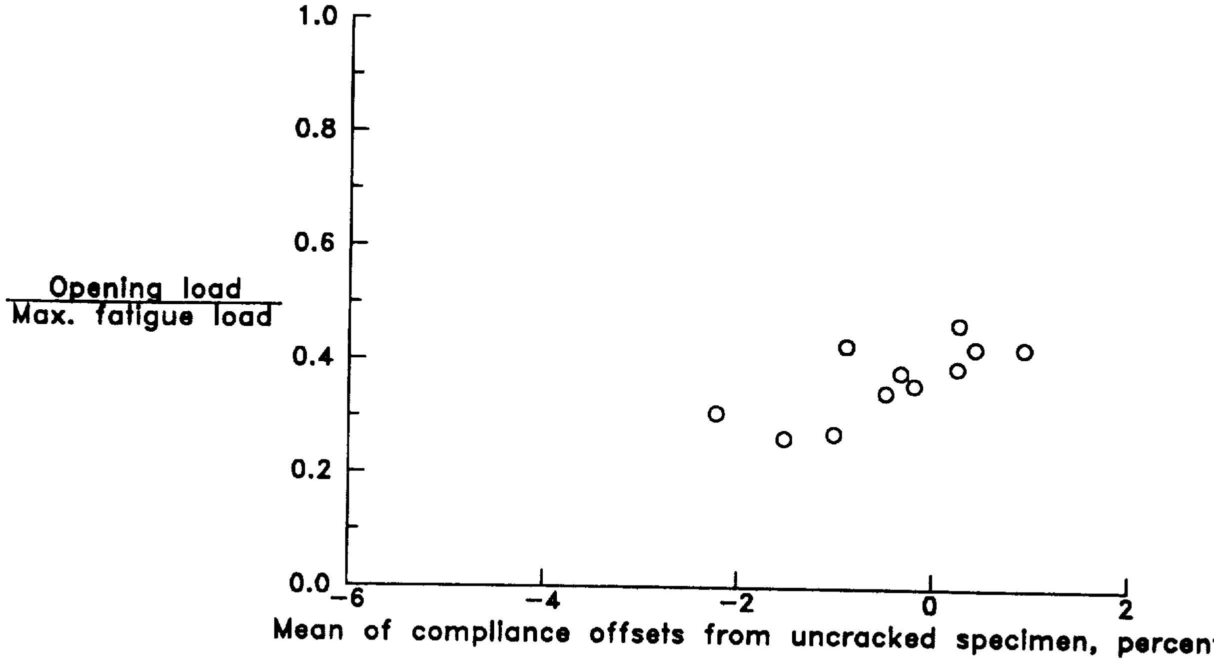


(a) Compliance offset method (Compliance offset criterion=2%)

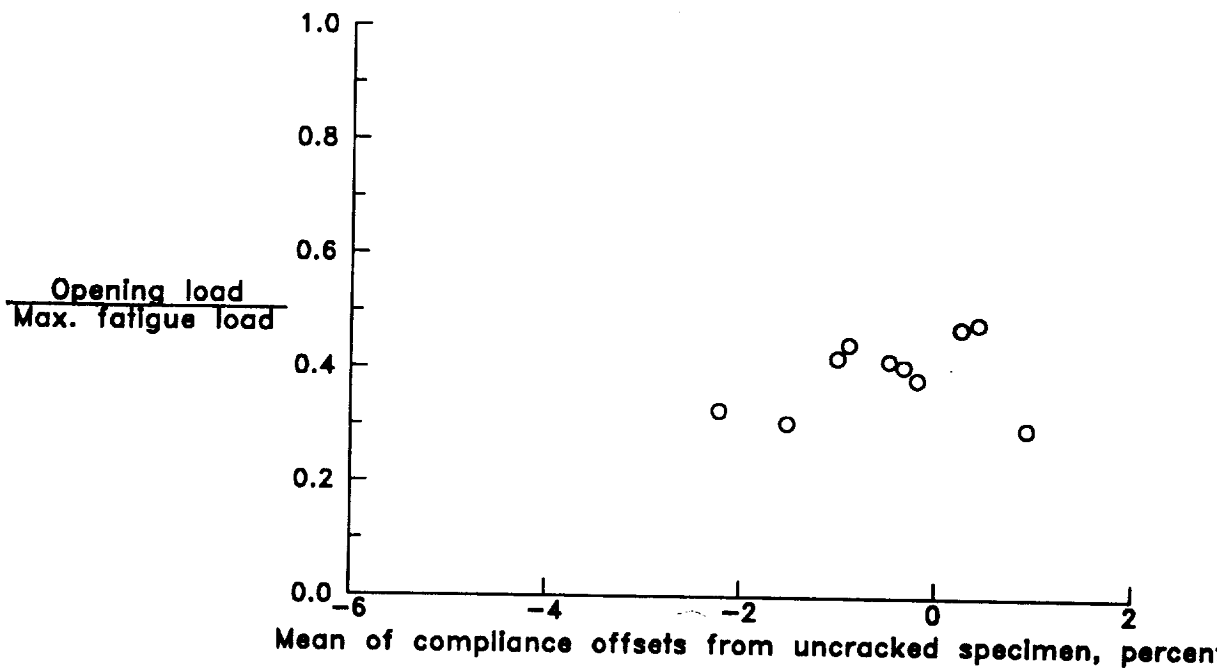


(b) Correlation coefficient method

Figure 11.– Correlation between the mean–compliance–offset data quality measure and the opening loads determined by the compliance offset and correlation coefficient methods at a crack length of 25.4 mm.



(a) Compliance offset method (Compliance offset criterion=2%)



(b) Correlation coefficient method

Figure 12.– Same results as in Figure 11 except that tests with a standard deviation of compliance offsets greater than 2% have been excluded.

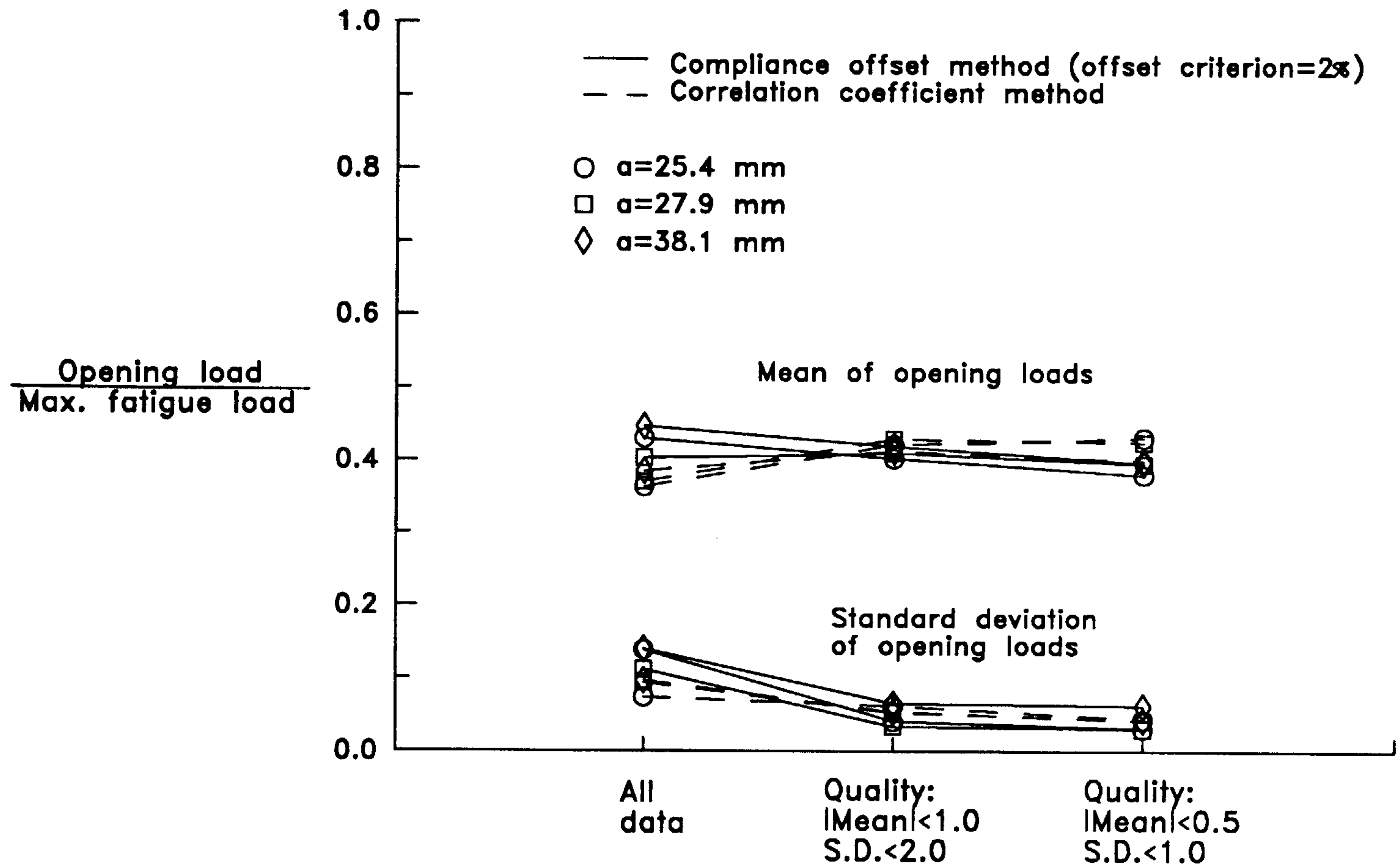
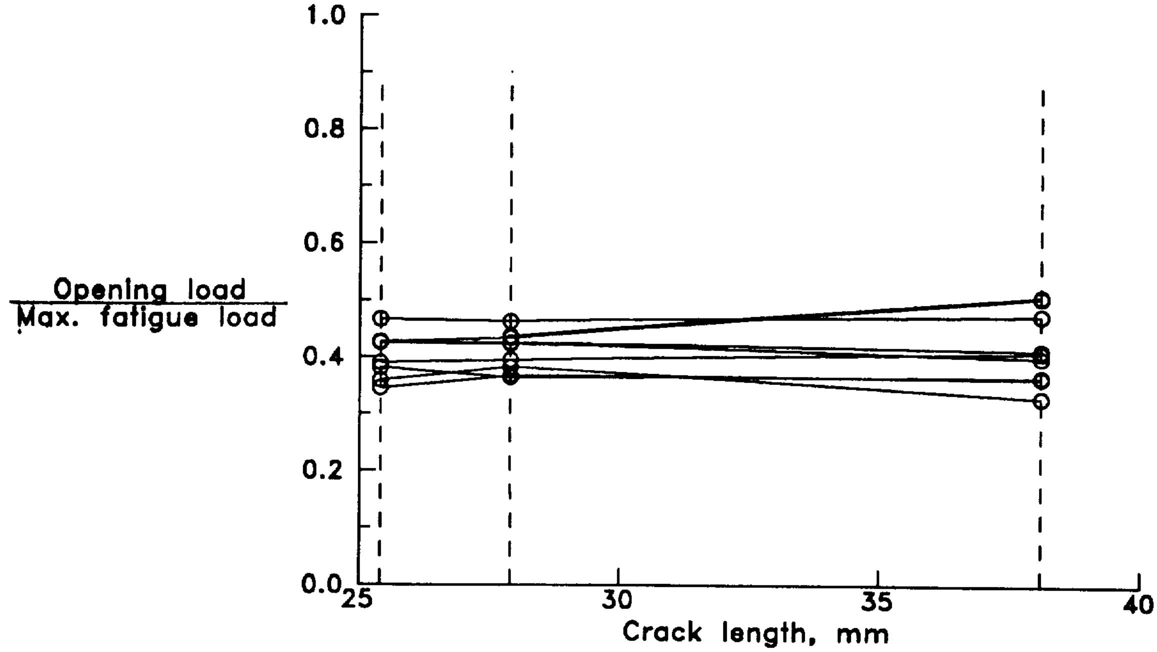
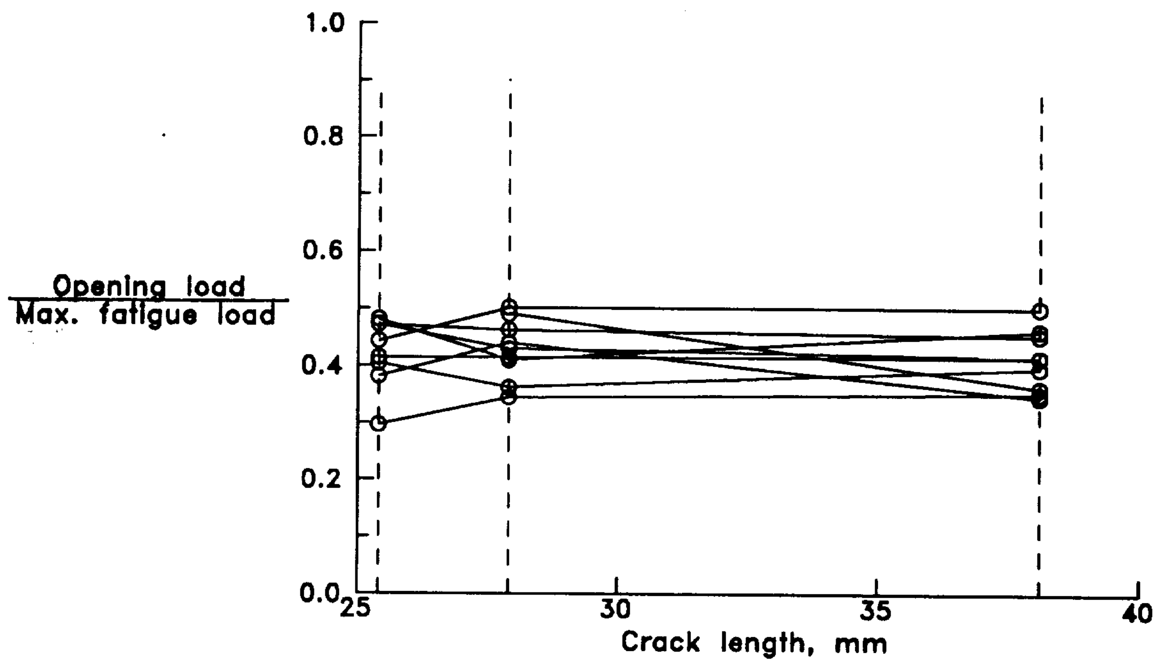


Figure 13.– Effect of applying data quality accept/reject criteria based on compliance offsets on the opening load results from the constant ΔK tests.



(a) Compliance offset method (Compliance offset criterion=2%)



(b) Correlation coefficient method

Figure 14.– Opening load values determined by the compliance offset and the correlation coefficient methods for tests meeting the |m|<1,SD<2 data quality criterion based on compliance offsets.

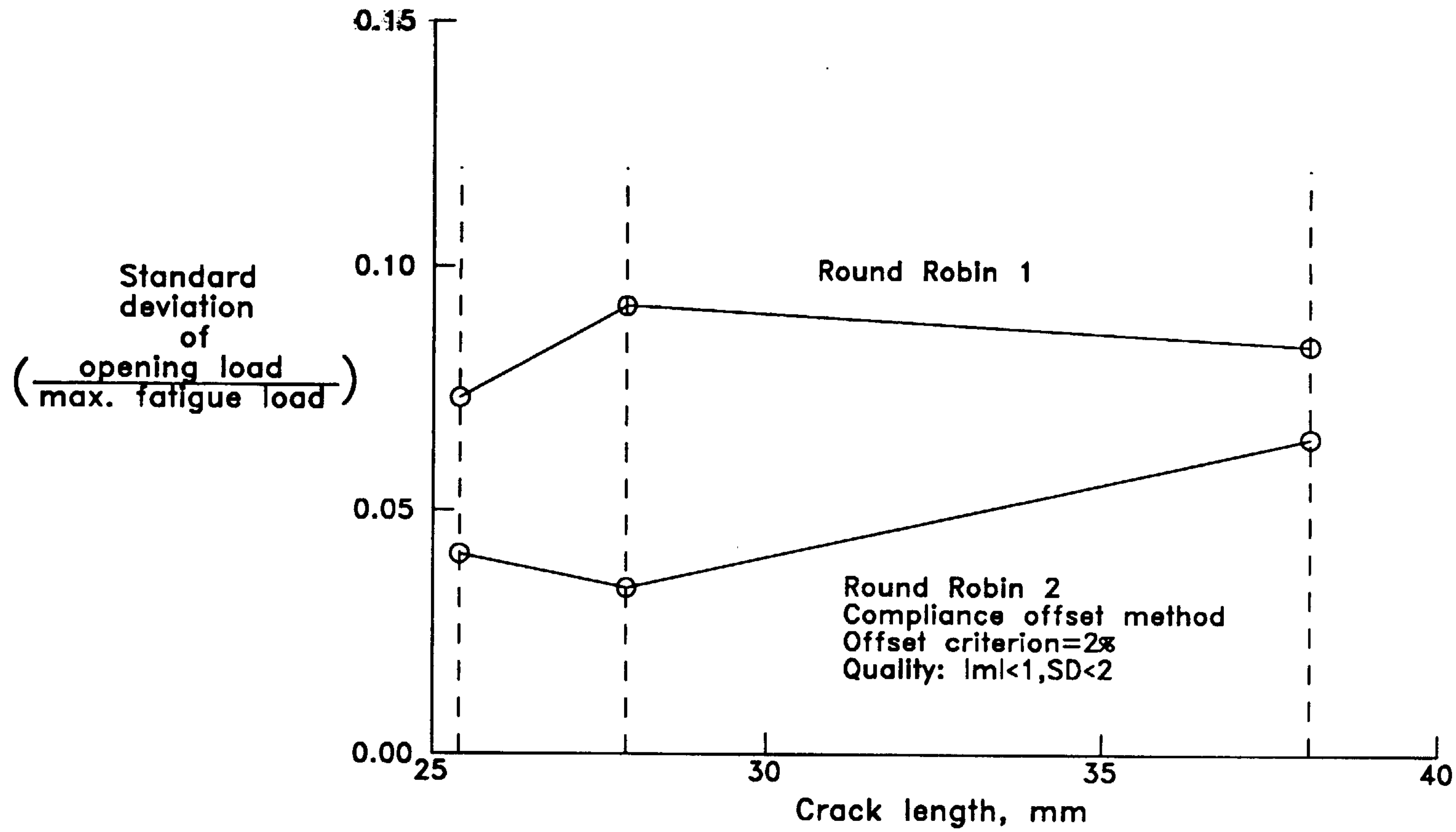


Figure 15.– Comparison of scatter in opening loads from constant ΔK tests in the first and second Round Robins.

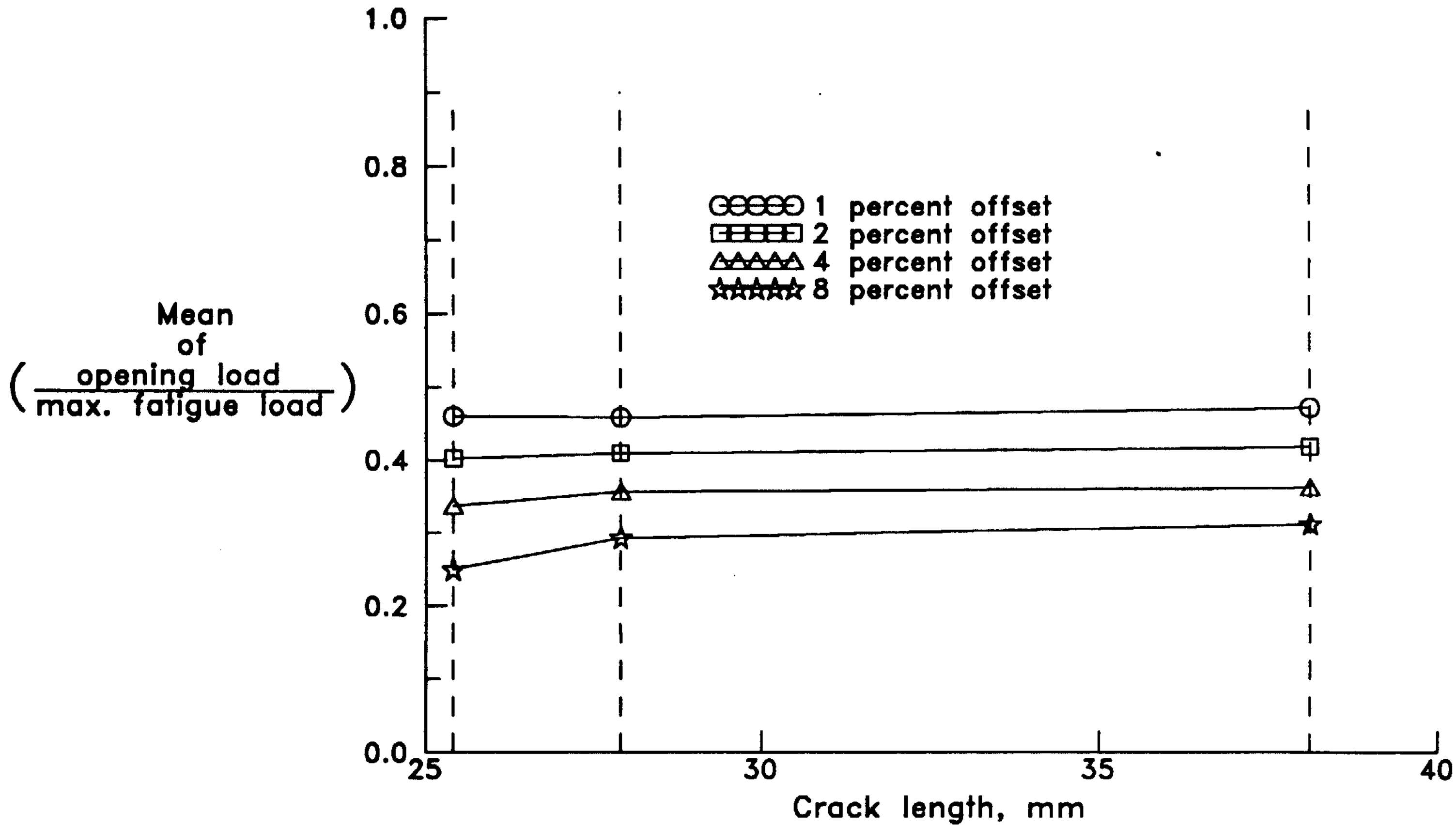


Figure 16.– Variation of the mean of the opening loads from the constant ΔK tests (data quality: $|m|<1, SD<2$) as a function of the offset criterion used in the compliance offset analysis method.

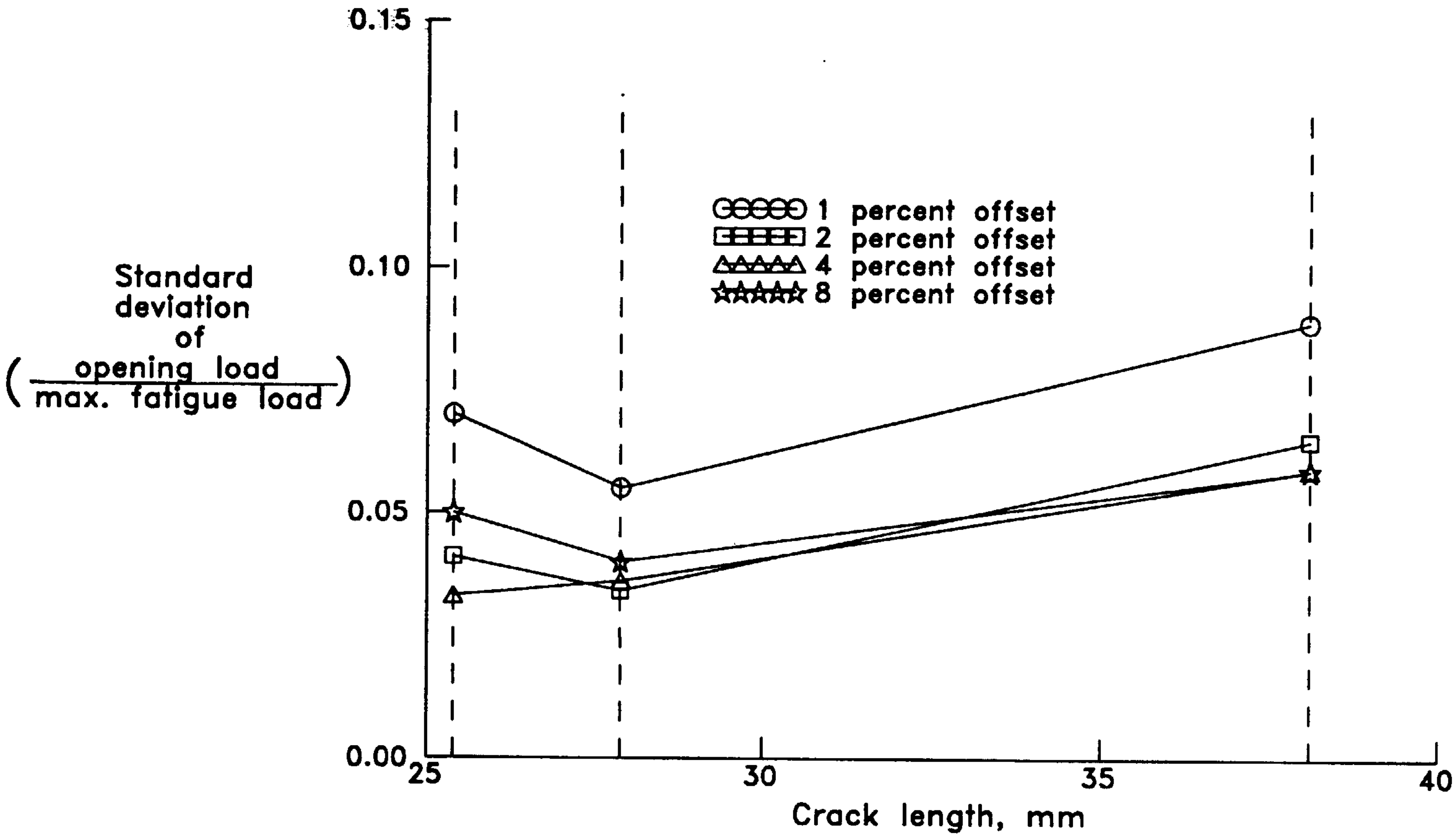


Figure 17.– Variation of the standard deviation of opening loads from the constant ΔK tests (data quality: |m|<1,SD<2) as a function of the offset criterion used in the compliance offset analysis method.

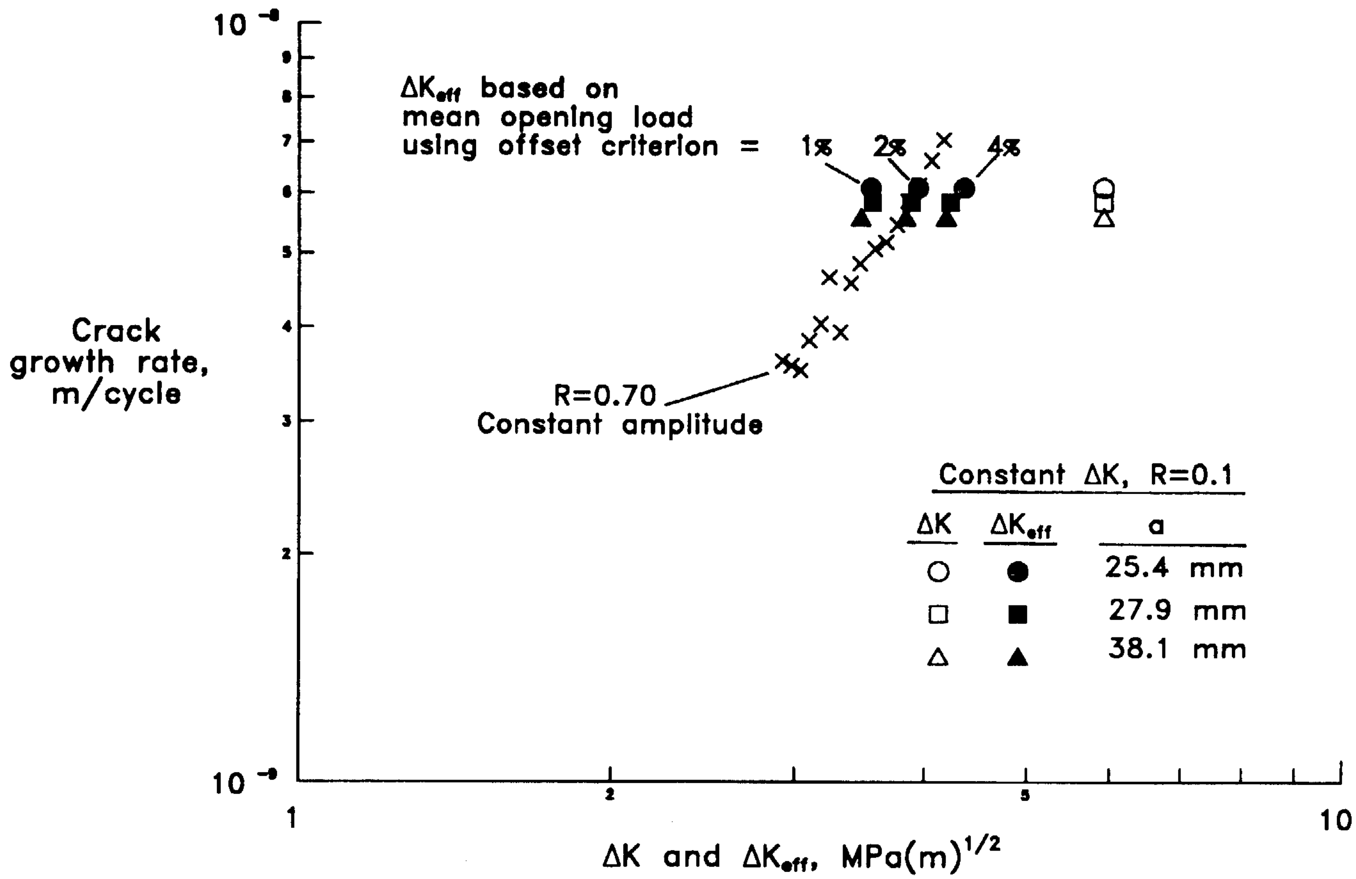


Figure 18.– Comparison of ΔK_{eff} values based on measured opening loads from R=0.1 Round Robin tests (data quality: |m|<1,SD<2) with ΔK values from a R=0.7 test.

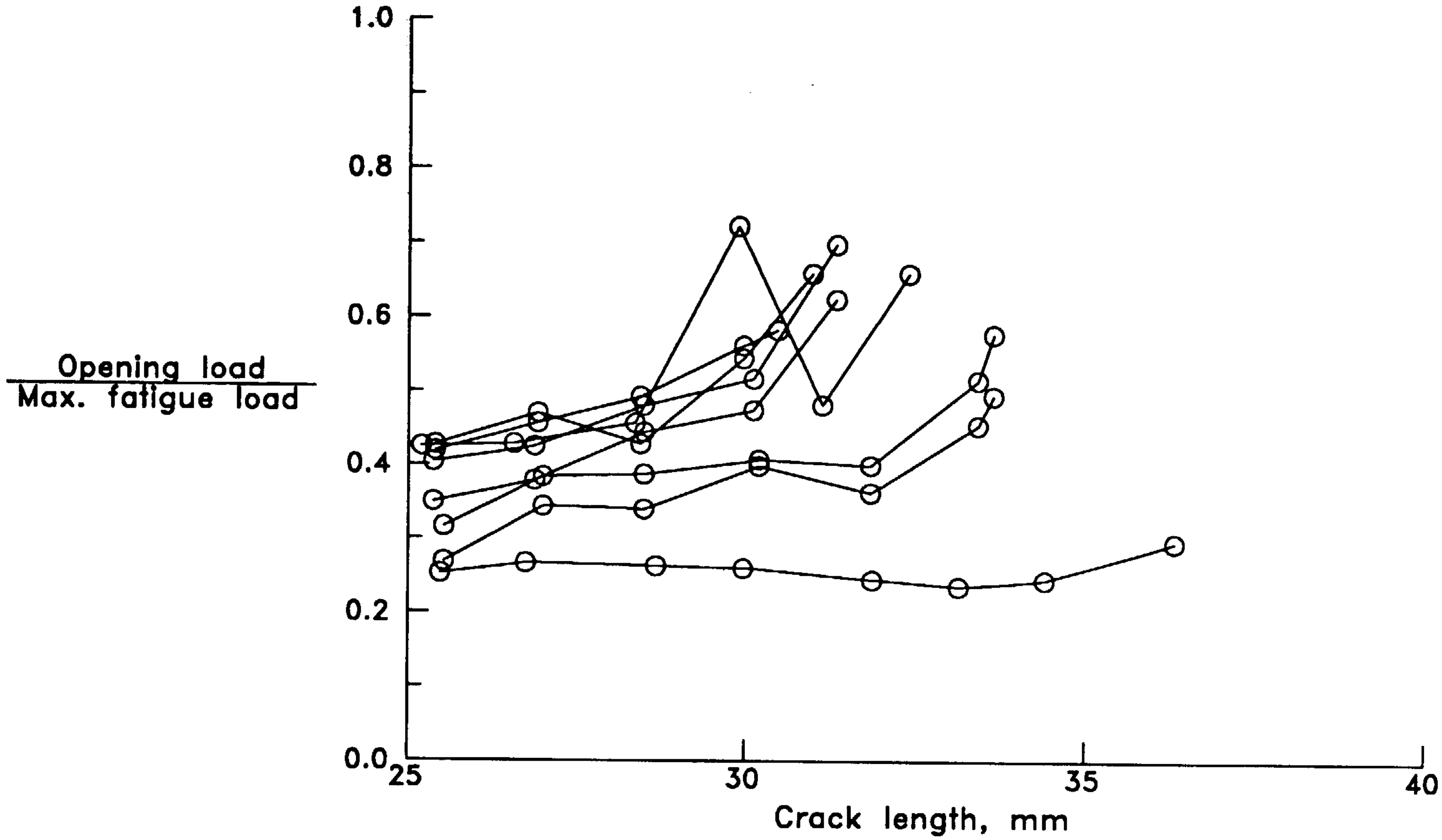


Figure 19.– Opening load values determined by the compliance offset method for all of the threshold tests (offset criterion=2% and data quality: |m|<1,SD<2).

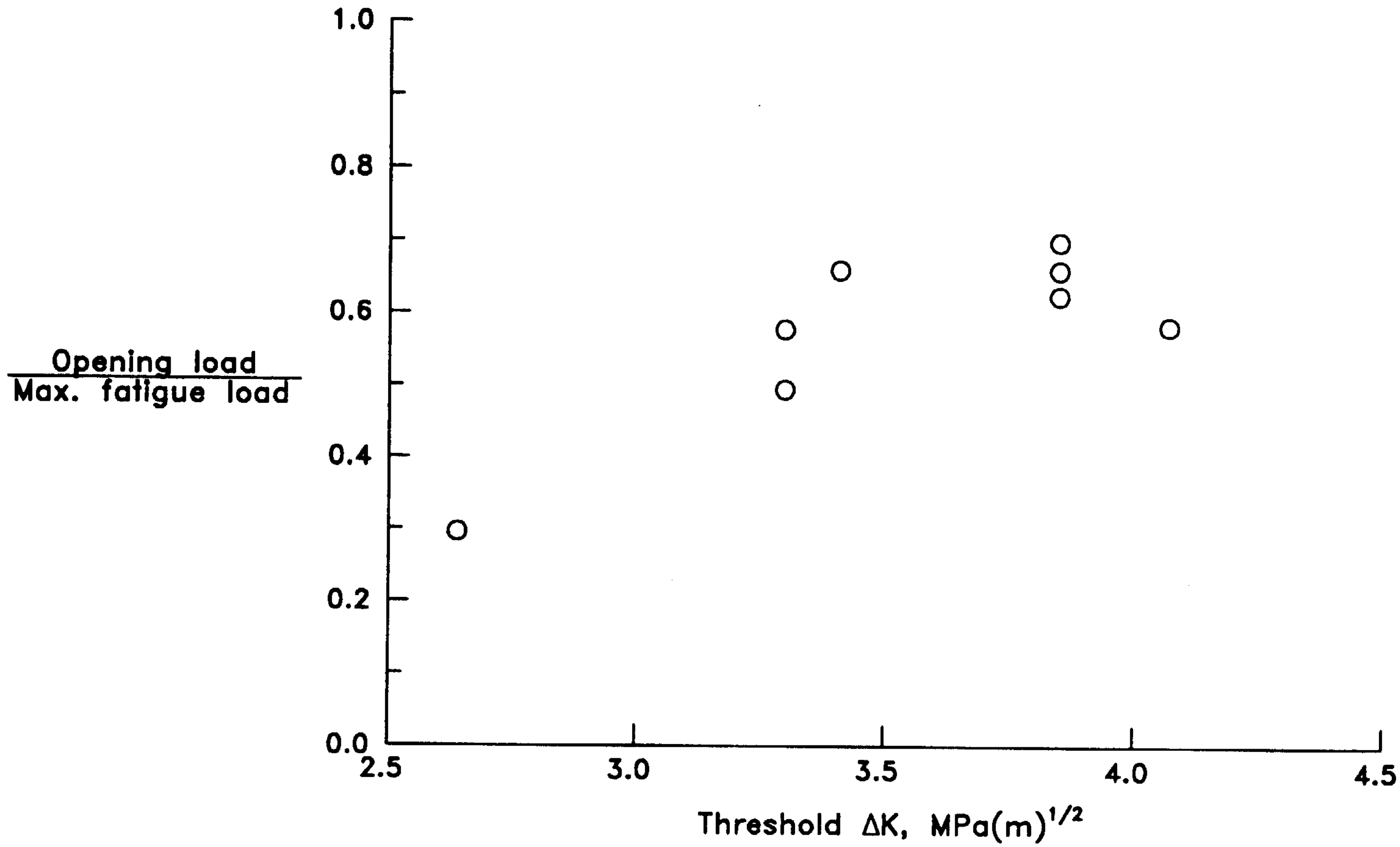


Figure 20.– Correlation between opening loads determined by the compliance offset method at threshold and the threshold ΔK values (offset criterion=2% and data quality: |m|<1,SD<2).

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE
November 1993

3. REPORT TYPE AND DATES COVERED
Technical Memorandum

4. TITLE AND SUBTITLE
Results of the Second Round Robin on Opening-Load Measurement Conducted by ASTM Task Group E24.04.04 on Crack Closure Measurement and Analysis

5. FUNDING NUMBERS
WU 50-63-50-04

6. AUTHOR(S)
E. P. Phillips

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
NASA Langley Research Center
Hampton, VA 23681-0001

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Langley Research Center
Hampton, VA 23681-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA TM-109032

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited

Subject Categories 39 and 05

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

A second experimental Round Robin on the measurement of the crack opening load in fatigue crack growth tests has been completed by the ASTM Task Group E24.04.04 on Crack Closure Measurement and Analysis. Fourteen laboratories participated in the testing of aluminum alloy compact tension specimens. Opening-load measurements were made at three crack lengths during constant ΔK, constant stress ratio tests by most of the participants. Four participants made opening-load measurements during threshold tests. All opening-load measurements were based on the analysis of specimens compliance behavior, where the displacement/strain was measured either at the crack mouth or the mid-height back face location. The Round Robin data were analyzed for opening load using two non-subjective analysis methods--the compliance offset and the correlation coefficient methods. The scatter in the opening load results was significantly reduced when some of the results were excluded from the analysis population based on an accept/reject criterion for raw data quality. The compliance offset and correlation coefficient opening load analysis methods produced similar results for data populations that had been screened to eliminate poor quality data.

14. SUBJECT TERMS
Cracks; Crack closure; Crack propagation; Fatigue (materials); Metal Fatigue

15. NUMBER OF PAGES
37

16. PRICE CODE
A03

17. SECURITY CLASSIFICATION OF REPORT
Unclassified

18. SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

19. SECURITY CLASSIFICATION OF ABSTRACT

20. LIMITATION OF ABSTRACT

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102