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The Effect of Rotation on Load-Line Displacement Measurements Using Capacitance Gages in a Compact Tension Specimen

by

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Non-contacting electrical or optical transducers are attractive for dynamic fracture toughness testing because their frequency response is not limited by the inherent vibration characteristics of the clip gage, which is typically used for quasi-static testing. One such transducer uses the principle of capacitance to measure displacement between the gage and an electrically grounded target. The problem with capacitance transducers is that the reference points used for measurement move as the separating specimen halves rotate under applied load. The purpose of this study was to investigate the effect of specimen rotation on the displacement measured by a capacitive gage, and to determine how close the measured displacement was to the actual load-line displacement. Errors in load-line displacement measurement for contacting (clip gage) and non-contacting capacitive (cap gage) transducers were compared. It was found that both types of transducers show a similar trend of increasing error with increasing displacement, however, the error was always less than the 1% allowable in the ASTM test method for fracture toughness testing. The error in the cap gage measurements was actually less than the clip gage error. Consequently, rotation of the specimen halves does not adversely affect the load-line displacement measurements taken with a capacitance gage.

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Summary

Non-contacting electrical or optical transducers are attractive for dynamic fracture toughness testing because their frequency response is not limited by the inherent vibration characteristics of the clip gage, which is typically used for quasi-static testing. One such transducer uses the principle of capacitance to measure displacement between the gage and an electrically grounded target. The problem with capacitance transducers is that the reference points used for measurement move as the separating specimen halves rotate under applied load. The purpose of this study was to investigate the effect of specimen rotation on the displacement measured by a capacitive gage, and to determine how close the measured displacement was to the actual load-line displacement. Errors in load-line displacement measurement for contacting (clip gage) and non-contacting capacitive (cap gage) transducers were compared. It was found that both types of transducers show a similar trend of increasing error with increasing displacement, however, the error was always less than the 1% allowable in the ASTM test method for fracture toughness testing. The error in the cap gage measurements was actually less than the clip gage error. Consequently, rotation of the specimen halves does not adversely affect the load-line displacement measurements taken with a capacitance gage.

Introduction

For some types of materials loading rate can have a significant effect on fracture toughness. This rate effect has stimulated efforts to develop methods and procedures for dynamic fracture toughness testing. High rate testing presents some unique challenges. One of those challenges is the measurement of displacement of the specimen during crack initiation and growth under dynamic loading.

Clip gages are typically used to measure displacement in quasi-static tests. However, they are not suitable for dynamic testing because they rely on spring force to maintain contact with the specimen. The mass and inherent vibration characteristics of the clip gage cause it to lose contact with the specimen during impact loading. Non-contacting electrical or optical transducers are attractive for dynamic testing because their frequency response is not limited by the inherent vibration characteristics of the gage. One such transducer uses the principle of capacitance to measure displacement between the gage and an electrically grounded target. The output from this capacitive gage is inherently non-linear. The amplifier used with this gage takes the non-linear input from the gage and, after careful calibration, produces a reasonably linear DC output representing the desired displacement. The amplifier also has sufficient frequency response to capture the transient events that occur during impact loading.

The problem with the capacitance gage is that the reference points used for measurement move when the specimen halves rotate under applied load, as they do in the compact tension [C(T)] specimen [1]. When a test begins, the center of the cap gage is aligned with the load line (LL) of the specimen. A line centered on the cap gage and perpendicular to its face lies on the load line of the specimen. As load is applied to the specimen, the "arms" of the specimen rotate causing the cap gage and its target to rotate relative to one another. At this time the gap is no longer parallel, and the point on the target where the perpendicular line intersects moves away from the load line. The purpose of this study is to investigate the effect of specimen rotation on the displacement measured by a cap gage and to determine how close the measured displacement is to the actual load-line displacement.

The Test Fixture

To determine what effect the relative rotation of the cap gage and its target have on its ability to accurately measure load-line displacement, a test fixture was designed that simulates the rotation of a C(T) specimen as load is applied (Figure 1). This fixture was made from a 1 in. thick C(T) specimen. The C(T) design used (see Figure 2) has integral knife edges to mount a clip gage and a notch designed to mount the cap gage, thereby allowing the specimen to be tested either dynamically or quasi-statically without additional machining or specimen preparation.

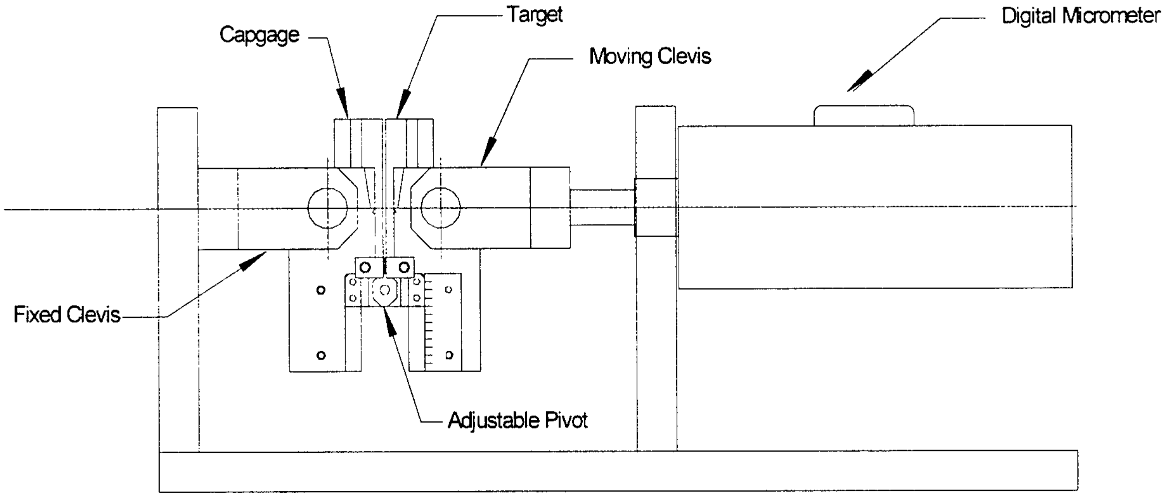

Figure 1. Fixture used to simulate rotation in C(T) specimen

The C(T) specimen was cut in half on its centerline (centerline of the notch) and an adjustable pivot was added between the two halves. This pivot allows the rotation point (Rp) to be adjusted from Rp/W = 0.5 to Rp/W = 0.9, where W is the distance from the centerline of the loading holes to the un-notched face of the specimen. The fixture consists of two aligned clevises, one attached to the fixture and the other mounted to a calibrated digital micrometer. The micrometer was used to measure the load line (LL) displacement of the pins. A spring was placed between the two C(T) halves to remove any slack in the fixture and to provide some pre-load against the pins.

The initial calibration of the cap gage was done using a fixture that kept the gage parallel with the target during calibration. The particular gage used in this study had an approximate linear range of 0.150 in. This is the absolute gap width, so the initial gap is subtracted to obtain the working range. The amplifier can become unstable when the gap width goes to zero, therefore an initial gap of 0.020 in. was used in the calibration. The cap gage was calibrated from 0.020 to 0.170 in. gap in 0.005 in. increments and the gain was adjusted to obtain a 0-10 volt range (approx. 0.015 in./volt).

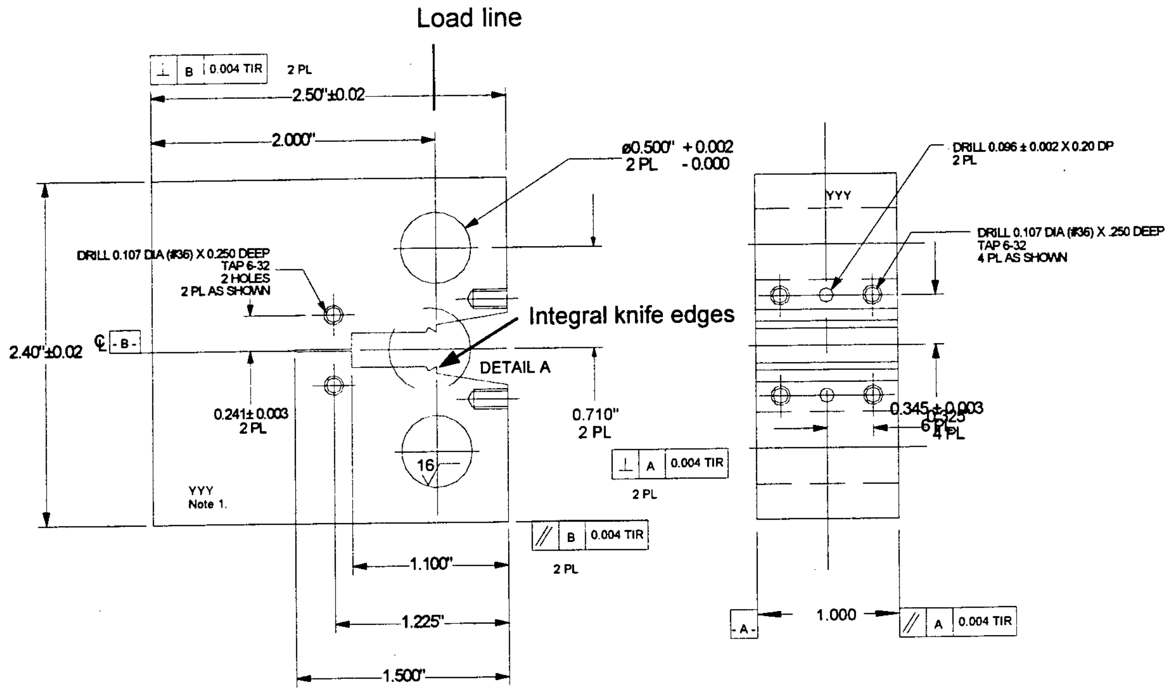

Figure 2. C(T) design for either quasi-static or dynamic testing.

Rotation Effect on Cap Gage Accuracy And Linearity

As stated previously, capacitance is a non-linear function of the distance between the gage and target. The amplifier for the cap gage has linearization circuitry to correct for the non-linearity. The calibration points used were, 0.030 in. (0.667 v), 0.065 in. (3.000 v), 0.075 in. (3.667 v), 0.120 in. (6.667 v), 0.130 in. (7.333 v), 0.170 in. (10.000 v). A linear regression was performed on the measured voltages to obtain a linear slope of 0.014965 in./volt and an offset of 0.01999 in. The linearity of the gage was checked by looking at the difference between the actual gage output and the ideal output for perfect linear response. The ideal output was determined by using the calibrated slope and offset to calculate the voltage at each of the displacement increments. Relative percent error was then calculated by taking the measured output minus the ideal output and dividing by the full scale output of 10 volts. Figure 3 shows the relative error for this calibration. The oscillation of the relative error is a result of the multi-point linearization circuitry of the amplifier. Note that within the range of the gage (0.150 in. absolute gage width) the relative error is less than about ±0.21%, which is close to the ±0.2% recommended by ASTM E1820 [1] for compliance measurement. With some additional adjustment the error could be brought to within the required ±0.2%. Outside of the range (beyond 0.150 in.) the error increases. Once the calibration was completed, no further adjustments were made to the gain, linearization or offset.

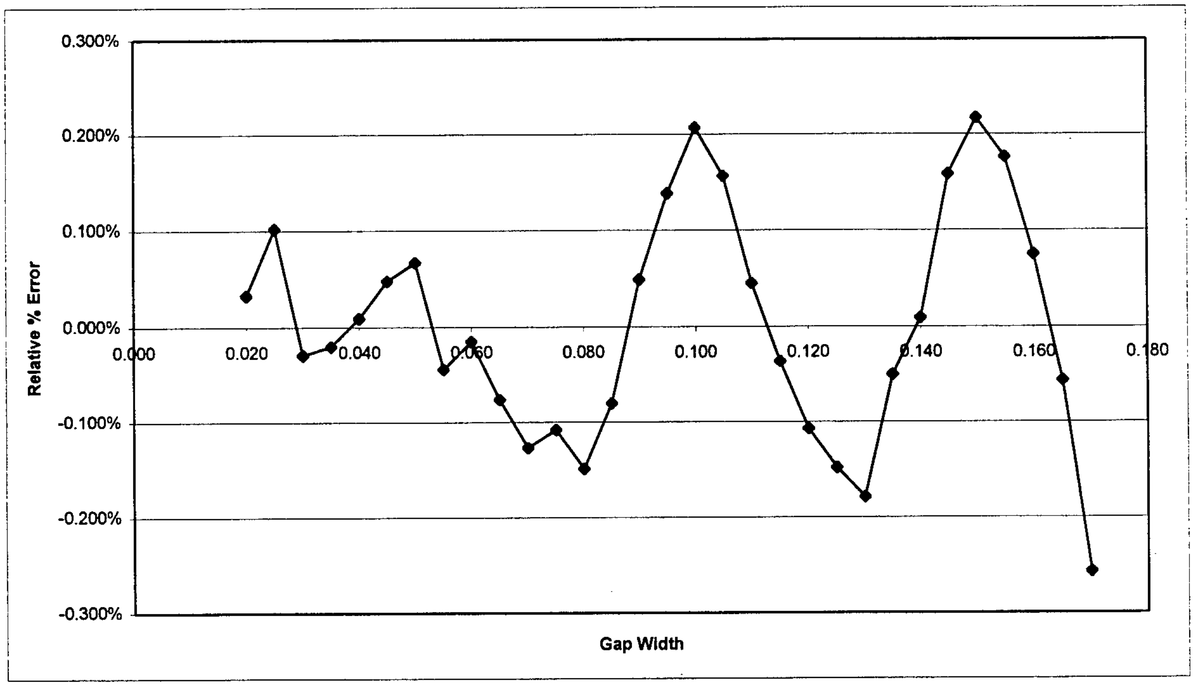

Figure 3. Parallel plate calibration error.

Before testing in the fixture it was necessary to determine the spacing of the clevises that would make the cap gage and target parallel. This was done by placing the two clevises in contact with each other. When the clevises were touching the centers of the holes were 0.75 in. apart. According to the C(T) design used (See Figure 2) the centers of the holes are 1.42 in. apart. Subtracting these two values, it was determined that the clevises need to be opened 0.67 in. from when they are touching to ensure that the cap gage and target are parallel. The cap gage was placed in the fixture and the initial voltage reading was 0.55 v. This indicated that the initial gap was 0.028 in.

To determine the effects of rotation, 6 rotation points were used ranging from Rp/W=0.50 to Rp/W=0.75 in increments of 0.05. At each rotation point the gage output was recorded for each 0.005 in. increment in clevis displacement from 0.000 in. to 0.120 in. (approx. 0.030 in. to 0.150 in. actual gap). The gap was limited to 0.150 in. because the calibration showed increasing error above this value. Since the range in these tests was limited to 0.030 - 0.150 in., rather than the 0.020 - 0.170 in. used in the parallel calibration, the linear regression of the parallel calibration was repeated using this smaller range to obtain a slope of 0.014536 in./volt and an offset of 0.02005 in. This calibration was used to convert the measured voltages to displacement. These displacements were then compared with the true pin (or load-line) displacement as determined by the digital micrometer. Relative error between these two was calculated by subtracting measured displacement from true displacement and dividing by 0.150 in. The resulting error for each rotation point is shown in Figure 4. The parallel calibration is also shown for reference. Note that the relative error comes from two sources, the inherent non-linearity of the gage and the rotation of the gage relative to the target. The parallel calibration relative error shows the inherent non-linearity without rotation effects. The difference between the parallel calibration error and the other error plots is due to the effects of rotation. The data show that while rotation does appear to have some effect, there is no clear trend relating the magnitude of the error to the position of the rotation point. The maximum relative error is about 0.7%. In general the measured displacement is less than the true displacement. Only the data for Rp/W = 0.60 violates this trend. Excluding the data for Rp/W = 0.50 and 0.60, the difference appears to increase as the gap increases. It is interesting that the data for Rp/W = 0.65 almost tracks right on the parallel calibration for most of the range.

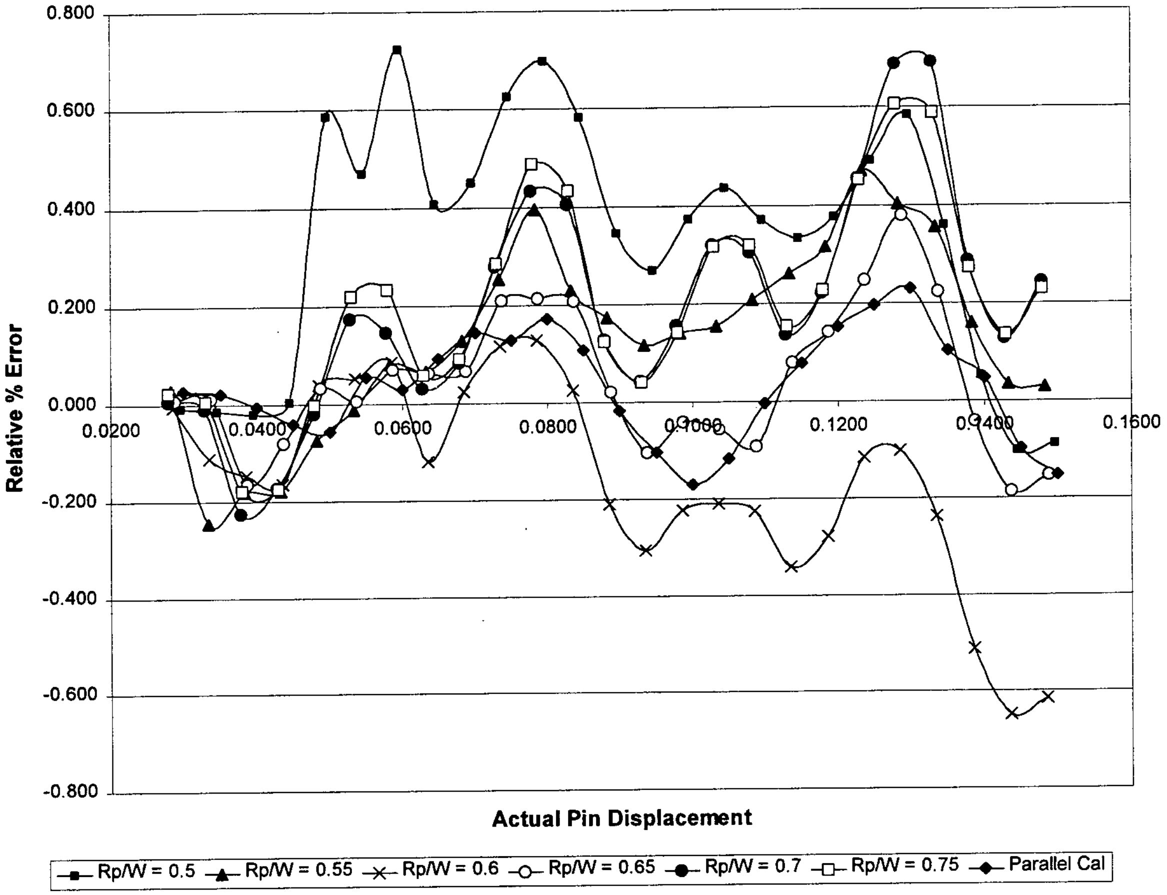

Figure 4. Rotation effect on error in cap gage measurement of load-line displacement.

Another way of looking at the effects of rotation is to perform a linear regression on the data for each rotation point to examine the slope and linearity for each data set. Table 1 lists the slopes and offsets resulting from each regression. Figure 5 plots the slopes to determine if there is any trend to the slopes as the rotation point changes. The point for the parallel calibration is arbitrarily shown at Rp/W = 0.8, where actually Rp/W would be infinity in this case. There is a slight trend of increasing slope with increasing Rp, but it is not a strong trend and the parallel calibration does not fit the trend. The difference between the highest and lowest slope is less than 0.7% of the nominal slope of 0.015 in./volt.

Table 1. Results from Linear Regression of Cap Gage Data

Rp/W	Slope	Offset
Parallel Plate Calibration	0.0149654	0.01999
0.50	0.0149445	0.02054
0.55	0.0150233	0.01988
0.60	0.0148633	0.02017
0.65	0.0149620	0.02003
0.70	0.0150430	0.01989
0.75	0.0150298	0.01996

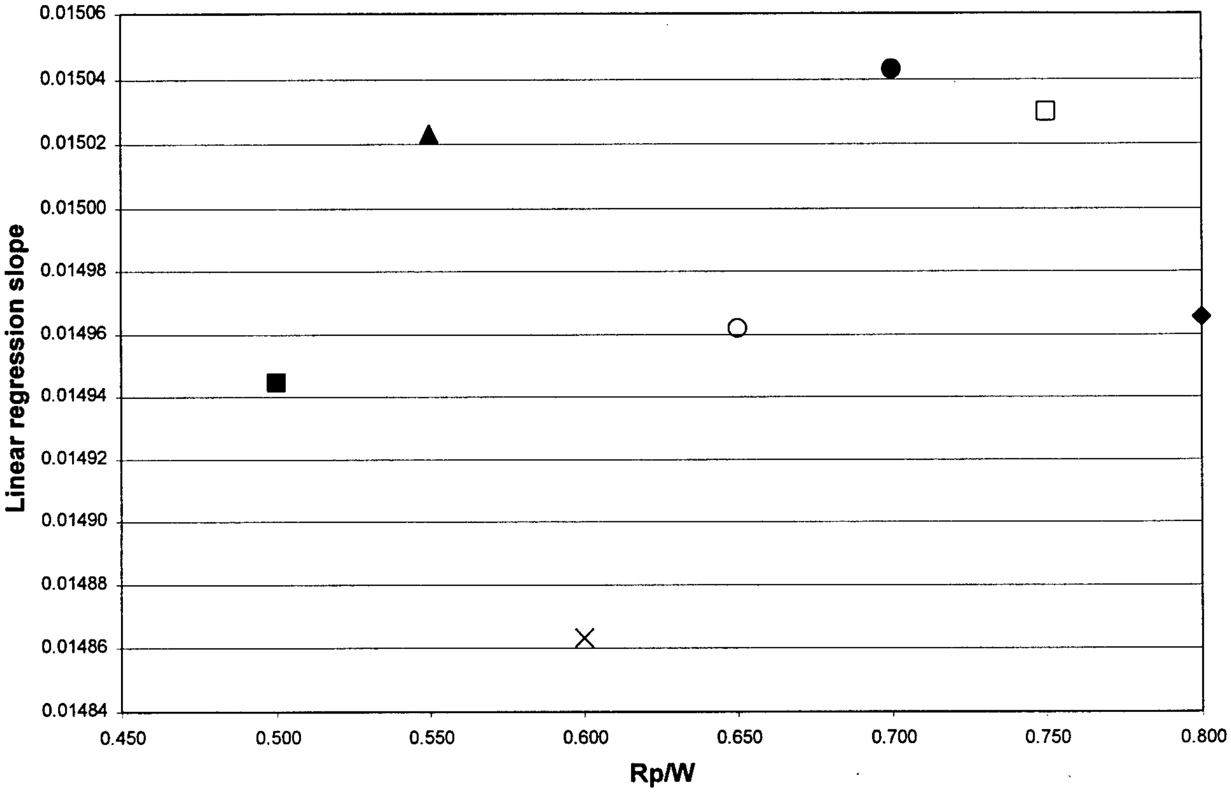

Figure 5. Effect of rotation on slope of cap gage output.

Figure 6 shows the relative deviation from linearity of all rotation points tested, as well as the original parallel calibration. Once again the relative error is the measured voltage minus the regression voltage, the difference of which is divided by full scale (10 volts). Excluding the data for the shortest rotation point (Rp/W = 0.5), there is no apparent effect of rotation point on linearity and all of the data falls within about ±0.32%. Also note that all of the relative errors fall close to the parallel calibration except for Rp/W = 0.5, which shows larger error near the beginning and the end of the displacement range.

The data indicate that the rotation of the cap gage in the C(T) during testing does not have a significant effect upon the accuracy or linearity of the gage. It was previously mentioned that for compliance measurement the gage should be accurate and linear to ±0.2%. In dynamic testing compliance is not measured during the test. The accuracy and linearity requirements specified in ASTM E1820 for displacement measurement without compliance are both ±1%. The accuracy and linearity of the cap gage is within ±1% for all values of the rotation point considered. Since movement of the rotation point does not have a significant effect on the accuracy of the gage, crack growth during a test should not introduce significant errors in the measured load line displacements.

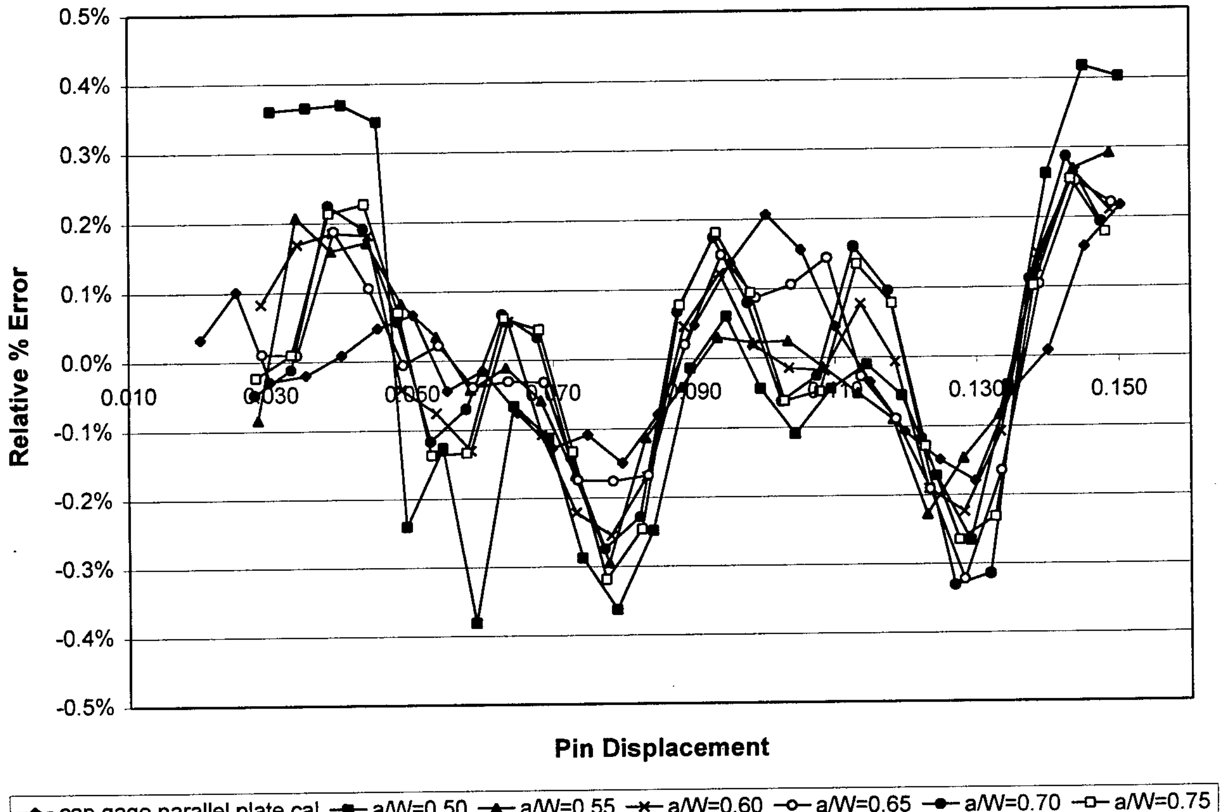

Figure 6. Linearity of cap gage for various rotation points.

Some perspective on the magnitude of the error in the cap gage measurements can be gained by repeating the tests using a clip gage mounted on the load-line integral knife edges and comparing the resulting accuracy and linearity of the two different gages.

Rotation Effect on Clip Gage Accuracy

For quasi-static testing of C(T) specimens, a clip gage is typically mounted on knife edges on the load-line of the specimen. This method of measuring displacement is well established and widely accepted provided the gage calibration requirements specified in ASTM E1820 are met. For this study a standard MTS clip gage was calibrated to 0.015 in./volt, with full scale being 0.15 in., or 10 volts. The calibration was done initially using an analog blade micrometer with an accuracy of ±0.0005 in., and a second calibration was done with a digital micrometer accurate to ±0.00005 in. In both cases the clip gage was mounted on knife edges that separated linearly without rotation. Figure 7 shows the relative error of the analog and digital calibrations based on linear fits to the data. While both calibrations are acceptable, the digital calibration has a smaller overall error. Because of the higher resolution and improved linearity of the digital micrometer, all of the subsequent clip gage calibrations for this study were done using the digital micrometer.

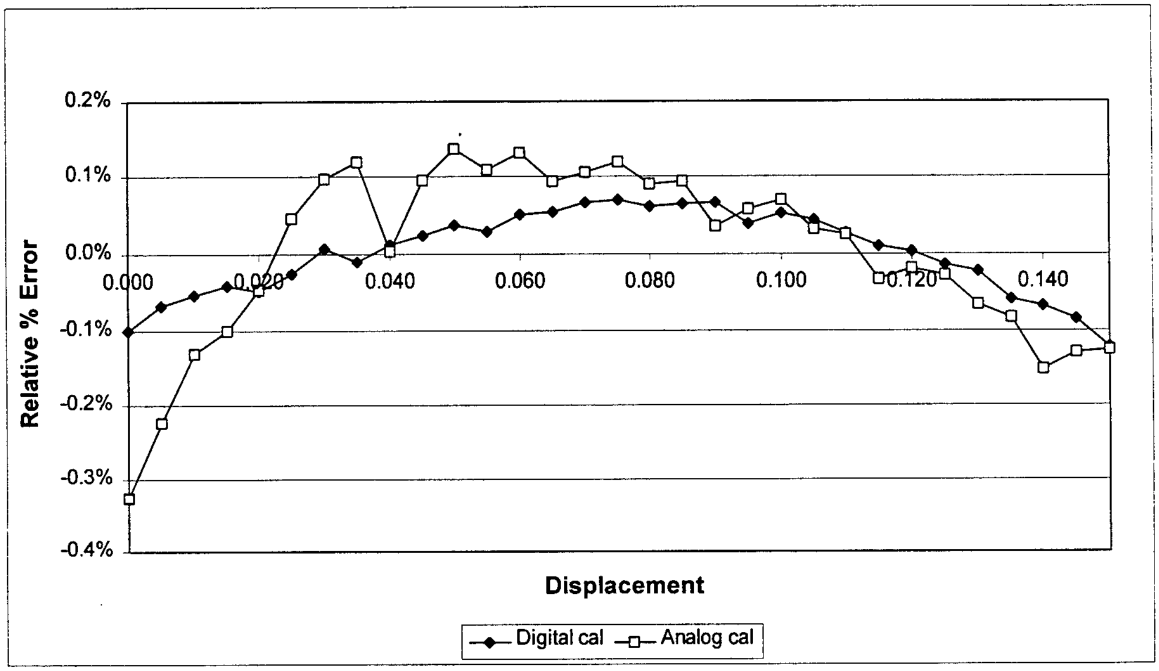

Figure 7. Comparison of error for digital and analog micrometer calibrations of clip gage.

It was mentioned previously that a clip gage is a contacting transducer, and consequently the reference points for measurement are fixed points on the specimen. However, the rotation of the specimen "arms" actually causes the measurement points to move off the load-line of the specimen (the load-line is defined by the line between the centers of the loading holes). For this reason it is not expected that the clip gage measurements will be exactly the same as the pin displacements. This rotation effect is only considered significant when measuring compliance. The difference between the knife edge and pin hole displacements is not significant when calculating energy input to the specimen, and no attempt is made in ASTM E1820 to correct for the rotation effect in the calculation of energy.

For the following tests the calibrated clip gage was placed on the knife edges in the rotation fixture and the rotation point was moved from Rp/W = 0.5 to Rp/W = 0.75, as in the cap gage tests. The voltage readings were converted to displacement and relative error from the actual pin displacement was calculated as before. The resulting error includes both the inherent non-linearity of the gage and the rotation effect of the fixture. In an effort to separate the two sources of error, a second order polynomial was used to fit the calibration data for the clip gage. This non-linear fit eliminates the parabolic shape to the error shown in Figure 7. The error for the non-linear fit is shown in Figure 8. Note that the error no longer has the parabolic shape and the maximum error has decreased from about –0.12% to 0.042%, or a factor of 3 improvement.

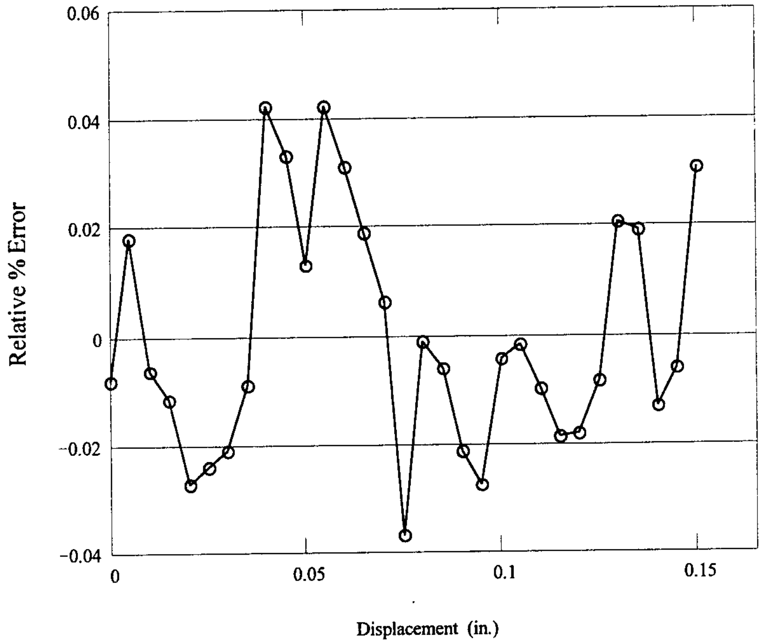

Figure 8. Relative error for non-linear fit to clip gage calibration data.

The non-linear fit was used to convert measured voltages to displacement for each of the different rotation points. The relative error of the measured displacements from the actual pin displacements is shown in Figure 9. The data shows a clear trend of increasing error with both increasing displacement and increasing Rp. The maximum error is still less than 1%, so it is still acceptable according to ASTM E1820. The error in this case is a geometric effect caused by relative movement of two points on the specimen during rotation, and the definition of load line displacement.

It is interesting to compare the error for the clip gage with the error for the cap gage (Figure 4). Keeping in mind that the inherent non-linearity of the cap gage response has not been subtracted from the error in Figure 4, there is a similar trend in increasing error with increasing displacement (disregarding the cap gage data for Rp/W = 0.60). In both cases the measured displacements are less than the actual pin displacement (Note that this changes at large displacement for the clip gage at Rp/W = 0.50). Generally, the cap gage actually shows less effect of rotation than the clip gage.

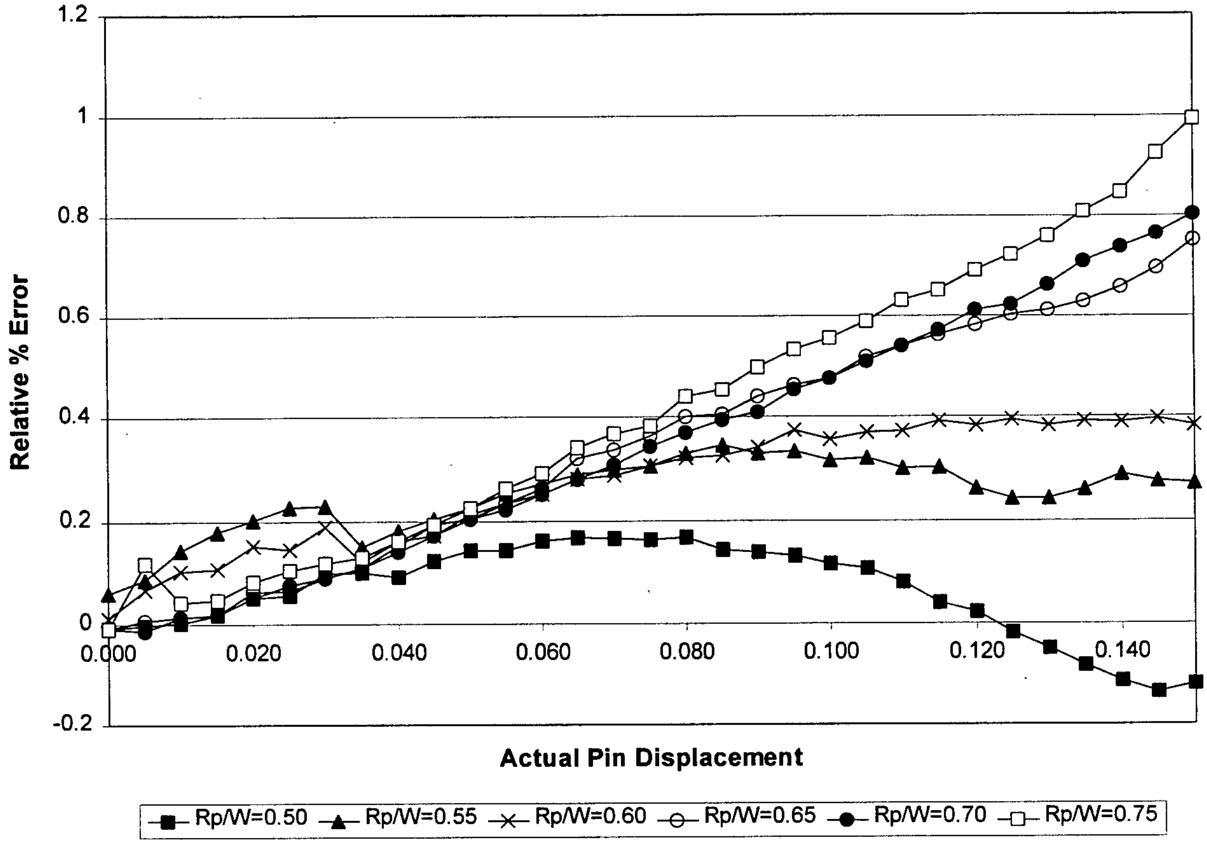

Figure 9. Rotation effect on error in clip gage measurement of load-line displacement.

Conclusions

This study compared the errors in load-line displacement measurement for contacting (clip-gage) and non-contacting (cap gage) transducers. It was found that both types of transducers show a similar trend of increasing error with increasing displacement, however, the error was always less than the 1% allowed in ASTM E1820 for measuring displacement without compliance. The errors in the cap gage measurements were actually less than the clip gage errors. Consequently, this study showed that rotation of the specimen halves under applied load does not adversely affect load-line displacement measurements taken using capacitance gages.

The test results also showed that rotation does not significantly effect either the accuracy or the linearity of the cap gage response for Rp/W greater than 0.5. Therefore, the rotation fixture used for this study could be used for calibration of cap gages with no detrimental effect on the resulting calibration as long as the rotation point is set at an Rp/W of 0.55 or greater.

References

1. "**Standard Test Method for Measurement of Fracture Toughness,**" E1820-96, Volume 03.01, *Annual Book of ASTM Standards*, American Society for Testing and Materials, 1998, pp. 981 – 1013.

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