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IEEE 693 SEISMIC QUALIFICATION OF COMPOSITES FOR SUBSTATION HIGH-VOLTAGE EQUIPMENT

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SUMMARY

This paper discusses research on the application of IEEE Standard 693 seismic qualification requirements for hollow-core composite insulators used on high-voltage instrument transformer substation equipment. The IEEE 693 qualification procedure of time history shake-table and static-pull tests as well as the acceptance criteria is evaluated. Failure modes for composite insulators are discussed. Experimental observations show that the acceptance criteria are invalid for qualifying hollow-core composites. The need for a static-pull test following vibration qualification tests is presented. The need for post-vibration-test measurement of damping is discussed. Changes to the IEEE standard and potential research are recommended

INTRODUCTION

IEEE Standard 693-1997, "IEEE Recommended Practice for Seismic Design of Substations" [1], is a major improvement in the way the power industry seismically qualifies substation high-voltage equipment. The standard has established discrete qualification levels with associated controlling response spectra, and well-defined qualification procedures and acceptance criteria. In addition to general procedures for analysis and testing, special procedures and criteria are developed for individual classes of equipment that reflect their unique characteristics and earthquake performance.

The standard provides two seismic qualification performance levels that are defined by excitation response spectra. Acceptance criteria are established so that equipment shake table-tests qualification need only be subjected to an excitation half of those defined by the performance response spectra. While not explicitly stated in the standard, it is the view of the authors that testing to half of the performance level requires that the failure modes of the equipment are understood and that associated critical variables, such as a strain, can be measured. The acceptance

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criteria require that the measured values of the critical variables be half their ultimate value. This procedure also assumes that the critical variables that are monitored are approximately linear. The current standard does not explicitly specify the long-term serviceability of the equipment after surviving an input excitation at the qualification level, but it is generally expected that it not be affected.

Special tests and acceptance criteria are established for fiber-wound polymer-impregnated insulators. These are referred to as composite insulators. Composite insulators of the hollow-core designs are used for post insulators, instrument transformers, surge arresters, and bushings. The hollow-core type composite design is the subject of this paper. The composite tube is fitted with metal flanges at its ends and silicon-rubber sheds are applied to the outside of the composite tube. For some application identified above, the tube assembly is supplied to power equipment manufacturers where it is used to fabricate the final product, such as an instrument transformer.

DESIGN AND FABRICATION OF HOLLOW-CORE COMPOSITE INSULATORS

The structural designs used by some manufacturers are equivalent although details of fabrication may vary. A composite manufacturer may provide a tube and flange fittings to meet the specifications of the power equipment manufacturer using the composite. Other power equipment manufacturers may be developing or using composite components of their own design and these may be different from those described below.

It is useful to know the general design and fabrication method of hollow-core composites in understanding qualification tests, acceptance criteria, and potential failure modes. For many applications the composite tube is a constant diameter circular cylinder. For some bushings the tubes are tapered circular cylinders. Some of the variables involved in fabricating the tube include the diameter of the tube, its wall thickness, the angle used to wind the fiber, and the thickness and number of fiber layers. There may also be variation in the properties of the fiber and polymer used in fabrication. The tube is wound on a mandrel and its outside diameter is carefully controlled to fit its end flanges. After the tube is fabricated, it is cut to length.. The metal end assembly is illustrated in Figure 1. This figure does not show the shed material that is added after the flange is attached to the tube. It should be noted that this illustration shows an end fitting with gussets, but some manufacturers have designs without gussets. Also, the number of connection bolts can vary and are typically more numerous than illustrated. Important end-flange parameters include the inside diameter to assure a good fit to the outside diameter of the tube, wall thickness, and the length that the tube engages the flange (penetration length). The end of the flange may be open so components can be inserted into the tube when fabricating electrical equipment, such as an instrument transformer.

Prior to assembling the tube to the flange, the flange is heated so that it expands. A bonding compound is applied to the tube or flange, and the tube is inserted into the heated flange. When the flange cools, it shrinks providing a compressive fit to the tube. Thus, two mechanisms are at play in the tube-flange connection, a compressive stress due to the shrink fit of the flange to the tube and the bonding of the tube-flange interface surface.

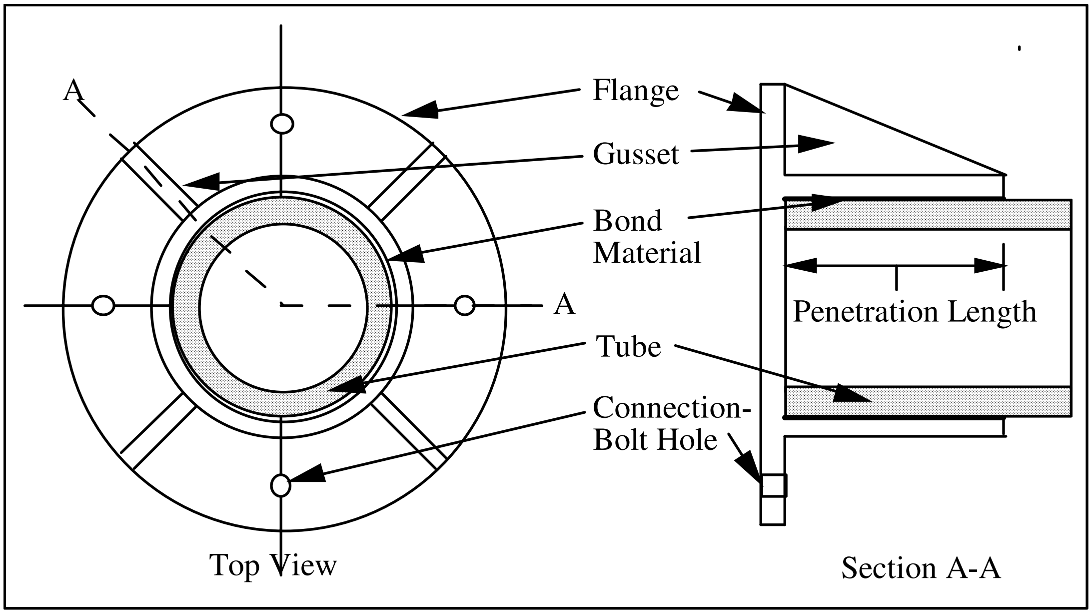

Figure 1 Schematic diagram of section of hollow-core composite flange assembly

SEISMIC STRUCTURAL FAILURE MODES

Four failure modes are discussed: bond degradation, bond failure, tube degradation, tube layer delamination. These failure modes are associated with the composite insulator. Other system failure modes can be associated with the deformation or failure of the flange, the failure of the connection bolts, or the failure of the member to which the composite insulator is attached, such as the lid of an instrument-transformer box. The failure of the shed seal is not considered here. These failure modes have been observed over the historic development of hollow-core composites, but may not be observed using current designs under seismic qualification or earthquake loads.

The most severe load that can cause failure is a lateral load during the qualification testing process or during an earthquake. This subjects the lower flange-tube connection to large bending moments. It is interesting to note the difference in the seismic performance of porcelain and composite insulators. When porcelain fails, the failure is catastrophic and obvious. As discussed below, composite damage is generally incremental and in many cases non-catastrophic damage may be difficult to detect.

Bond Degradation

When a round tube is subjected to bending, it tends to deform into an oval shape. This deformation and the reaction forces introduced by a lateral load to the tube will subject the tube-flange interface bond opposite the direction of the load to a peeling force and shear force. Typically, peeling forces are most severe to a bonded connection, as high stress is concentrated along a line rather than over an area subjected to the shear forces. A local bond separation near the upper edge of the flange will have several effects. The shear forces on the bond that remains are increased and the stiffness of the connection is reduced. When subjected to vibration it is possible for that part of the bond that has separated to be mobilized, that is, there can be relative motion across the separated surface of the bond. This can introduce additional damping to the system. It should be noted that there is still compressive stress on the connection due to the shrink fit used to assemble the connection. A partial bond separation, or bond degradation, will not jeopardize the integrity of the seal between the tube and the flange if it does not extend over the full length of the bond.

Severe Bond Degradation
If the bond degradation progresses, two types of failure can occur. The bond separation can extend to the base of the flange so that the seal between the tube and flange can be compromised. If the entire bond fails, the tube can partially pull out of the flange and break the silicon rubber that covers the top of the flange as shown in Figure 2.

Figure 2 Bond failure and tube partially pulled from flange breaking shed rubber

Tube Degradation
When the polymer-impregnated fiber is subjected to bending or any load, some fibers will break, even at very low stress levels. A small number of fiber breakage would not be considered damage. As loads increase the number of fibers that break increases and at some point the tube would be considered damaged. As the load increases, eventually a hinge will form and a large displacement response of the tube at the hinge would be obvious. It is this condition that the current standard criteria address. Before a hinge develops, the effects of fiber breakage will be a reduction in stiffness of the composite member and in increase in damping. The silicon-rubber sheds that cover the composite will obscure direct observation of the damaged composite material.

Tube Layer Delamination
In fabricating the tube, a layer of fibers is put down with the fibers in a given direction followed by another layer of fibers in a skewed direction. When subject to stress, a crack can form between these layers and this is referred to as delamination. While this will result in some reduction in strength, a more significant problem is that electrical corona can develop across the crack when the unit is energized and eventually cause an electrical failure.

QUALIFICATION PROCEDURES FOR IEEE 693

The procedure for qualifying composite insulators requires that the insulator stack be anchored to a stiff support and be subjected to a cantilever pull test to 1/2 the Specific Mechanical Load (SML). The SML is the manufacturer-specified load the insulator will withstand without visual damage, but that is above the damage limit zone. The 1/2 SML is below the damage threshold for the item being tested. During this test, the relative deflection at the top of the stack is measured and this deflection is used as the acceptance criteria for the shake-table test. When the 1/2 SML is removed, the residual deflection, that is, the deflection remaining when the load is removed, is measured. This deflection must be less than 5% of the peak deflection observed at the 1/2 SML. During shake-table tests, the standard allows the relative deflection to be measured directly with wire potentiometers or indirectly by double integrating the accelerations at the top and bottom of the composite member.

The test to determine the SML, which is done by the tube manufacturer independently of the equipment qualification test, is much different than that used to determine the ultimate strength of a porcelain member. The load that causes failure of composite member is a function of the duration that the load is applied. The SML is the load that causes the composite insulator to fail when the load is applied for one minute. A composite will fail if it is subjected to a load of 70% of the SML, if it is applied for a sufficient amount of time.

DESCRIPTION OF RESEARCH STUDY

A research program conducted by a consortium of 10 utilities and the California Energy Commission administered under the Electric Power Research Institute evaluated composite instrument transformers at a commercial testing laboratory. Because of the research character of the program, additional measurements, tests, and analyses were conducted to evaluate the composites and the IEEE 693 standard used to qualify them. Some of these supplemental activities are described below. The configuration of an instrument transformer is illustrated in Figure 3. The figure does not show the 2.4 m (8 feet) support structure used in the test. It does show the location of some of the accelerometers used during shake-table tests and the laser pointer location used during the pull test. The picture represents a 500 kV unit that is fabricated from two composite members, although some designs use more than two members.

Instrumentation

The instrumentation described below is related to the data discussed in the paper. Other instruments not included are accelerometers at the center of gravity, accelerometers at the top of the support structure, strain gages near the base of the support structure, and load bolts used to anchor the support structure.

Laser Pointer

During the static pull tests a laser pointer was attached to the base of the column and positioned horizontally to measure rotation at the base of the column. Rotation can be due to distortion of the box lid, compression of the gasket between the box lid and box, and deformation of the box, particularly near the anchor bolts. The laser pointer was projected on a vertical surface located a distance from the column equal to the column height. As the cantilever load was applied in increments, the deflection of the laser spot was recorded. The rotation at the base contributed to the deflection at the top that is not associated with insulator deformation. The measurement and potential effects of the instrument transformer box lid rotation is not addressed in the IEEE 693 Standard.

Strain Gages on Bottom Flange

Two strain gages were mounted on the flange barrel, aligned parallel to the longitudinal axis, near to the top edge of the flange. There were concerns about using double integration of the accelerations to estimate the deflection at the top. For this and other reasons discussed below, the strain gages were added. They are shown in Figure 3. This is instrumentation not required by the standard.

Accelerometers

Three accelerometers are mounted at the top of the instrument-transformer column measuring the vertical and two horizontal accelerations. Two accelerometer are also located at the base of the column that measure horizontal accelerations. Both sets of horizontal accelerations are used to estimate the relative deflection of the column. These measurements are required by the standard.

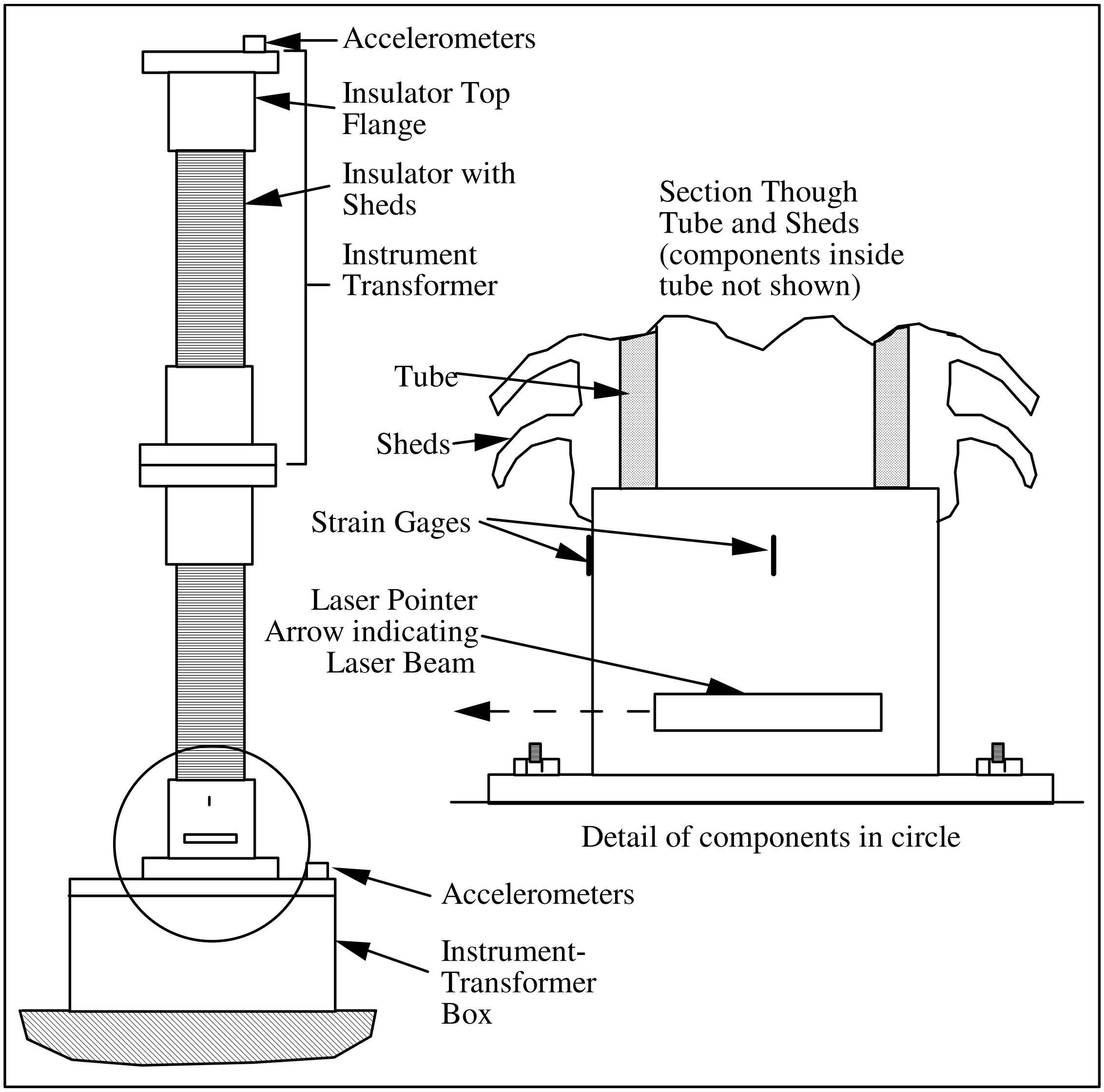

Figure 3 Illustration of instrument transformer and instrumentation locations

TESTS AND ANALYSES NOT REQUIRED BY IEEE 693 STANDARD

Man-Shake Test

Generally, after a large amplitude shake-table test a man-shake test was performed. This was usually done by using a ladder on the shake table to gain access to the composite member and then attempt to shake it at its first resonant frequency to get as large an amplitude as possible and then allow the motion to decay. This data was used to estimate the damping and the damped-natural frequency. As it turned out, it was also used to identify bond degradation.

Static-Pull Test Following Shake-Table Tests

Because of concern that the acceptance criteria used by the standard, that is dynamic deflection less than the 1/2 SML deflection, may not adequately characterize composite performance, a pull test was done after the vibration test. Since this was not part of the standard, it was not clear what deflection results would constitute acceptance.

Additional Analyses

As part of the research program, all test data was requested from the test laboratory and most data was provided. Strain gage and deflection data collected from the pull tests were evaluated and compared to each other. This data was used to calibrate strain measurements from the composite member flange to deflections at the top and applied moment. Damped sine waves were fitted to the man-shake response data to estimate damped natural frequencies and damping. Horizontal acceleration data from the composite member was double integrated to get displacements. A sinusoidal top acceleration was assumed and closed-form expressions for the velocity and displacement were developed and compared to data derived from numerical integration. This model was used to evaluate the effect of cross talk between acceleration axes resulting from accelerometer rotation associated with the bending of composite members. The deflection obtained from analog double integration of the top acceleration data and strain data during shake-table tests were compared. Response data from 0.25g and 0.5g tests are compared and response data from 0.5g and 1g data are compared.

ACCEPTANCE CRITERIA

There were several concerns associated with the acceptance criteria. First, the standard allows double integration of acceleration to estimate relative deflection of the composite member, and this was the method of choice of the testing laboratory. Any offset in the acceleration measurement will cause the estimated displacement to get unrealistically large. The static-pull test and the first mode dynamic response primarily introduce bending in the column. Associated with this bending is a rotation at the top of the column where accelerometers are located. Thus, an accelerometer installed with its axis of sensitivity aligned in a horizontal direction when the composite member is vertical, will have this axis rotate as the column bends. This results in cross-axis sensitivity so that as the column bends the accelerometer will pick up vertical acceleration that will be interpreted as horizontal input. This will give an inaccurate measure of the top deflection, particularly when the acceleration data is integrated twice.

The cantilever load in the static-pull test applies a moment at the base of the composite member. The base moment is the critical variable that is most likely to cause damage to the composite member. The deflection at the top is a good measure of the base moment for this load. In the dynamic test the load on the composite member is distributed over its length rather than concentrated at the top, so that the dynamic deflection will give a slightly higher base moment for the same deflection at the top. Thus, this is a non-conservative estimate of the base moment. The dynamic response will be influenced by the stiffness of the base connection and by the damping of the system. A loss of stiffness due to degradation of the bond or partial failure of tube fibers will tend to increase the response, so that the acceptance criteria may not be satisfied. However, damping also increases with damage and this will tend to reduce the response. It is not clear which effect will have the largest influence. In shake-table tests higher vibration modes can be excited and the deflection at the top will not be an accurate measure of the moment at the base.

Finally, rotation at the base of the composite member will contribute to the top deflection. This component of the top deflection is not associated with member distortion. This has the effect of relaxing the residual deflection criteria.

RESULTS FROM TESTS AND ANALYSIS AND THEIR INTERPRETATION

In the following discussion of test and analysis results, reference will be made to degradation of the bond between the tube and flange. The degradation has been inferred by the interpretation of the data, however, there has not been direct observation by the sectioning of the connection or by ultra-sound measurements.

Preliminary Static-Pull Test

During the static-pull test of smaller diameter, composite insulator instrument transformers, a loud, energetic popping sound was observed on some units. In one case, as the load approached the 1/2 SML the output of the strain gage mounted on the flange that was in tension suddenly dropped when the sound was heard. An investigation of the strain gage and the installation of a new strain gage indicated that there was a drop in the strain on the flange at that location. An additional strain gage was installed closer to the base of the flange and strain was observed. The popping sound and loss of strain was interpreted to be due to bond degradation. The extent of bond degradation is not known. The presence of strain in the lower strain gage that was added may indicate the integrity of the bond to that level, but this strain could also be observed without bonding.

The use of the laser pointer to measure rotation at the base of the composite member indicated that 10% to 15% of the peak deflection at the top was due to the rotation at the base. One unit that was tested used a relatively thick cork gasket to seal the instrument-transformer box lid to the box, and this increased the rotation at the base of the composite member. The increase in peak deflection has the effect of relaxing the residual deflection criteria of the standard.

On a large diameter composite instrument transformer, the strain gage output was scaled to represent the deflection at the top by using one of the data points obtained during the static-pull test. The scaled strain and the deflection plotted in Figure 4 show that these parameters track well up to the 1/2 SML.

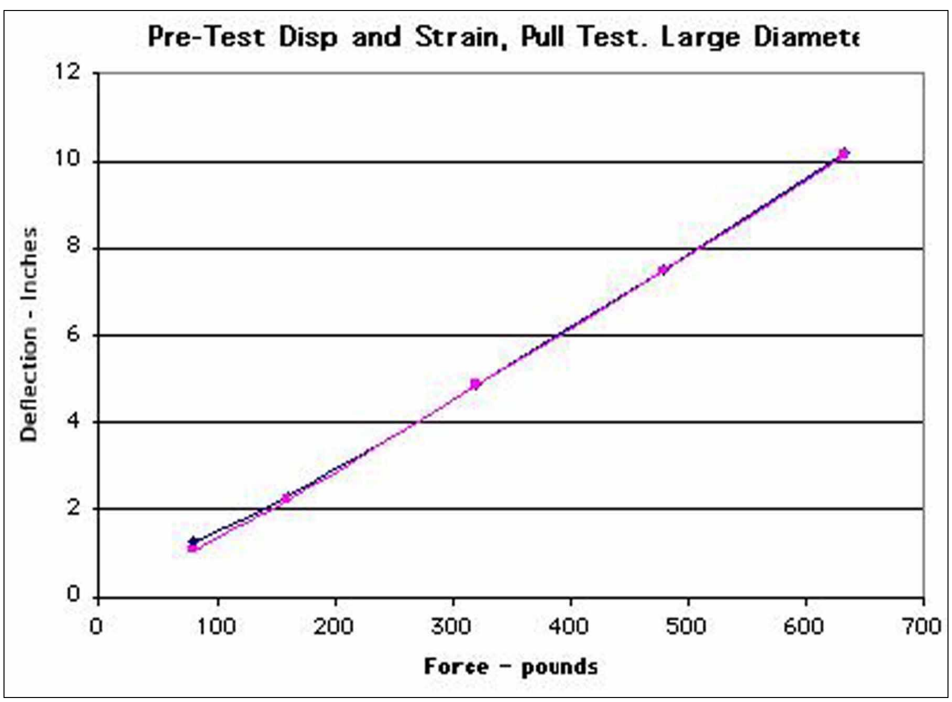

Figure 4 Scaled strain and top deflection of initial static-pull test

Vibration Tests
During the vibration tests of some composite instrument transformers, a loud popping sound was heard. In one case, the output of accelerometers mounted on the composite member exhibited a large spike, about twice the acceleration value of the largest amplitude observed during vibration tests. This unit also experienced popping during the initial static-pull test. An inspection of the response before and after the pop did not show any marked difference in the performance.

During a test at the 1g level there was a sudden failure of a tube-flange joint, as shown in Figure 2. Oil contained in the composite member ran from the joint. All indications of a test at 0.5g indicated that the unit was performing well. This nonlinear characteristic of the failure means that testing to 0.5g and extending the results to 1g is inappropriate for this type of equipment.

Figure 5 shows the superposition of the response of a large diameter, composite instrument transformers during 0.25g and 0.5g tests. The 0.25g test was scaled by a factor of two in this plot. This unit had not been subjected to an initial static-pull test. Most of the mismatch of the responses is due to a slight time shift in the two records.

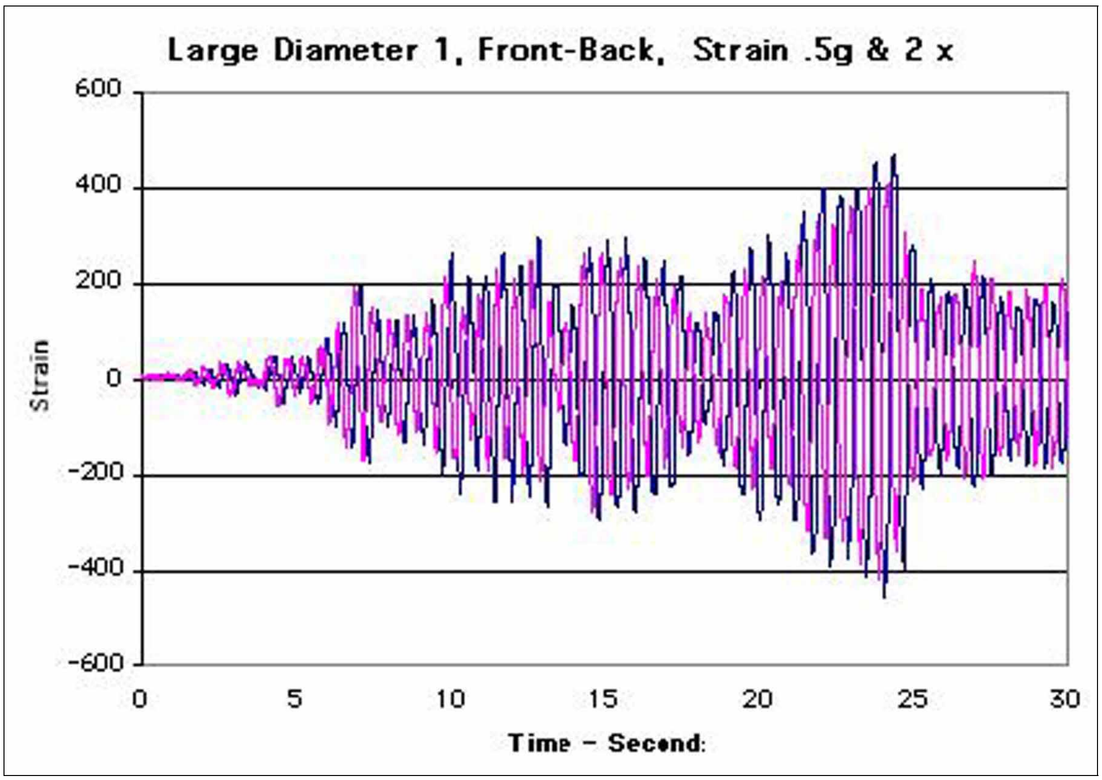

Figure 5 Scaled 0.25g and 0.5g response tracked well on unit not subjected to a static-pull test

It is interesting to compare the responses of two units subjected to 0.5g tests, Figure 6. At times the time histories track well and at other times the unit that was subjected to the pull test in the front-back direction has a much smaller response. This is attributed to the mobilization of a degraded bond in the unit that was subjected to the pull test. During the time-history response the bond separation is mobilized and there is an increase in damping but when the response amplitude drops, they generally track better again. This is attributed to the shrink-fit compressive stress locking the bond separation at low amplitudes.

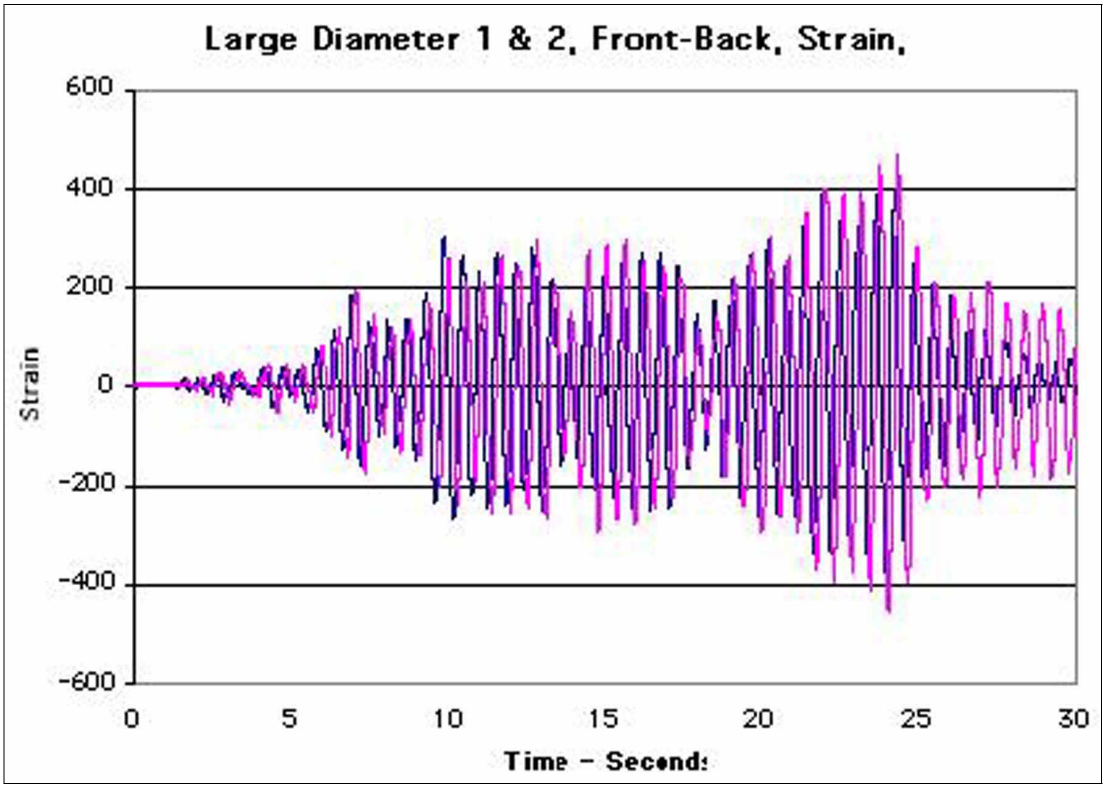

Figure 6 Two identical units subjected to 0.5g input but unit that had a static-pull test at times exhibits lower response that is attributed to increased damping

Finally, the response of a small diameter, composite instrument transformers to 0.5g and 1g are superimposed, with the same scales, Figure 7. Note that the responses are about the same amplitude even thought the input of one is twice the value of the other. It is felt that the bond of the unit was severely damaged at the end of the 0.5g test or at the beginning of the 1g test. The results of the man-shake test and final static-pull test are discussed below.

Man-shake tests

The man-shake test performed after the shake-table test on one composite instrument transformer showed that at the largest amplitudes, which are about 10% of those observed during the 0.5g tests, the fraction of critical damping was 0.02. However, as the amplitude decayed, the fraction of critical damping suddenly changed to 0.0023. Figure 8 shows the plots in which a damped sine wave was fitted to the response data. Plot A is the large amplitude part of the response and Plot B continues where Plot A stopped. While it is recognized that damping generally decreases as amplitude decreases, the damping changed by a factor of 8 and the shift occurred during one cycle. The interpretation of the change in damping is that at large amplitudes the portion of the degraded bond was mobilized so that the fractured surfaces rubbed and increased damping. At lower amplitudes the compressive stress associated with the shrink fit locked the fractured surface and there was a sudden drop in damping.

The response of a small diameter, composite instrument transformer that was subjected to 1g test had a single damping value of 0.048 that was independent of amplitude. The authors believe that the bond in this unit was severely damaged and that accounted for the larger damping.

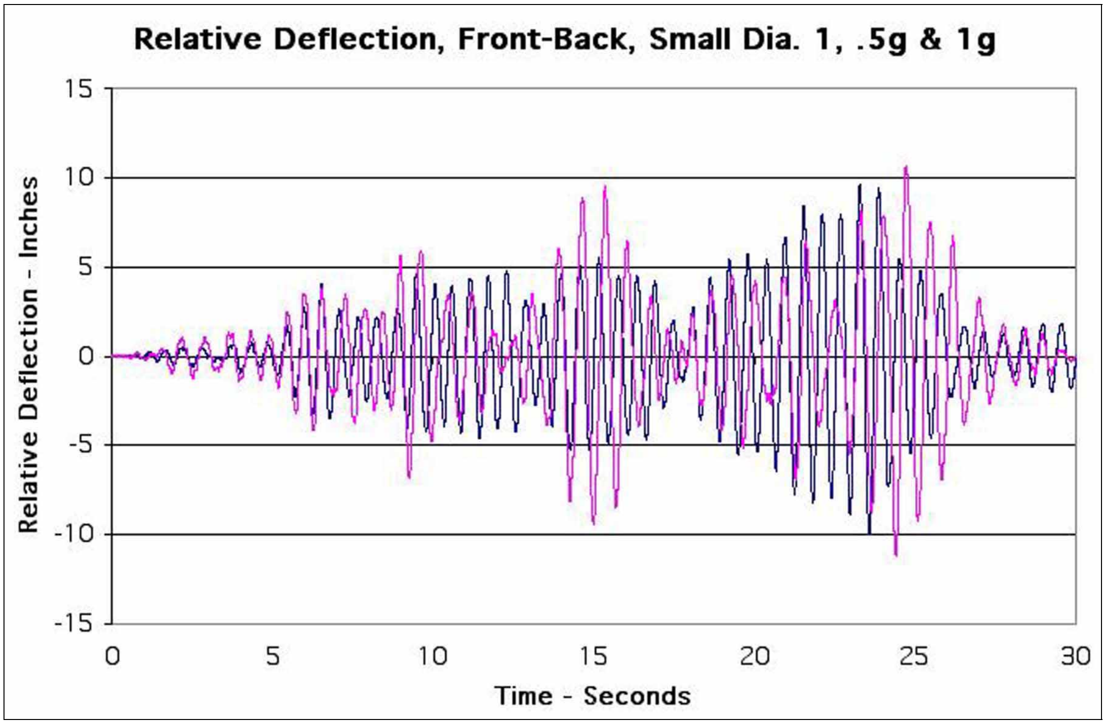

Figure 7 The response of a unit to 0.5g and 1g are approximately the same

Final Static-Pull Test

The final static-pull test for the small diameter, composite instrument transformer that was subjected to 1g input exhibited a loud grinding noise as the load was applied. Just prior to reaching the 1/2 SML, and there was a drop in load and an increase in deflection. The initial and final pull tests are compared in Figure 9 and show that the deflection of the final pull test is about 50% higher than the initial pull test. Using existing acceptance criteria this unit would have been qualified.

Figures 10 A and B show the comparison of the strain and deflection of the initial and final pull tests on a large diameter composite instrument transformer. While this unit appears to have performed well when subjected to a 1g test, the increase in the strains and deflections suggests that there was some bond degradation. The loss of some of the bond increased the strain on the remaining bond area and the loss of stiffness due to bond degradation increased the relative deflection.

RECOMMENDTIONS AND SUGGESTED CHANGES TO IEEE 693 STANDARD

The criteria for the applicability of the general procedure used in the IEEE 693 standard to test to half of the performance level as a means to qualify to the projected performance level are not satisfied for hollow-core composites. Potential of bond degradation, tube fiber damage and fiber delamination cannot be directly observed or measured and these types of failures are nonlinear in character. Thus, potential damage variables cannot be observed and evaluated to assure that the values of the critical variables are less than the value observed during the 1/2 SML static-pull test. Thus, it is recommended that hollow-core composites should be tested to the performance level. This reflects the character of the failure modes. While the results are based on the evaluation of a small number of composite members, they clearly show the deficiencies in the standard more than basic a problem with the inherent seismic capacity of this type of equipment.

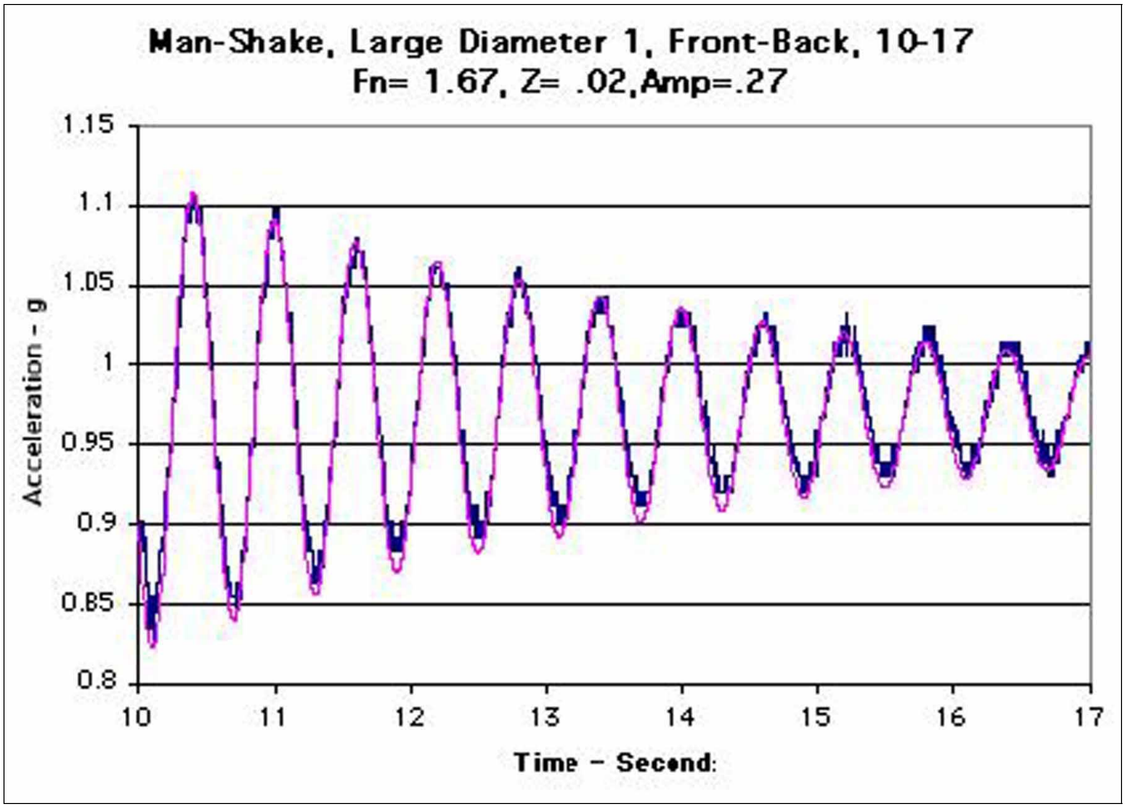

Figure 8 A The large response to man-shaking and a fitted damped sine wave

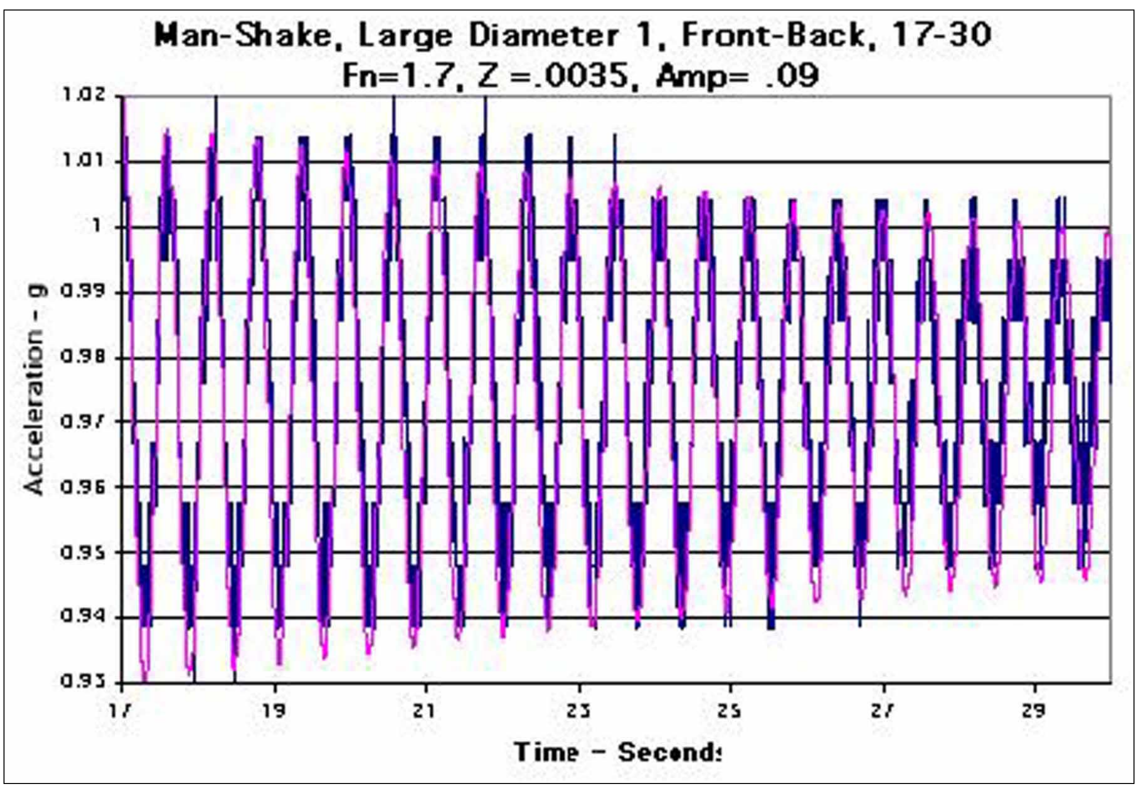

Figure 8 B The small response to man-shaking and a fitted damped sine wave

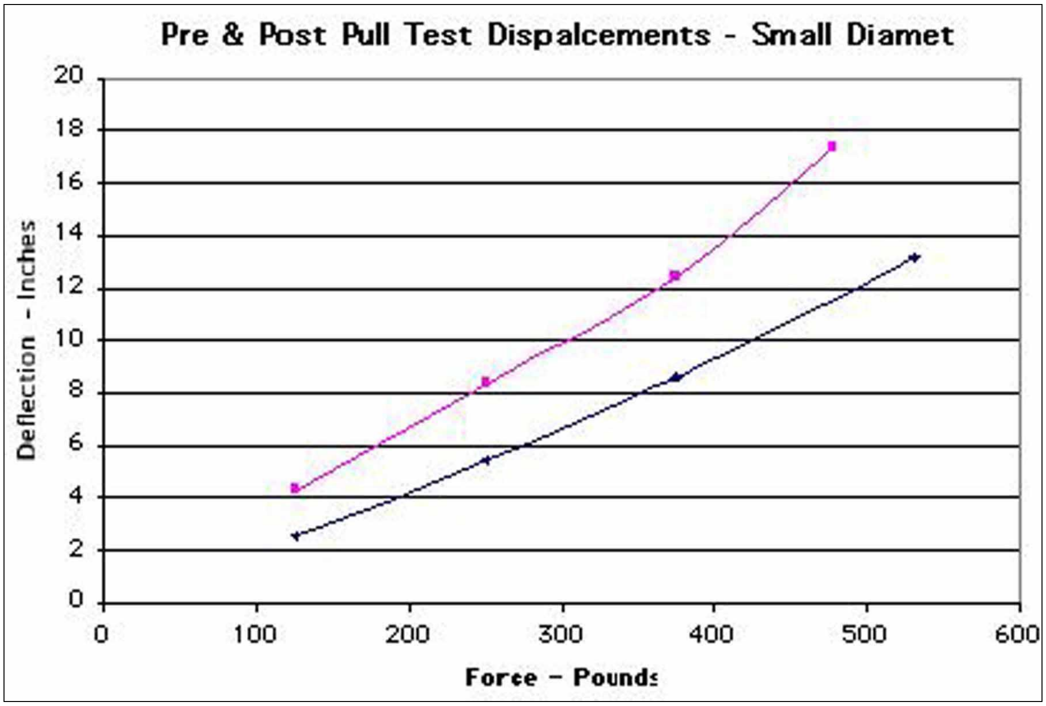

Figure 9 The deflection in the final pull test is about 50% higher than the initial pull test

The acceptance criteria should consist of a static-pull test after the shake-tables tests are complete. As an interim measure, the deflection at the 1/2 SML should be no more that 15% larger than that observed in the initial pull test. Since differences in performance were observed in test data in the different directions, a pull test should be conducted in both the front-back and the side-side directions.

In each orientation, the pull test need only be performed once, and the residual deflection should be less than 5% of the peak deflection. This suggestion is a departure from current practice, as it would eliminate dynamic measurements during testing as part of the acceptance criteria and rotation at base would not matter. Until research substantiates the validity of the above tests, it is recommended that a snap-back vibration test to 3/8 SML be conducted to determine the extent of bond degradation.

SUGGESTED RESEARCH

The acceptance criteria suggested above are based on a very limited research effort. The authors feel that a static-pull test is needed after the shake-table testing is complete. It is anticipated that there will be an increase in deflection at the 1/2 SML as a result of the shake-table testing, however, additional research is needed to establish the magnitude of the increase that can be accepted without indicating the presence of unacceptable damage.

The test data suggests that the extent of bond degradation can be estimated by the level of motion required to mobilize the degraded bond. Research could establish the relation between bond degradation and vibration amplitude needed to mobilize the joint. This could be used to determine if the degradation was sufficient to jeopardize the integrity of the tube-flange seal. The research may also demonstrate that the increase in deflection during or the residual deflection measured in the post-vibration static-pull test is adequate to assure seal integrity.

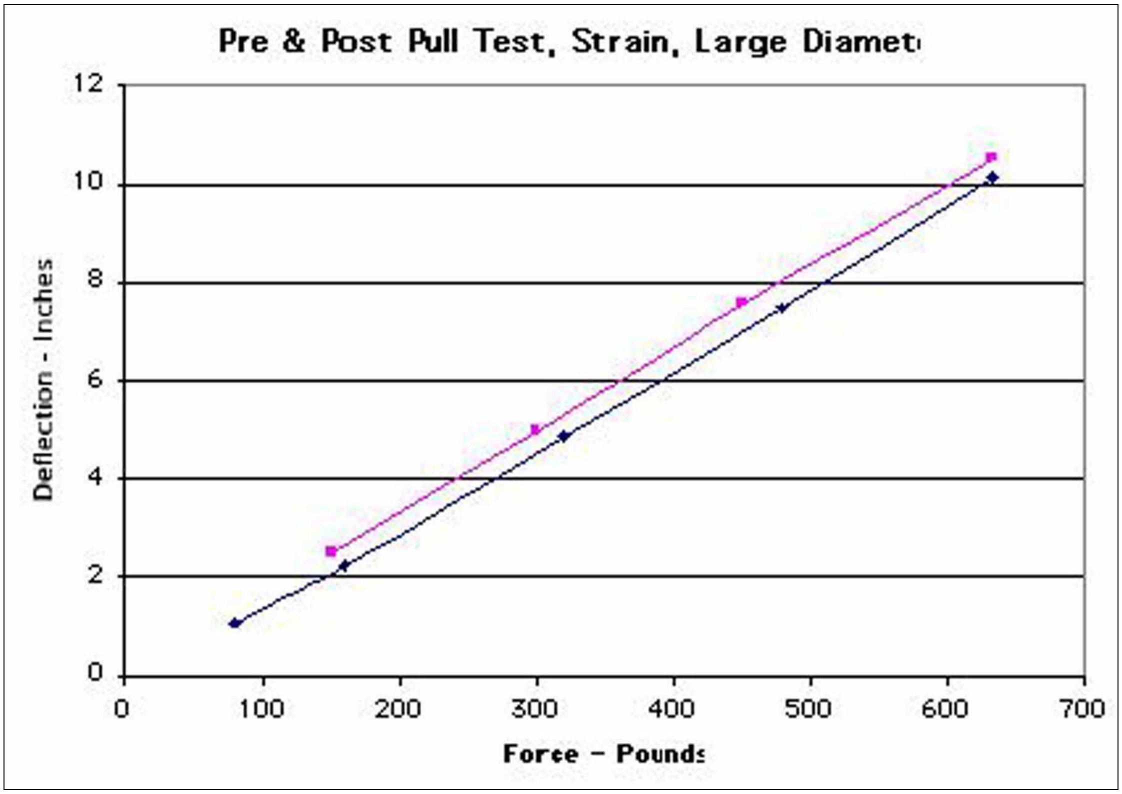

Figure 10 A Relative strains increase in final static-pull test

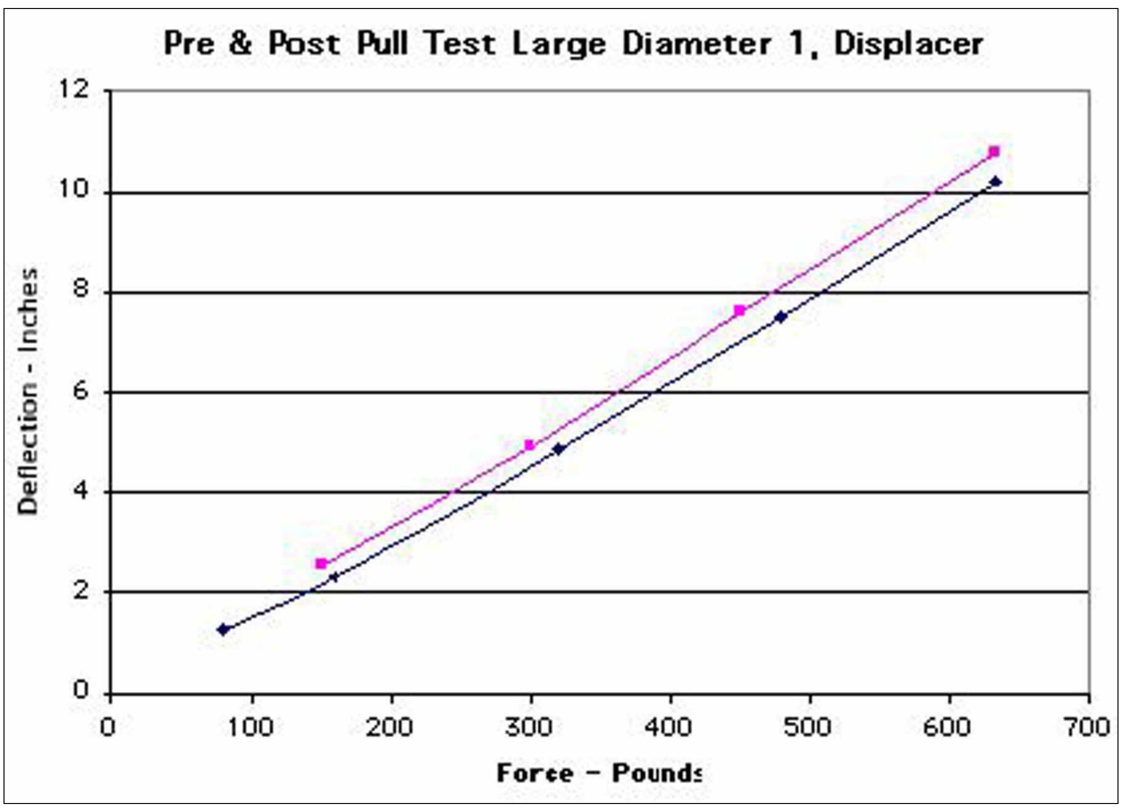

Figure 10 B Relative deflections increase in final static-pull test

Research should be conducted to see if bonding at the top part of the flange could be eliminated. This could eliminate bond degradation and also increase system damping and thus improve the dynamic response of the unit. As part of this effort, the stiffness of the flange could be investigated to see if increased stiffness would reduce bond degradation.

The test data suggests that the penetration length of the tube into the flange as a percentage of the diameter should be investigated. Smaller diameter tubes appeared to have more problems with bond degradation. It may be necessary that smaller diameter tubes have a larger penetration relative to their diameter to mitigate bond degradation. Changes in pre- and post-test damping could be used as a measure for establishing acceptance criteria of composite insulator bond integrity in high voltage equipment. The test data showed changes in damping that could be the result of bond degradation. Research should be conducted to determine the sensitivity of damping values relative to the level of bond degradation.

There is a need to assess the implications of popping sounds observed during tests on bond degradation. The assumption that this only corresponded to bond degradation rather than bond failure should be substantiated.

REFERENCES

1. IEEE Standard 693, IEEE Recommended Practice for Seismic Design of Substations, Institute of Electrical and Electronic Engineers, Inc., 345 East 47th Street, New York, NY, 10017,USA, 1997