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*Poloidal Field Coil
Stress Analysis for the
ZTF Machine*

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POLOIDAL FIELD COIL STRESS ANALYSIS FOR THE ZTH MACHINE

by

Steven P. Girrens, Joel G. Bennett, and Dennis M. Murphy

ABSTRACT

Three-dimensional finite element analysis of representative equilibrium field and ohmic heating coils for the Los Alamos ZTH air core machine was performed to determine static stress levels developed within the coil structure caused by Lorentz-force loading. Because of the complex coil configuration in cross section (copper conductors embedded in an epoxy insulating matrix), the study was performed in three steps: a bulk orthotropic material property determination, a bulk material coil section analysis, and a detailed composite cross section of selected thickness analysis. Computational procedures used with coil stress and displacement results that were obtained are presented. Extensive work was performed to investigate the magnitude of the error in coil stress predictions arising from the use of the three-step analysis procedure. Analytical and numerical procedures used to perform the estimate of error study are also presented.

I. INTRODUCTION

The ZTH is a reverse field pinch fusion machine being designed for construction and operation at the Confinement Physics Research Facility (CPRF) at the Los Alamos National Laboratory. The plasma magnetic confinement and reverse field are accomplished by poloidal field (PF) and toroidal field (TF) coils. The 18 PF coils are divided into two subsets according to their function (10 ohmic heating and 8 equilibrium field). The PF coils are symmetrical in geometrical arrangement across a horizontal midplane; this results in nine mirror image pairs. The PF coils are made with copper conductors separated by insulating materials--fiberglass, G10 epoxy fiberglass, and Kapton. Support

for the coils is provided by 16 equally spaced, radially directed, G10 bulk-heads that lie in vertical planes. PF coil stress calculations in the past have relied heavily upon a modified Princeton coil analysis code that considers hoop, bending, and torsional effects in the metal conductors. To model the elastic behavior of composite coils containing copper in an insulation matrix, a reduced section modulus was calculated for each coil using an empirically derived shear factor. Though past calculations and tests indicate that a shear factor of 0.4 to 0.5 will accurately model coil behavior if the ratio of copper cross section to glass insulation is 10:1, full-scale coil samples need to be tested to estimate the shear factor for particular coil configurations. Coil analyses using the above-described code adequately predict stress levels in the copper conductors. However, stress levels in the insulation, particularly the shear stress, are not determined. This report details the three-dimensional finite element analysis performed to determine static stress levels developed within both the copper and the insulation of representative PF coils caused by magnetic Lorentz-force loading.

II. COMPUTATIONAL METHOD

Because of the complex coil configuration and degree of detail required to obtain significant results, the computational study was performed in three distinct steps, as illustrated in Fig. 1. In step one, a portion of the coil cross section and circumference, including the copper conducting coils inside the insulating epoxy matrix, was modeled. The step-one model was independently loaded in all three normal directions, plus torsionally, to obtain the principal stress, σ , and accompanying strains, ϵ . For normal loading, the principal stress was determined by calculating an area average of the normal stress in the copper and insulation. The three principal strains were determined by averaging the displacements on the unconstrained surfaces and dividing by the appropriate length. For torsion, the angle of rotation and shear stress at the location of maximum shear stress were used to compute the shear modulus. Orthotropic material properties representing a bulk or smeared coil material were computed by substituting the results from the independent computations into

$$\begin{Bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \sigma_{12} \\ \sigma_{13} \\ \sigma_{23} \end{Bmatrix} = \begin{bmatrix} C_{1111} & C_{1122} & C_{1133} & 0 & 0 & 0 \\ C_{1122} & C_{2222} & C_{2233} & 0 & 0 & 0 \\ C_{1133} & C_{2233} & C_{3333} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{2323} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{1313} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{1212} \end{bmatrix} \begin{Bmatrix} \epsilon_{11} \\ \epsilon_{22} \\ \epsilon_{33} \\ \epsilon_2 \\ \epsilon_{23} \\ \epsilon_{13} \end{Bmatrix} \quad (1)$$

and solving for the stiffness coefficients, C . The six stiffness coefficients relating the principal stresses and strains were solved for by substituting the normal loading results into

$$\begin{bmatrix} \epsilon_{11} & \epsilon_{22} & \epsilon_{33} & 0 & 0 & 0 \\ 0 & \epsilon_{11} & 0 & \epsilon_{22} & \epsilon_{33} & 0 \\ 0 & \epsilon_{11} & 0 & \epsilon_{22} & \epsilon_{33} & 0 \\ 0 & 0 & \epsilon_{11} & 0 & \epsilon_{22} & \epsilon_{33} \\ 0 & 0 & \epsilon_{11} & 0 & \epsilon_{22} & \epsilon_{33} \\ \epsilon_{11} & \epsilon_{22} & \epsilon_{33} & 0 & 0 & 0 \end{bmatrix} \begin{Bmatrix} C_{1111} \\ C_{1122} \\ C_{1133} \\ C_{2222} \\ C_{2233} \\ C_{3333} \end{Bmatrix} = \begin{Bmatrix} \sigma_{11} \\ 0 \\ \sigma_{22} \\ 0 \\ \sigma_{33} \\ 0 \end{Bmatrix} \quad (2)$$

where rows 1-2 in Eq. (2) contain information obtained from the 1-direction normal loading, rows 3-4 contain 2-direction normal loading information, and rows 5-6 contain 3-direction normal loading information.

Step two of the analysis used symmetry to evaluate a bulk material coil section of actual dimension suspended between supporting bulkheads and undergoing axial and radial Lorentz-body-force gradients. In step two, support boundary conditions were applied with consistent element area weighted springs to simulate the compliance of the bulkheads. The spring constant for each coil bulkhead interface was calculated by using the coil loading and resulting bulkhead displacement obtained from a bulkhead stress-displacement analysis. For all coils studied, the step-two model represents a 11.25° section of

the coil circumference. Symmetric displacement boundary conditions were applied to both end faces of the model on the radial plane containing the machine axis. Lorentz-body-force gradients were applied by using a two-dimensional quadratic spline fit of the discrete conductor forces given to interpolate body force values at the element integration points. Results from the step-two analysis indicated the circumferential coil location of maximum stress.

In step three, a detailed coil cross section, including the copper conductors in the insulation matrix (approximately 5 cm in circumferential thickness), was considered. The nodal displacements computed at two radial cross sections bracketing the region of maximum stress in the bulk model were used to interpolate displacement boundary conditions on the appropriate faces of the step-three model. On step-three model faces, with orientation containing the circumferential direction, the nodal displacement boundary conditions were interpolated linearly between values applied at the two cross-section faces. The step-three calculations produced stress results in both the conductors and in the insulation matrix.

III. ANALYSIS RESULTS

The analysis procedure detailed in the previous section was applied to the PF coils described in Table I. Material properties used for the copper and insulation are summarized in Table II.

TABLE I
GEOMETRIC CHARACTERISTICS OF PF COILS ANALYZED

Coil	Centroid Mean Radius (m)	Width (m)	Height (m)	Area Ratio of Conductor	Support Width (m)	Conductor Width (cm)	Conductor Height (cm)
OH3	1.7530	0.1597	0.3798	0.600	Continuous	3.49	3.81
OH5	3.5400	0.1330	0.2613	0.453	0.10	2.22	5.08
EF9	3.1192	0.1708	0.1294	0.496	0.30	0.64	1.27

TABLE II
MATERIAL PROPERTIES

	<u>Copper</u>	<u>Insulation</u>
Modulus of Elasticity (MPa)	12.4×10^4	1.03×10^4
Poisson's Ratio	0.35	0.36
Shear Modulus (MPa)	4.62×10^4	0.38×10^4

Bulk orthotropic material properties obtained from the step-one calculations are contained in Table III.

TABLE III
COMPUTED COIL BULK MATERIAL STIFFNESSES (MPa x 10^{-4})

<u>Coefficient</u>	<u>OH3</u>	<u>OH5</u>	<u>EF9</u>
C1111	3.7	3.6	3.7
C1122	2.1	2.1	2.1
C1133	2.4	2.3	2.3
C2222	8.5	8.3	8.7
C2233	3.2	3.0	3.0
C3333	5.0	4.7	5.9
C1212	0.6	0.7	4.2
C1313	4.6	4.6	4.6
C2323	0.6	0.7	4.2

1-radial, 2-circumferential, 3-axial

Figures 2-4 illustrate Von Mises stress contours computed in the step-two analysis for coils OH3, OH5, and EF9, respectively. The actual bulkhead support widths used in the calculations producing Figs. 3 and 4 were one-half the support widths reported in Table I, as required by symmetry. The body force loads applied result from full OH and EF coil current. As shown in Figs. 2-4, the maximum coil stresses occur in the region located near the center of the bulkhead. Displacement results from this region were used in the step-three analysis to obtain detailed stress levels in the copper and insulation. The step-two results provide useful information in addition to input for the

step-three analysis. For example, Fig. 5 is a plot of axial bearing pressure transferred from the coils to the bulkhead as a function of distance from the bulkhead center. Figure 6 illustrates maximum vertical displacement for all coils vs circumferential location from bulkhead centerline to coil midspan between bulkheads.

The TF fringe field effect on coil EF9 was also investigated. When the TF coils are operating, the resultant axial and radial forces per unit coil length vary as illustrated in Fig. 7. The computed Von Mises stress contours, including the TF fringe field effect, are shown in Fig. 8. The maximum Von Mises stress is less when the TF coils are operating. This observation is evidenced by comparing the maximum contour stress levels in Figs. 4 and 8. This result is probably due to the out-of-phase load variation between the radial and axial body forces observed in Fig. 7. Including the TF field fringe effect reduces the maximum vertical coil displacement, as shown in Fig. 9. No further analysis was performed, including TF field effects in EF9, because neglecting these variations produced more conservative stress-displacement results.

Figures 10-12 show the step-three mesh configurations for all three PF coils studied. Because of varying coil cross section complexity, the entire cross section of only one coil, OH5, could be modeled. Figures 13-18 are stress fringe plots of the maximum principal and maximum shear stress in all composite step-three coil models. Table IV summarizes stress results obtained from the step-three analysis of all coils studied. The values of maximum shear were computed using

$$\tau_{\max} = (\sigma_{11} - \sigma_{33})/2 , \quad (3)$$

where σ_{11} is the maximum principal stress and σ_{33} is the minimum principal stress. As seen from Table IV, stress levels in the conductors were found to have values 4-12 times greater than those computed in the insulation. For all coils studied, conductor and insulation stress levels developed were below yield and shear strength limits.

TABLE IV
MAXIMUM STRESSES (MPa)

	<u>Von Mises</u>	<u>Maximum Principal</u>	<u>Maximum Shear</u>
OH3			
Conductor	143.0	132.0	80.0
Insulation	21.2	18.3	12.1
OH5			
Conductor	77.0	41.0	43.0
Insulation	12.3	11.2	6.3
EF9			
Conductor	117.0	116.0	60.0
Insulation	11.7	9.5	6.5

Table V compares the three-dimensional finite element results with stress values computed using the modified Princeton coil analysis code. Stress levels calculated in the copper conductors using the two methods are seen to be in fairly good agreement.

TABLE V
CONDUCTOR STRESS COMPARISON (MPa)

	<u>Maximum Principal</u>	<u>Maximum Shear</u>
OH3		
Finite Element	132.0	80.0
Modified Princeton	130.0	65.0
OH5		
Finite Element	41.0	43.0
Modified Princeton	51.0	25.0
EF9		
Finite Element	116.0	60.0
Modified Princeton	118.0	59.0

IV. ESTIMATE OF ERROR

Extensive work was performed to independently investigate possible error in stress prediction arising from the use of the three-step analysis procedure. The loading on the PF coils consists of an axial bending body force and a radial hoop body force. Hoop loading does not generate any direct shear but does generate shear stresses associated with the principal planes. However, bending loads do result in direct shear and might result in shear stress error when modeling composite structures using bulk material methods.

Two-material beam theory and finite element analysis were applied to investigate normal and shear stresses developed in the two-dimensional laminated beam shown in Fig. 19. The beam is thin, with a 10:1 length-to-height ratio, and was subjected to a shear load at the midpoint. The beam consists of three laminations, the outer layers having a modulus 20 times greater than the inner layer. The finite element mesh of the beam is shown in Fig. 20 and models the region between the two axes of symmetry, the fixed-end condition, and the loaded midsection. The finite element analysis was performed with both linear and quadratic interpolation elements.

Experience has proven that little error is produced in predicting normal bending stresses in beams. Therefore, for the laminated beam under consideration, the beam section undergoing counterflexure was studied because the direct shear dominates the stress response. Using two-material beam theory, it can be shown that the equations for the shear stress, τ_{xy} (psi), at the point of counterflexure are

$$\tau_{xy} = C[20 y (\frac{3-y}{2})] \quad 0. \leq y \leq 1. \quad (4)$$

$$\tau_{xy} = C[20 + (1 - \frac{y}{2})(y - 1)] \quad 1. \leq y \leq 1.5 \quad (5)$$

$$\tau_{xy} = C[20 + (2 - y)(y - 1)/2] \quad 1.5 \leq y \leq 2. \quad (6)$$

$$\tau_{xy} = C[10 y (3 - y)] \quad 2. \leq y \leq 3. \quad , \quad (7)$$

where $C = 57.6$ and y is the distance in inches from the base of the beam through the thickness. Figure 21 shows the comparison of these equations with ABAQUS finite element output for the nodal stresses along a line corresponding to the point of counterflexure in the beam. Note that the linear element predicts slightly lower shear stress values than does the quadratic element for equivalent mesh size. However, because the mesh is fine enough to approximate the derivative, $\partial u / \partial y$, both elements give about the same shear stress results. Figure 22 shows a comparison between the Von Mises stress computed with the finite element models and the two-material beam theory. Again, good agreement is evidenced between the two analyses.

Having compared the two-dimensional two-material beam theory with numerical calculations, a three-dimensional composite beam test model of representative PF coil dimension, shown in Fig. 23, was investigated. The beam model considered was 5-in. wide, 7-in. high and 20-in. long. The composite structure used 1 in. by 1 in. copper conductors in an insulation material matrix. Symmetry end conditions were applied to both ends of the beam and a constant bending body force was the applied loading. Quadratic 20-node bricks were used in the ABAQUS analysis.

The transformed shear flow, q_T , across a cross section is determined by

$$q_T = \frac{VQ_T}{I_T} \quad , \quad (8)$$

where V is the shear load, Q_T is the transformed first moment of the area above the point of interest about the neutral axis, and I_T is the transformed moment of inertia of the entire section about the neutral axis. The total shear force across a cross section equals the shear force in the insulation plus the shear force in the copper conductors. This relation can also be written as

$$q_T t_T = q_{CU} t_{CU} + q_{INS} t_{INS} \quad , \quad (9)$$

where t_T is the transformed section thickness, t_{CU} the actual copper thickness, t_{INS} the actual insulation thickness, q_{CU} the shear flow in the

copper, and q_{INS} the shear flow in the insulation. Assuming that the deformation associated with the shear flow is a function of the stiffness, the following can be written

$$q_{CU} = q_{INS}/n \quad , \quad (10)$$

where n is the ratio of insulation shear modulus to copper shear modulus. Upon substitution of Eq. (10) into (9) and solving for q_{INS} , the following is obtained

$$q_{INS} = \frac{n t_T q_T}{t_{CU} + n t_{INS}} \quad . \quad (11)$$

An expression for the shear stress in the insulation, τ_{INS} , is obtained by dividing q_{INS} by the insulation thickness, using Eq. (8) for q_T , and recognizing that $t_{CU} + n t_{INS} = t_T$. Thus,

$$\tau_{INS} = n \frac{V Q_T}{I_T t_{INS}} \quad . \quad (12)$$

Similarly, an expression for the shear stress in the copper, τ_{CU} , may be derived resulting in

$$t_{CU} = \frac{V Q_T}{I_T t_{CU}} \quad . \quad (13)$$

Equations (12) and (13), with the following expressions for the normal stress in the copper, σ_{CU} ,

$$\sigma_{CU} = My/I_T \quad , \quad (14)$$

where y is the coordinate from the beam neutral axis to the point of interest and the normal stress in the insulation, σ_{INS} ,

$$\sigma_{INS} = nMy/I_T \quad , \quad (15)$$

were used to obtain the two-material beam theory results shown in Figs. 24-26. These results were compared with the finite element calculations obtained analyzing the three-dimensional composite beam test model. The good comparison between the analytical and numerical results illustrated in Figs. 24-26 indicates that the two-material beam theory could be applied to the three-step coil analysis to obtain an estimate of the error arising in the calculations.

The two-material beam theory was applied to coils EF9 and OH5 and was compared with the normal and shear stresses computed with finite element calculations for a bending-only loading condition. The results from this comparison are shown in Figs. 27-30 for coil EF9 and Figs. 31-34 for coil OH5. For both coil configurations, the normal stress comparisons were so good that no further effort was made to determine a normal stress error estimate. For coil EF9, the maximum shear stress in the copper was under-predicted with finite elements by a factor of 5.6, but the shear stress computed in the insulation with the two procedures was in agreement. To determine an estimate of error for the maximum shear stress, $\tau_{\max}$, in the copper, the conductor element in the finite element analysis containing the maximum shear stress value was identified. The state of stress in this element was modified by multiplying the bending shear stress component by the factor 5.6. Using the modified state of stress, new principal stresses were computed using standard techniques. Before modification, the maximum principal stress, σ_{11} and $\tau_{\max}$ were 16,235 psi and 8,683 psi, respectively. After modification, these values were computed to be 16,238 psi for σ_{11} and 8,685 psi for $\tau_{\max}$. The estimate of error using the described methods for EF9 were, therefore, determined to be insignificant for both stress values. Similar results were obtained when applying the bending-only comparison results for coil OH5 into the state of stress correction procedure. These results were not unexpected because normal stresses dominate the state of stress. This statement is true even at the point of counterflexure because of the large hoop stress component.

An estimate of error was computed for coil OH3 by performing a two-dimensional axisymmetric finite element analysis on the composite cross section. Because OH3 is continuously supported, an axisymmetric analysis was permissible. The 2-D analysis used a mesh cross section identical to the

step-three analysis mesh used in the three-step procedure. Table VI compares specific stress values computed using the two procedures.

TABLE VI
COIL OH3 STRESS COMPARISON (psi)

<u>Analysis Method</u>	<u>Von Mises</u>	<u>Maximum Principal</u>	<u>Maximum Shear</u>
3-D (three step)	20,750	19,090	11,610
2-D (axisymmetric)	18,810	18,610	9,860

The maximum difference in stress computed using the two models was 15% in the maximum shear stress. A large portion of this difference might be associated with the dissimilar techniques used to apply the spatially varying body loads rather than the procedural differences. The axisymmetric analysis assumed a constant body force at each integration point throughout the conductor as opposed to the quadratic spline fit used in the 3-D analysis described in step two of Section II.

V. SUMMARY

As a result of this study, the location and level of the maximum combined and the maximum shear stress in both the copper conductors and insulating matrix for representative ZTH-PF coils were quantified. Stress levels developed in all coils studied were found to be below yield and shear strength limits for the Lorentz-loading applied. The computational procedures developed provide a method to perform detailed stress-displacement analysis of complex field coils. Extensive work was performed to investigate possible error in stress predictions arising from the use of the procedures developed. The error study, based on composite beams loaded in bending only, found the error generated in normal and shear stress to be negligible.

Fig. 1. Computational method outline for coil analysis.

ZTH COIL OH3 BULK
CONTINUOUS BULKHEAD
VON MISES

10003 = A

9908 = B

9813 = C

9718 = D

9623 = E

9528 = F

9433 = G

9338 = H

9243 = I

9148 = J

9053 = K

8958 = L

8863 = M

8769 = N

8674 = O

Fig. 2. Von Mises stress contours in OH3 bulk model (contour levels in psi).

4589	=	A
4277	=	B
3966	=	C
3654	=	D
3342	=	E
3031	=	F
2719	=	G
2407	=	H
2095	=	I
1784	=	J
1472	=	K
1160	=	L
849	=	M
537	=	N
225	=	O

Fig. 3. Von Mises stress contours in OH5 bulk model (contour levels in psi)

Fig. 4. Von Mises stress contours in EF9 bulk model (contour levels in psi).

Fig. 5. Bearing pressure on bulkhead support.

Fig. 6. Maximum coil vertical displacement vs circumferential location.

Fig. 7. Axial and radial force/length variation in EF9 due to TF fringe effect.

Fig. 8. Von Mises stress contours in EF9 bulk model, including TF fringe effect (contour levels in psi).

Fig. 9. TF fringe effect on vertical displacement in EF9.

ZTH COIL OH3
COMPOSITE HALF SECTION
LIGHT - INSULATION
DARK - CONDUCTOR

Fig. 10. Coil OH3 step-three mesh configuration.

ZTH COIL OH5
 COMPOSITE WHOLE SECTION
 LIGHT - INSULATION
 DARK - CONDUCTOR

Fig. 11. Coil OH5 step-three mesh configuration.

ZTH COIL EF9
COMPOSITE QUARTER SECTION
LIGHT - INSULATION
DARK - CONDUCTOR

Fig. 12. Coil EF9 step-three mesh configuration.

ZTH COIL OH3
COMPOSITE HALF SECTION
MAXIMUM PRINCIPAL

Fig. 13. Maximum principal stress in OH3 composite model (stress levels in psi).

ZTH COIL OH3
COMPOSITE HALF SECTION
MAXIMUM SHEAR

Y
X
Z

11607.

8910.

6214.

3517.

820.

D

Fig. 14. Maximum shear stress in OH3 composite model (stress levels in psi).

ZTH COIL OH5
COMPOSITE
MAXIMUM PRINCIPAL

Y
X
Z

6008.

4288.

2568.

847.

-873.

D

Fig. 15. Maximum principal stress in OH5 composite model
(stress levels in psi).

ZTH COIL OH5
COMPOSITE
MAXIMUM SHEAR

Fig. 16. Maximum shear stress in OH5 composite model (stress levels in psi).

ZTH COIL EF9
COMPOSITE QUARTER SECTION
MAXIMUM PRINCIPAL

16791.

12763.

8736.

4708.

681.

D

Fig. 17. Maximum principal stress in EF9 composite model
(stress levels in psi).

ZTH COIL EF9
COMPOSITE QUARTER SECTION
MAXIMUM SHEAR

Fig. 18. Maximum shear stress in EF9 composite model (stress levels in psi).

POISSON'S RATIO = 0.30 FOR ALL MATERIALS

Fig. 19. Three-layer laminated beam.

Fig. 20. Finite element mesh of laminated beam.

SHEAR STRESSES, TWO-MAT. BEAM THEORY VS ABAQUS

Fig. 21. Shear stress comparison for laminated beam.

Fig. 22. Von Mises stress comparison for laminated beam.

Fig. 23. Composite beam test model.

NORMAL STRESS AT X=19 ABAQUS VS THEORY

Fig. 24. Shear stress comparison in composite beam along vertical strip containing both copper and insulation.

SHEAR STRESS Z=10 CU/G10 STRIP 2 OR 4

Fig. 25. Shear stress comparison in composite beam along vertical strip containing insulation only.

SHEAR STRESS Z=10 ALL G10 STRIP 3 OR 1/5

Fig. 26. Normal stress comparison in composite beam for copper and insulation.

EF9 NORMAL STRESS IN CU - BENDING LOAD ONLY

Fig. 27. Comparison of bending normal stress in EF9 copper.

EF9 NORMAL STRESS IN G10 - BENDING LOAD ONLY

Fig. 28. Comparison of bending normal stress in EF9 insulation.

EF9 SHEAR STRESS IN THE CU - BENDING LOAD ONLY

Fig. 29. Comparison of bending shear stress in EF9 copper.

EF9 SHEAR STRESS IN THE G10 - BENDING LOAD ONLY

Fig. 30. Comparison of bending shear stress in EF9 insulation.

OH5 NORMAL STRESS IN CU - BENDING LOAD ONLY

Fig. 31. Comparison of bending normal stress in OH5 copper.

OH5 NORMAL STRESS IN G10 - BENDING LOAD ONLY

Fig. 32. Comparison of bending normal stress in OH5 insulation.

OH5 SHEAR STRESS IN THE CU - BENDING LOAD ONLY

Fig. 33. Comparison of bending shear stress in OH5 copper.

OH5 SHEAR STRESS IN THE G10 - BENDING LOAD ONLY

Fig. 34. Comparison of bending shear stress in OH5 insulation.