INFLUENCE OF REINFORCEMENT ANISOTROPY ON THE STRESS DISTRIBUTION IN TENSION AND SHEAR OF A FUSION MAGNET INSULATION SYSTEM

K. Humer[1], S. Raff[2], R. Prokopec[1], and H. W. Weber[1]

[1]Atomic Institute of the Austrian Universities,
Vienna University of Technology, 1020 Vienna, Austria

[2]Institut für Reaktorsicherheit
Forschungszentrum Karlsruhe, 76021 Karlsruhe, Germany

ABSTRACT

A glass fiber reinforced plastic laminate, which consists of half-overlapped wrapped Kapton/R-glass-fiber reinforcing tapes vacuum-pressure impregnated in a cyanate ester/ epoxy blend, is proposed as the insulation system for the ITER Toroidal Field coils. In order to assess its mechanical performance under the actual operating conditions, cryogenic (77 K) tensile and interlaminar shear tests were done after irradiation to the ITER design fluence of 1×10^{22} m^{-2} (E>0.1 MeV). The data were then used for a Finite Element Method (FEM) stress analysis. We find that the mechanical strength and the fracture behavior as well as the stress distribution and the failure criteria are strongly influenced by the winding direction and the wrapping technique of the reinforcing tapes.

KEYWORDS: fusion magnet insulation; finite element methods; epoxy, cyanate ester.

INTRODUCTION

The magnet insulation systems of ITER are affected by Lorentz forces (mechanical stresses) at cryogenic temperatures and by a radiation environment, which impose certain constraints especially on the insulating materials. Since many years, the mechanical material behavior of newly developed fiber composites has been investigated [1,2] and modelled by Finite Element Method (FEM) [3,4] to assess their suitability for ITER.

A glass fiber reinforced laminate, based on a radiation resistant cyanate ester (CE)/epoxy blend, is now proposed as the insulation system for the ITER Toroidal Field coils. Based on our experimental results obtained for this innovative insulation system [5], this paper addresses some deformation and failure properties assessed by detailed FEM and is aimed at getting a better understanding of the failure behaviour and at allowing a material description for deformation and failure as well.

CP986, *Advances in Cryogenic Engineering: Transactions of the International Cryogenic Materials Conference - ICMC, Vol. 54,* edited by U. Balachandran

MATERIAL AND FEM MODELLING

The newly developed CE/epoxy blend system was fabricated by Marti-Supratec Corporation, Switzerland. This laminate consists of combined R-glass/Kapton reinforcing tapes (width 25 mm), which were wrapped half-overlapped around a steel plate, as would be done during the coil manufacturing process. After a defined drying process at ~100 °C, the tapes were vacuum pressure impregnated with the matrix systems, i.e. the CE AroCy-L10/DGEBA epoxy PY-306 blend (40/60 ppw). After the heat treatment, the laminate was cut along the two longitudinal sides of the steel plate to obtain two sample plates. Because of the "wrapping technique" the material properties are anisotropic. The material was characterized in tension and interlaminar shear using a flat dog-bone shaped tensile and a short-beam-shear specimen, respectively. The specimen geometries and the test procedures as well as the results are given in [2,5].

In the FEM analysis the different layers of the material and the specimen geometries were modelled. FIGURE 1 shows the FEM models used for 0° and 90° direction. 13 layers of Kapton separate 14 layers of the glass fibre/blend resulting in a 4 mm thick plate of material from which the specimens were cut. Because of the wrapping technique, inclusions of resin material were modelled perpendicular to the reinforcing tapes, which led to additional orthotropic material properties of the insulation material especially in the layer plane.

In the FEM analysis evaluation two failure criteria were used: the Tsai-Wu criterion for the ply failure of each layer and the Brewer-Lagace criterion for the delamination of the layers. For both the risk parameter formulation as described in [4] was used. The risk parameter $0 \leq \epsilon \leq 1$ reaches 1 at failure. The Tsai-Wu criterion was evaluated from an internal ANSYS macro, the Brewer Lagace criterion by a user macro [3].

The input of the material properties and the parameters for the Tsai-Wu failure criterion and for the Brewer-Lagace delamination criterion in ANSYS was partly taken from separate tests and partly from literature, whereas some were determined in this study from data evaluated from two test methods, the tensile and the short-beam-shear (SBS) test. The FEM analysis was done by adjusting the material parameters (deformation and failure properties) in such a manner that at least one of the two failure criteria was indicating the failure of the specimen at the measured integral failure loads.

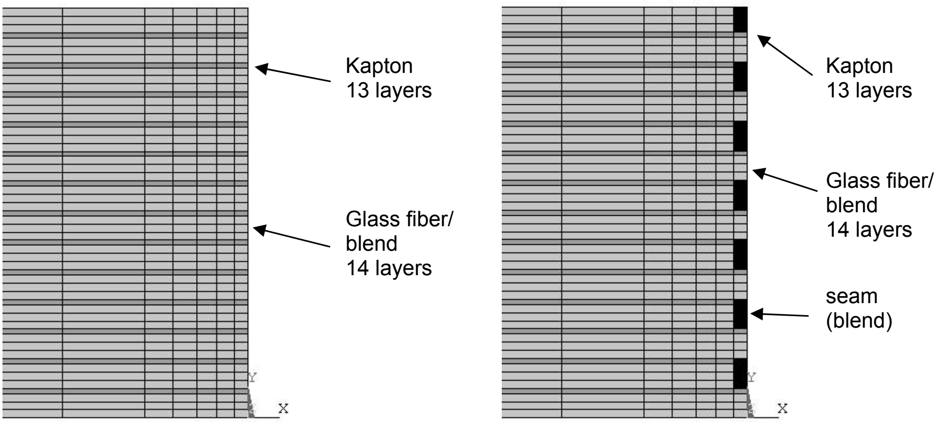

FIGURE 1. FEM models for 0° (left) and 90° (right) orientation including 14 layers of glass fibre/blend (0.24 mm) and 13 layers of Kapton (0.05 mm).

RESULTS AND DISCUSSION

Material Parameters

The deformation and failure parameters for Kapton and for the blend were taken from our own data base and from literature [2]. The values for the fabric/blend (i.e. the ratio of in-plane and out-of-plane material parameters) were taken from [4] but employing a scaling factor to fulfil the failure criterion just at the load obtained from the experiment. The scaling factor turned out to be 2.0. The failure parameter values for delamination were fitted to the SBS tests.

TABLES 1–3 present the material parameters. The italic numbers are the values from [4] multiplied by the above mentioned iterated scaling factor. The interlaminar shear failure values (cf. TABLE 3) are higher than in [4] by 5 – 20%.

TABLE 1. Deformation properties

material	E_x [MPa]	E_y [MPa]	E_z [MPa]	G_{xz} [MPa]	G_{xy} [MPa]	G_{yz} [MPa]	ν_{xz} [-]	ν_{xy} [-]	ν_{yz} [-]
glass fabric/blend	*56000*	*24000*	*56000*	*24000*	*24000*	*24000*	0.2	0.42	0.42
blend	7000						0.37		
kapton	11000						0.33		

E_x, G_{xz} = elastic modules, etc. ν_{xz}= lateral contraction etc.
x = in plane fabric layer; z = in plane fabric layer orthogonal x; y = direction orthogonal to fabric layer

TABLE 2. Material parameters for the Tsai-Wu failure criterion

material	R_{xT} [MPa]	R_{xC} [MPa]	R_{yT} [MPa]	R_{yC} [MPa]	R_{zT} [MPa]	R_{zC} [MPa]	R_{xy} [MPa]	R_{yz} [MPa]	R_{xz} [MPa]
glass fiber/blend	*1340*	*-1500*	*180*	*-800*	*1340*	*-1500*	*300*	*300*	*300*
blend	112		112		98		98	98	98
kapton	320		320		320		224	224	224

$R_{xT,}$, R_{xC} = failure stress in tension and compression etc.; R_{xy}= failure shear stress etc.

TABLE 3. Material parameters for the Brewer-Lagace delamination criterion

	R^{IL}_{xy} [MPa]	R^{IL}_{zy} [MPa]	R^{IL}_{yy} [MPa]
layer interface	85	85	95

R^{IL}_{xy}= interlaminar shear stress failure value, etc.

Tensile behaviour

In the FEM analysis (symmetric properties), a quarter of the specimen was modelled. For 90°, (FIGURE 2), the blend inclusions - simulating the edges of neighbouring tapes - are located in the middle of the specimen, where the cross section has its minimum and, thus, the maximum effect of the seam is expected. In reality, the seam locations are randomly distributed along the gage length of the sample and, hence, some statistical spread occurs. FIGURES 2-4 show the stress distribution in the layered material at failure load. For 0°, the load bearing fibre layers reach a stress level of 1100 MPa, the Kapton layers 500 MPa. For 90°, the corresponding values are 600 MPa and 300 MPa, respectively. The results of the layer failure criterion (Tsai-Wu [6,7]) clearly indicate that failure occurs in the fabric layer (FIGURE 5). For 90° failure is indicated due to the stress in the blend inclusions in the seam. As expected, the delamination criterion (Brewer-Lagace [8]) will not indicate failure in tension in tape direction, but in orthogonal direction the delamination criterion is nearly fulfilled at the interface between Kapton and the fabric layer.

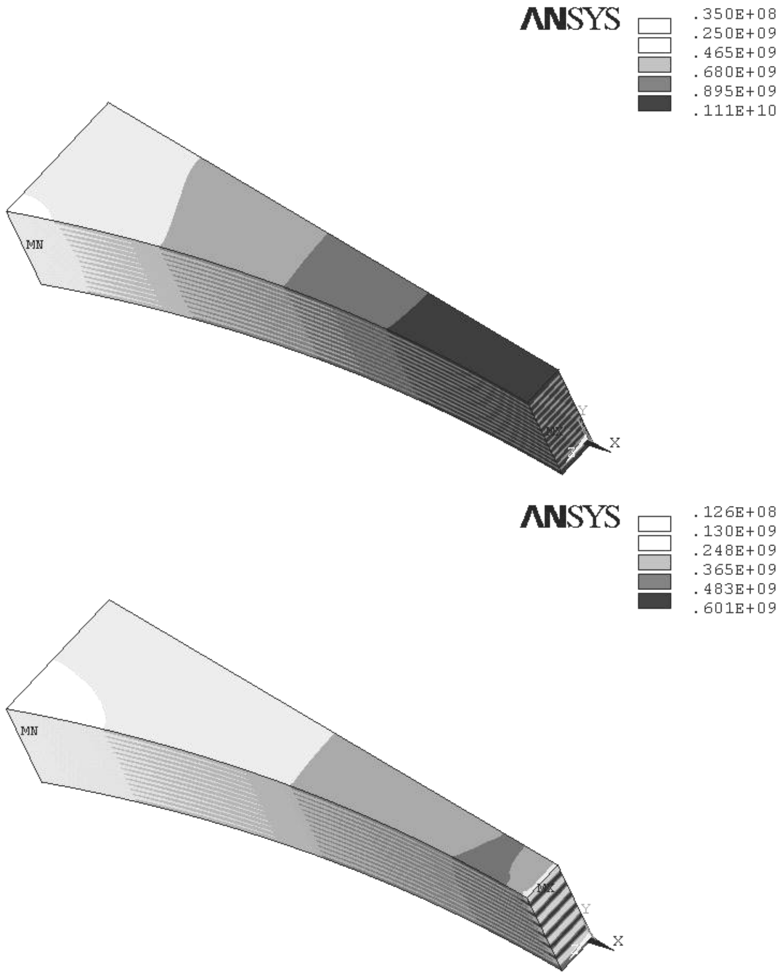

FIGURE 2. Tensile stress [Pa] at experimental failure load for 0° (top) and 90° (bottom) orientation.

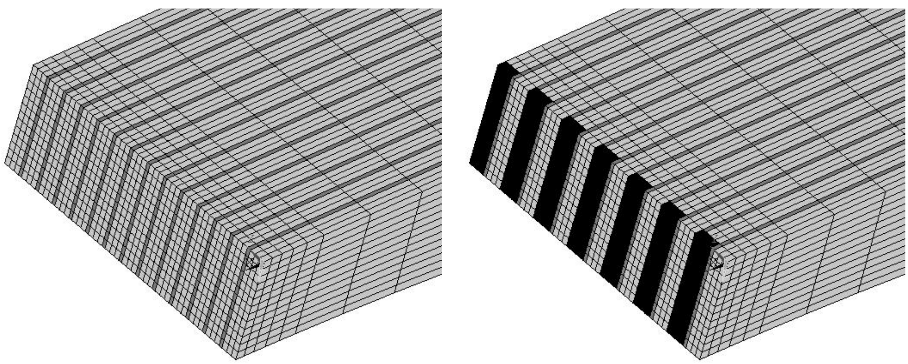

FIGURE 3. Middle part of the tensile specimen FEM model for 0° (left) and 90° (right) orientation.

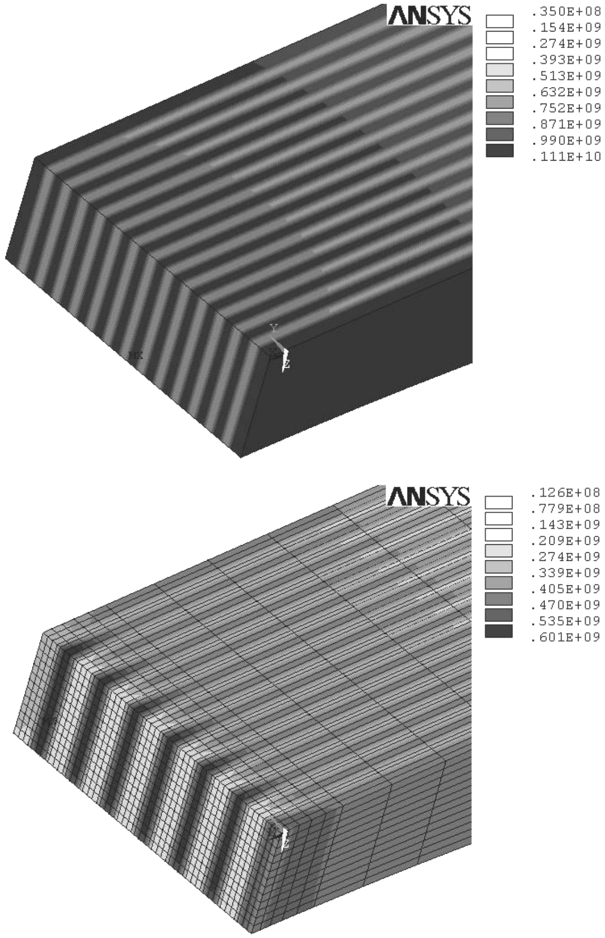

FIGURE 4. Detailed tensile stress [Pa] at failure load for 0° (top) and 90° (bottom) orientation.

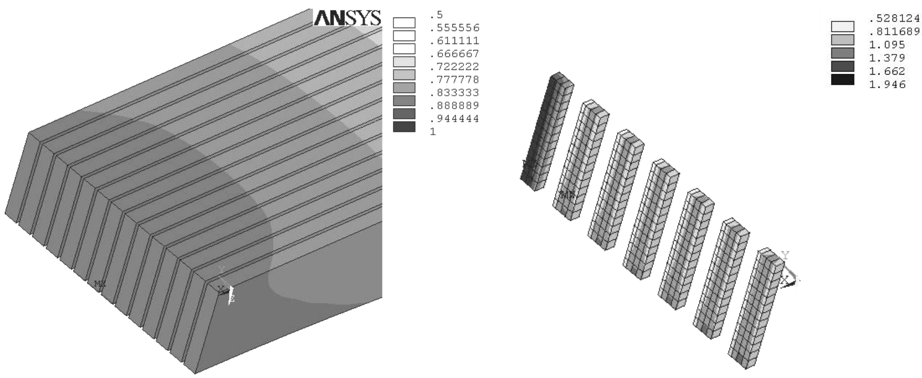

FIGURE 5. Ply failure criterion of the tensile specimen for the glass/blend in 0° orientation (left) and for the blend (seam inclusions) in 90° orientation (right).

Interlaminar shear behavior

FIGURE 6 shows the FEM model (quarter of a specimen) loaded in 0° and 90° direction (span length 20 mm, length x width x height 25 x 6.5 x 4.1 mm^3). It was assumed that for the 90° orientation the neighbouring tapes (blend inclusions) are located in a region with high shear stress (half way between load and support) and, hence, their influence on specimen failure will be maximal.

The shear stress distribution at failure load in y direction (height of sample) half way between the middle of the specimen and the support is shown in FIGURE 7. On the specimen edge the stresses are about 20 % higher than in the middle of the specimen. The application of the failure criterion (Tsai-Wu [6,7]) on different layers showed that this failure type was not dominant for this loading condition. Ignoring the small very local effects at the supporting and at the load spot, only in the blend inclusions of the 90° specimens some failure is indicated. The application of the delamination criterion (Brewer-Lagace [8]) is shown in FIGURE 8. This criterion is clearly dominant for shear probe failure. Some differences between 0° and 90° specimens were found. For 0°, the failure is initiated at the specimen edge and propagates to the center. For 90°, the delamination initiation takes place at the blend inclusions and the delamination propagates 'faster' from the edge to the center as compared to the 0° specimen.

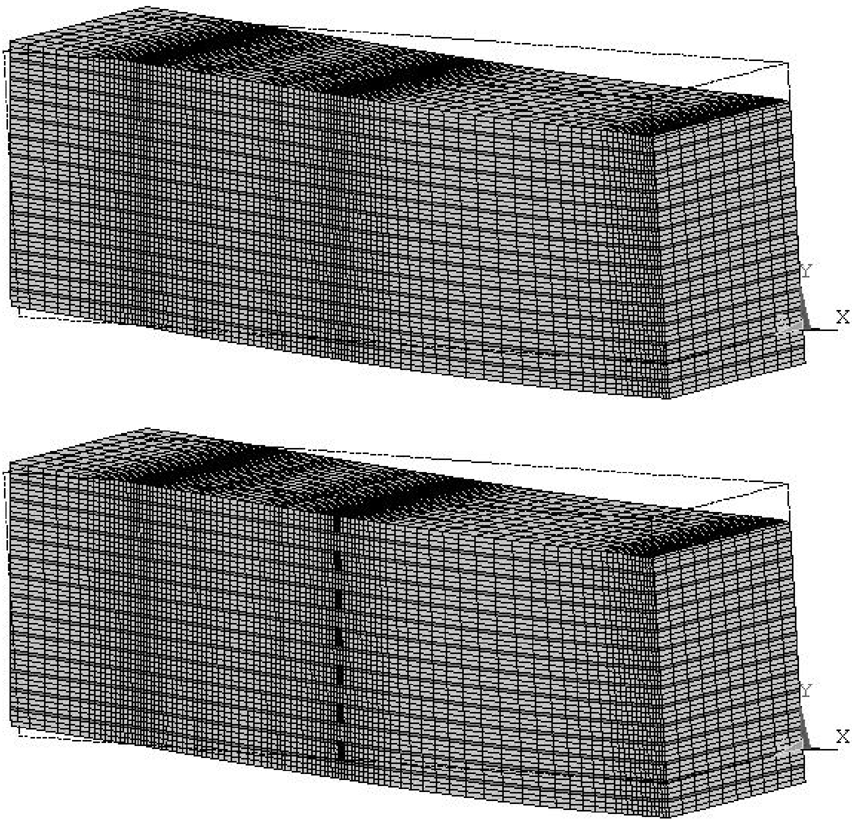

FIGURE 6. FEM models for a quarter short beam shear specimen in 0° (top) and 90° (bottom) orientation.

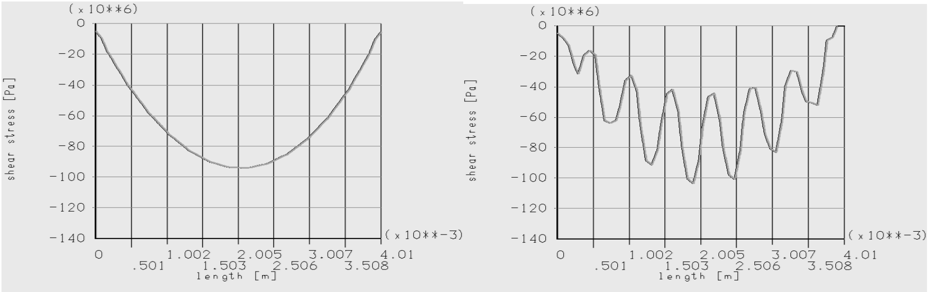

FIGURE 7. Interlaminar shear stress distribution for 0° (left) and 90° (right) orientation on edge of probe (along seam cross section in y-direction).

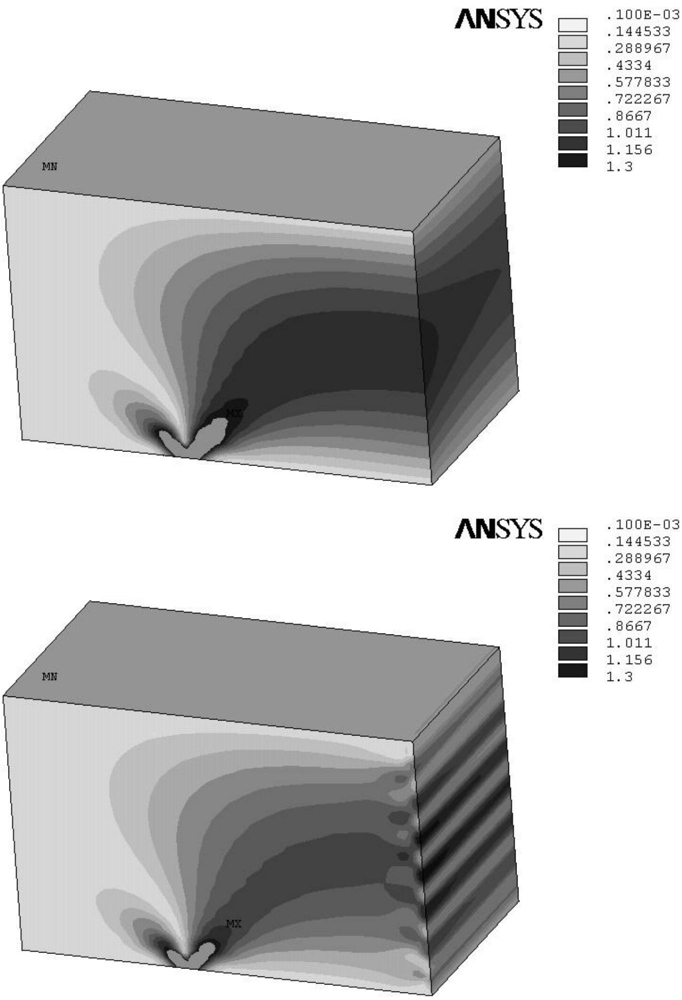

FIGURE 8. Delamination failure criterion of a short beam shear specimen for 0° (top) and 90° (bottom) orientation, cut of sample at half distance between supporting and load line.

SUMMARY

An innovative fiber reinforced plastic laminate based on a cyanate ester/epoxy blend is proposed as the insulation system for the ITER Toroidal Field coils and was investigated by FEM, in order to check for the stress distribution and the failure behaviour and to allow a material description for deformation and failure as well.

The results of the FEM analysis may be summarized as follows:

- Due to the assembly of the insulation material by wrapped overlapped R-glass/Kapton tapes the material properties are strongly orthotropic. This can be modelled using the components glass fiber/blend, Kapton and pure blend in the seams generated in perpendicular direction to the tape winding direction.
- In the tensile test the failure load perpendicular to the winding direction is only about 30% compared to the longitudinal direction. This is caused by blend inclusions which fail due to overstress and delamination.
- In the shear tests the failure load perpendicular to the tape direction is reduced by about 20%. The blend inclusions enhance an early delamination propagation.
- The deformation properties and failure criteria for the ply and the delamination seem to be adequate for describing the material behaviour. The material parameters were determined from tensile and shear test results.

ACKNOWLEDGEMENTS

This work, supported by the European Communities under the contract of Association between EURATOM, the Austrian Academy of Sciences and FZK, was carried out within the framework of the European Fusion Development Agreement. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

REFERENCES

1. Humer, K., Weber, H.W. and Tschegg, E.K. *Cryogenics* **35**, pp. 871-882 (1995).
2. Humer, K., Bittner-Rohrhofer, K., Fillunger, H., Maix, R. K., Prokopec R. and Weber H. W. *Fus. Eng. Des.* **81**, pp. 2433-2441 (2006).
3. Raff, S., Report to ATI, November 18, 2004.
4. Pahr, D. H., Rammerstorfer, F. G., Rosenkranz, P., Humer, K. and Weber, H. W. *Composites Part B* **33**, pp. 125-132 (2002).
5. Bittner-Rohrhofer, K., Humer, K., Fillunger, H., Maix, R. K. and Weber, H. W., "Performance of magnet insulation systems at low temperature and after reactor irradiation", in *Advances in Cryogenic Engineering* 50A, edited by U. B. Balachandran et al., AIP Conference Proceedings, New York, 2004, pp. 281-288.
6. Tsai, S. W. and Hahn, H. T., *Introduction to Composite Materials*, Technomic Publishing Company, 1980, Section 7.2.
7. Tsai, S. W., *Composites Design*, Think Composites, Dayton, Ohio, 1987, Third Edition, Section 11.6.
8. Brewer, J. C., Lagace, P. A., *J. Comp. Mat.* **22**, pp. 1141-1155 (1988).