THREE-DIMENSIONAL ANALYSIS OF COMPOSITE MATERIAL

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ABSTRACT

The structural analysis of a SiC/SiC composite first wall in a tokamak fusion reactor is explored using the finite element method. The analysis is done in three-dimensions under thermal and pressure loads. The effect of the three-dimensional analysis on the result is compared with that for the two-dimensional analysis. The comparison indicates that the two-dimensional analysis, which ignore the effect of the stacking sequence of the laminate and the effect of the interlaminar shear stress, is insufficient for reactor design.

INTRODUCTION

Ceramics have been considered ideal materials for high temperature applications because of their great stability, resistance to corrosion, and huge strength. The drawback to the use of ceramics has historically been a severe lack of ductility, but this has been corrected by the development of fiber composites, which provide both strength and resistance to fracture. These attractive features have led many recent fusion reactor system studies to adopt fiber composites as the primary structural material for one or all of the divertor, first wall, blanket and shield [1-4]. The composite receiving the most attention for fusion machines is silicon carbide, which combines the previously mentioned advantages with low afterheat and low activation, making this an important material from both the safety and waste disposal points of view. Many questions remain, though, regarding the leak-tightness and radiation damage resistance of this material.

The SiC/SiC composites are two-dimensional flat laminates made with SiC fibers stacked and then densified with a silicon carbide matrix which is typically deposited by chemical vapor-deposition (CVD). The structural behavior of a laminate can vary from very stiff and elastic to much less stiff and viscoelastic, depending on the orientation of the fibers in the various plies. Also one laminate may possess excellent fatigue strength while another laminate, similar in stiffness but dissimilar in fiber orientation and ply stacking order, may delaminate after relatively few cycles [5].

The design of a fiber-reinforced structure is considerably more difficult than that of a metal structure, principally due to the anisotropy of its properties. However, the anisotropic nature of a fiber-reinforced composite material creates a unique opportunity for tailoring its properties according to the design requirements. This design flexibility can be utilized selectively to reinforce a structure in the directions of major stresses, increase its stiffness in a preferred direction, fabricate curved panels without any secondary forming operation, and produce structures with zero coefficients of thermal expansion.

Unfortunately, the structural analysis of composite structures is also more complex than the analysis of metal structures. Both the stress analysis and the failure analysis must account for anisotropies in the material properties of a single layer, and for the orientations of the layers making up the structure. The failure analysis is particularly difficult, due to the many failure modes possible, and the many theories developed to account for these failure modes [6]. The scope of reactor design studies generally excludes detailed micromechanical analysis of composites, particularly since modeling of ceramic composites is still in its embryonic stage. That is, geometric variations in the third direction are not adequately modeled. Optimization of thick multilayer cylinders reveals that the radial layer sequence is critical for maximizing burst pressure. This radial layer sequence prediction can only be done by 3-dimensional analysis. Two dimensional analysis does not differentiate one sequence from another composed in the same layers. The validity of the thin wall solution is limited to wall thickness ratios (outer to inner diameter) less than 1.1.

All the previous work in this field was done using two dimensional analysis and as we mentioned above the two-dimensional analysis does not give us a complete information about what will happen through the thickness and the problems which can happen as a result of the normal and interlaminar shear.

In this paper the difference between using two-dimensional and three-dimensional analyses on the first wall of tokamak reactor will be presented. The effect of the choice of the boundary conditions on the mechanical behavior of the SiC composite material and the effect of choosing fiber orientation and stacking sequence of the laminate on the interlaminar shear stress are also studied.

MODELING

The model chosen for this analysis was a part of the first wall of the ARIES-I tokamak fusion reactor [7] made from SiC/SiC composite. The geometry of this model is given in Figure (1) and (2). The plasma - facing side of the model is coated with a 2 mm CVD SiC composite layer. This layer provides a highly dense barrier to coolant leaks; it also serves as a sacrificial layer for first wall sputtering. The SiC/SiC composite is modeled using four symmetric lamina per element. The fiber orientation for these lamina was $[90^\circ/45^\circ/0^\circ/-45^\circ]_s$. The contact surface between the units has a coupled boundary condition that allows the edge to move only in one direction with the same displacement. This models a plate which is free to expand, but not to bend. The 2-D model consists of 1169 triangular elements, while the 3-D model consists of 386 layered solid elements. A constant volumetric heating of 23.6 MW/m^3 was assumed for all the elements in the model and a heat flux of 0.55 MW/m^2 was assumed to be incident on the plasma face. On the blanket side of the first wall a surface heat load of 0.17 MW/m^2 was used. This is to model heat entering the first wall from the breeder. The coolant pressure inside the first wall considered was taken to be 5 MPa, and a constant heat transfer coefficient of 2200 $W/K.m^2$ inside the coolant channel was used. The silicon carbide fiber considered here is assumed to be isotropic and homogeneous, with properties which are independent of temperature, thus simplifying the analysis. The material properties of SiC/SiC composite that were used in this analysis are given in table (1) [7, 8]. The same cross-section was used for both the 2-D and 3-D analyses. The 2-D model reduces the fiber properties to a set of orthotropic properties and ignores variations of the deformation through the thickness. The 3-D model is a more accurate model of the ARIES-I structure because it accounts for the structure of the fibers themselves. This model uses a layered brick element that allows the user to set different properties for each layer. This allows one to model different configurations of fiber orientation, as well as calculating the interlaminar shear stress. This latter quantity is unavailable when one performs a 2-D analysis, but it can be an important failure criteria.

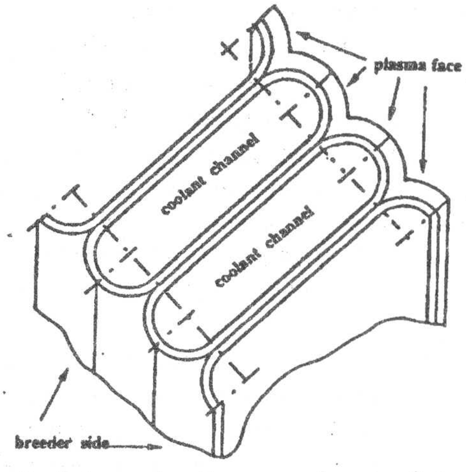

Figure 1. Schematic diagram of part of the first wall of ARIES-I.

Table 1. Material properties of SiC/SiC composite [7, 8].

Material property	SiC/SiC composite
fiber content	40%
porosity	10%
tensile strength	200 MPa
Young modulus	230 GPa
Poisson's ratio	
ν_{12}	0.05
ν_{13}	0.18
compressive strength	
in plane	580 MPa
through the thickness	420 MPa
Interlaminar shear strength	40 MPa
thermal expansion cofficient	
in plane	4.4×10^{-6} /K
through the thickness	4.3×10^{-6} /K
thermal conductivity	
in plane	19 W/K.m
through the thickness	9.5 W/K.m
fracture toughness	30 MPa.m$^{1/2}$
specific heat	630 J/K.kg
maximum temperature	1100 °C

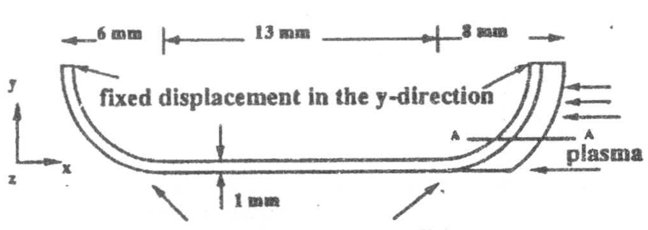

Figure 2. Model used for analysis of the first wall SiC.SiC composite.

RESULTS

Thermal Stresses

Figure (3) shows the temperature contours for the surface and bulk loads described earlier. This figure indicates that the temperature distribution in the CVD SiC layer facing the plasma is almost one dimensional and little conduction to the rear of the tube is observed. There is no noticeable difference between the temperatures calculated using the 2-D and 3-D models, since the loads are uniform over the structure. Figure (4) shows the stress distribution as a result of the thermal load. The peak thermal stress of 148 MPa is located towards the blanket side of the first wall for the two dimensional analysis, while that for the three-dimensional model is only 81.6 MPa and is at the same location. The difference between the two models is substantial. In this case the simplified (2-D) model over-predicts the stress, thus causing an overly conservative design. In either case, the stresses are below the limits given in table (1). Figure (5) gives the shear stress behavior in the two models. It indicates that the peak shear stress for the two-dimensional model is 76 MPa, while it is 80 MPa for the three-dimensional model. In this case, there is no appreciable difference between the results of the two analyses, and the calculated stress is again well below the limits in table (1).

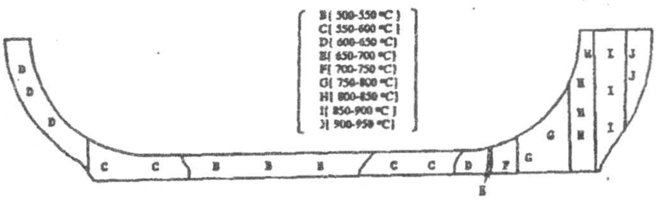

Figure 3. The temperature contour plot of the first wall due to the thermal loads.

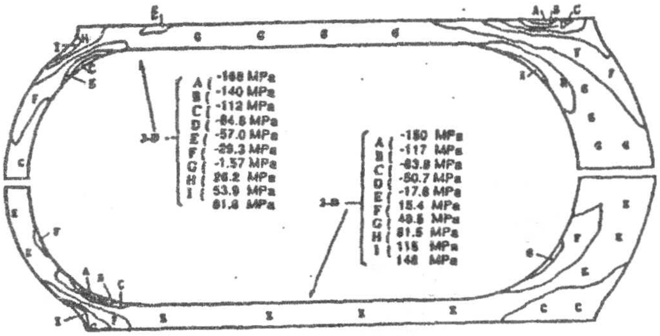

Figure 4. Stress contour plot, σ_x, of the first wall for the 2-D and 3-D due to the thermal load only.

Thermal and Pressure Analysis

The combined thermal and pressure stress is shown in Figure (6) and (7). For the two-dimensional model the peak stress is 182 MPa, while the peak stress in the three-dimensional case is only 106 MPa. As before, the two-dimensional analysis overestimates the stress by a factor of about 1.7, and the stresses are below the accepted limit. Figures (8) and (9) show a comparison between the two models for s_x at a certain section (section A-A in Figure (2)). It is clear from the figures that the 2-D analysis underestimates the stress values, especially at the plasma side. Also, the 2-D analysis levels off the stress distribution, reducing the difference between the maximum and minimum stresses. Figures (10) and (11) show the same comparison for the shear stress, s_{xy} . In this case the 3-D analysis exhibits higher stresses on both the coolant and the plasma sides of the model.

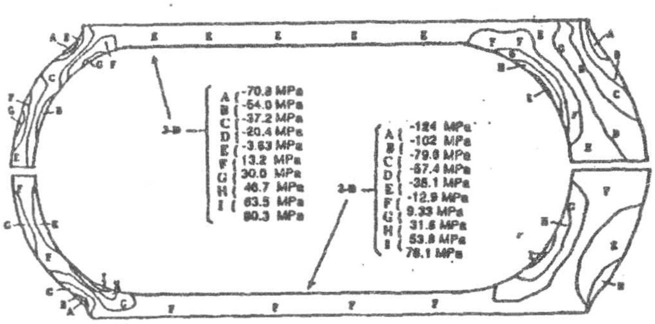

Figure 5. Shear stress contour plot, σ_{xy}, of the first wall for the 2-D and 3-D due to the thermal load only.

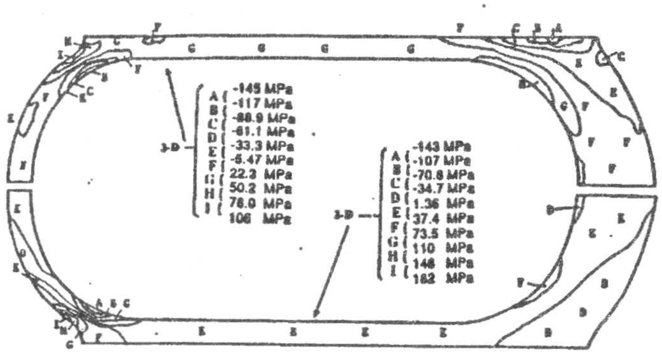

Figure 6. Stress contour plot, σ_x, of the first wall for the 2-D and 3-D due to the thermal land pressure loads.

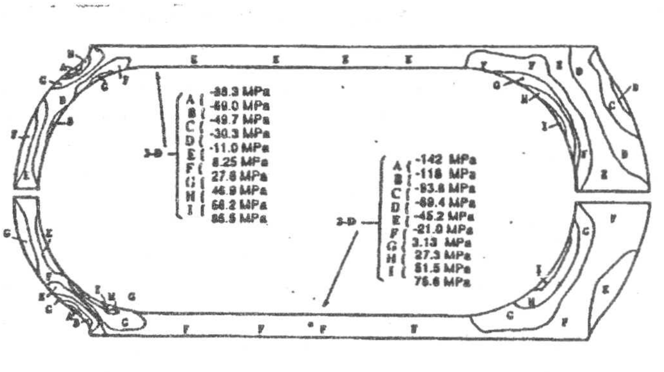

Figure 7. Stress contour plot, σ_{xy}, of the first wall for the 2-D and 3-D due to the thermal and pressure loads.

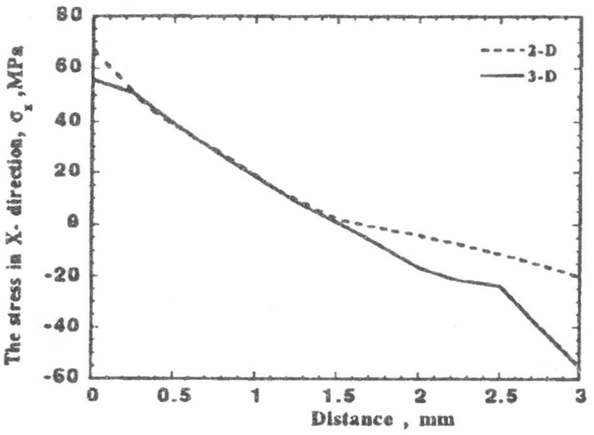

Figure 8. Variation of σ_x through the first wall as a result of the thermal load only.

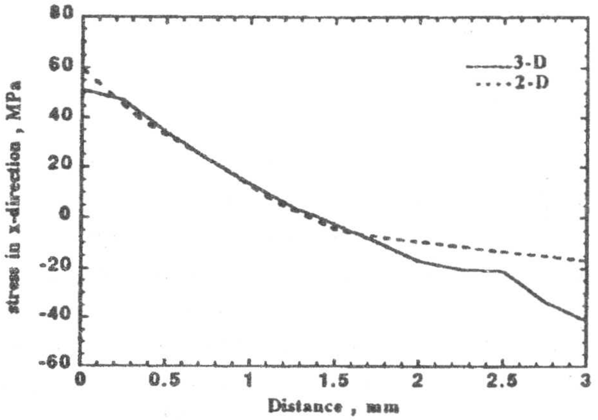

Figure 9. Variation of σ_x through the first wall as a result of the thermal pressure loads.

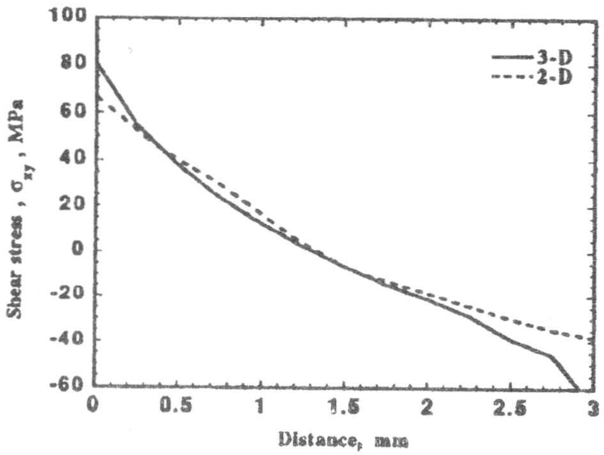

Figure 10. Variation of σ_{xy} through the first wall as a result to thermal load only.

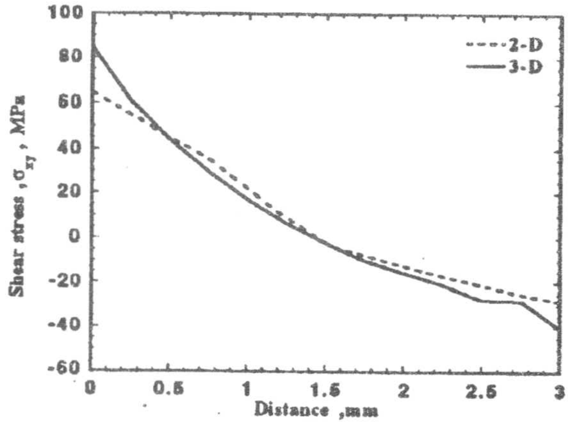

Figure 11. Variation of σ_{xy} through the first wall as a result to thermal and pressure loads.

DISCUSSION

The results shown above indicate that a simple, 2-dimensional analysis of a structure composed of fiber composites can both underestimate and overestimate the stresses in the structure. If the stress is overestimated, a design based on the analysis will be conservative and the result will not be as attractive as it could be. If the stress is underestimated, the structure may fail prematurely. Neither case is desirable. In addition, the 2-dimensional analysis does not yield important information regarding the interlaminar shear stress, which is an important parameter when delamination is a concern. Hence, a 3-dimensional analysis, which models the details of the fiber orientation, must be used when assessing the viability of a particular design for a SiC/SiC fusion component.

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