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Modeling Woven Polymer Matrix Composites With MAC/GMC

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August 2000

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MODELING WOVEN POLYMER MATRIX COMPOSITES WITH MAC/GMC

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Abstract

NASA's Micromechanics Analysis Code with Generalized Method of Cells (MAC/GMC) is used to predict the elastic properties of plain weave polymer matrix composites (PMCs). The traditional one step three-dimensional homogenization procedure that has been used in conjunction with MAC/GMC for modeling woven composites in the past is inaccurate due to the lack of shear coupling inherent to the model. However, by performing a two step homogenization procedure in which the woven composite repeating unit cell is homogenized independently in the through-thickness direction prior to homogenization in the plane of the weave, MAC/GMC can now accurately model woven PMCs. This two step procedure is outlined and implemented, and predictions are compared with results from the traditional one step approach and other models and experiments from the literature. Full coupling of this two step technique with MAC/GMC will result in a widely applicable, efficient, and accurate tool for the design and analysis of woven composite materials and structures.

1. Introduction

Composites with woven reinforcements are attractive due to their ease of manufacture compared to unidirectional composites and laminates. Reinforcement preforms can be woven (or braided) into complex shapes that will remain intact prior to infiltration with the matrix material. This can reduce costs associated with machining as near net-shaped components can be fabricated. Woven reinforcements are particularly effective in polymer matrix composites (PMCs) applications where cost is often a driving design factor.

The beneficial qualities of woven composites come at a cost in terms of analysis; their thermo-mechanical behavior is significantly more difficult to model due to the complex and inherently three-dimensional geometry associated with the woven reinforcement. Typically, woven composites have been modeled either by considering a simplified geometric representation and using homogenization techniques (usually iso-stress and iso-strain assumptions) or via analysis of the actual three-dimensional geometry using finite element analysis (FEA). For recent reviews of such efforts, the reader is referred to Bednarcyk and Pindera (1997) and Bednarcyk and Pindera (2000a). In general, the drawbacks of these approaches involve the accuracy of the predictions, geometric generality, computational efficiency, the ability to admit local (constituent scale) sub-models (i.e., viscoplasticity, damage, micro failure), or suitability to function in the framework of broader component level analysis techniques.

A modeling approach that overcomes many of the aforementioned drawbacks is the method of cells, developed by Aboudi (1991). The generalization of this model, the generalized method of cells (GMC) (Paley and Aboudi, 1992), and the three-dimensional triply periodic version of GMC (Aboudi, 1995) increased the breadth of applicability of the original method of cells considerably. The composite scale accuracy of GMC for modeling the thermo-mechanical behavior of continuous and discontinuous composites is well established. GMC also admits arbitrary doubly and triply periodic geometries, making the method completely general with respect to geometry (provided a geometric repeating unit cell can be identified). In its original form, GMC was quite computationally efficient as compared to FEA, see for instance Wilt (1995); however, the efficiency of the method was significantly increased via a reformulation by Pindera and Bednarcyk (1999) and Bednarcyk and Pindera (2000a). Since GMC provides the local stress and strain fields in simulated composite materials, it is ideal for inclusion of local sub-models, and, as it represents a material rather than a structure (such as a plate) it is well-suited for implementation in higher scale analysis techniques such as FEA.

Due to its useful characteristics summarized above, GMC was selected as the foundation for NASA Glenn Research Center's Micromechanics Analysis Code with Generalized Method of Cells (MAC/GMC) software package (Arnold et al., 1999). This product is available to (and in use by) U.S. industry and universities for composite design and analysis (see http://www.grc.nasa.gov/WWW/LPB/mac/). MAC/GMC takes advantage of GMC's beneficial properties and provides many additional features such as: i) the ability to simulate arbitrary thermo-mechanical loading histories, ii) a library of geometric repeating unit cells, iii) user-definable subroutines, iv) damage and local failure modeling, v) a library of elastic and viscoplastic material constitutive models, and vi) a seamless interface with the ABAQUS FEA package. Thus, MAC/GMC is an ideal candidate for modeling woven composite materials.

Bednarcyk and Pindera (2000a,b) used a stand-alone version of GMC (not MAC/GMC) to model a woven carbon/copper (C/Cu) metal matrix composite (MMC). In these studies, the original method of cells was used to represent the unidirectional infiltrated fiber yarns and embedded within the triply periodic version of GMC, which enabled representation of the composite's three-dimensional repeating unit cell. Local sub-models were incorporated to account for matrix plasticity and fiber-matrix debonding, allowing reasonably good agreement with experimental mechanical test data. However, due to GMC's inherent lack of coupling between the normal and shear stress and strain fields, the method has been unable to accurately model PMCs. In C/Cu, the dominant nature of the effects of matrix plasticity and fiber-matrix debonding muted the inaccuracies associated with GMC's lack of shear coupling, permitting accurate predictions for C/Cu. PMCs, on the other hand, can typically be modeled as elastic, and fiber-matrix debonding is often restricted to the near-failure regime of the PMC's response. Hence, GMC's predictions for the elastic properties of PMCs have been poor. Without the ability to predict accurately the effective properties of PMCs (the most common form of woven composites) the usefulness of GMC in modeling woven composites can be characterized as limited.

A concept that immediately exhibited potential for overcoming GMC's inability to model accurately woven PMCs was recently reported by Tabiei and Jiang (1999). These authors presented an approach to model a plain weave PMC in which, prior to homogenizing in the plane of the woven reinforcement, homogenization (via use of iso-stress and iso-strain assumptions) was performed *through the thickness of the weave*. As will be shown, Tabiei and Jiang's (1999) two step homogenization concept can be used in conjunction with MAC/GMC to enable accurate prediction of woven PMC elastic properties. Further, in the context of a fully embedded approach to modeling general woven and braided composites like that presented by Bednarcyk and Pindera (2000a,b), employing a through thickness homogenization step (before homogenization in the plane of the weave, but after homogenization of the fiber and matrix to obtain the infiltrated yarn behavior) is clearly warranted.

2. Model

The reader is referred to Paley and Aboudi (1992) and Aboudi (1995) for a presentation of doubly and triply periodic versions of GMC, and to Pindera and Bednarcyk (1999) and Bednarcyk and Pindera (2000a) for the corresponding reformulations. In the present study, NASA's MAC/GMC software package was employed. It is a testament to the wide applicability of this software that it could be so readily applied to a problem for which it had not been designed.

To examine the ability of MAC/GMC to predict the elastic properties of a woven PMC, comparison will be made with the results of Naik and Ganesh (1992) for plain weave 42% e-glass/epoxy and plain weave 41% graphite/epoxy, and the results of Dasgupta et al. (1996) for plain weave 35% e-glass/epoxy. To this end, consider the geometry of a plain weave reinforcement shown in Fig. 1 as viewed from above. The warp and fill yarns undulate in and out of the plane to form the pattern depicted. Also shown in Fig. 1 is the repeating unit cell for the weave, which remains the same even when the weave is infiltrated with a matrix material to form a plain weave composite.

Figure 2 shows a MAC/GMC repeating unit cell that represents the geometry of a plain weave composite. Clearly, a more refined geometric representation of the composite is possible, but for the present study, the unit cell shown in Fig. 2 is sufficient. The traditional procedure for modeling the plain weave composite with GMC would be to first determine the effective (homogenized) behavior of the infiltrated fiber yarns that occupy the three-dimensional subcells in Fig. 2, and then to homogenize these three-dimensional subcells in one step via the triply periodic version of GMC. If local effects such as matrix plasticity, damage, or local failure are included, this procedure is not simple because an embedded local model is needed to represent the infiltrated fiber yarns. Bednarcyk and Pindera (2000a) used the method of cells as such a local model so that the stresses and strains in the fiber and matrix phases were known during the simulated thermo-mechanical loading history on the woven MMC. However, in the present case of a woven PMC, a local model is needed only to determine the effective elastic properties of the infiltrated fiber yarns. Arnold et al. (1999) used MAC/GMC to first determine the yarn elastic properties before analyzing a plain weave repeating unit cell (similar to that shown in Fig. 2), also with MAC/GMC. Here, for comparison with the results presented by Naik and Ganesh

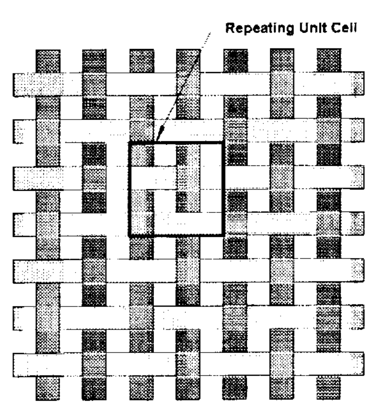

Fig. 1. Top view of the plain weave geometry and repeating unit cell.

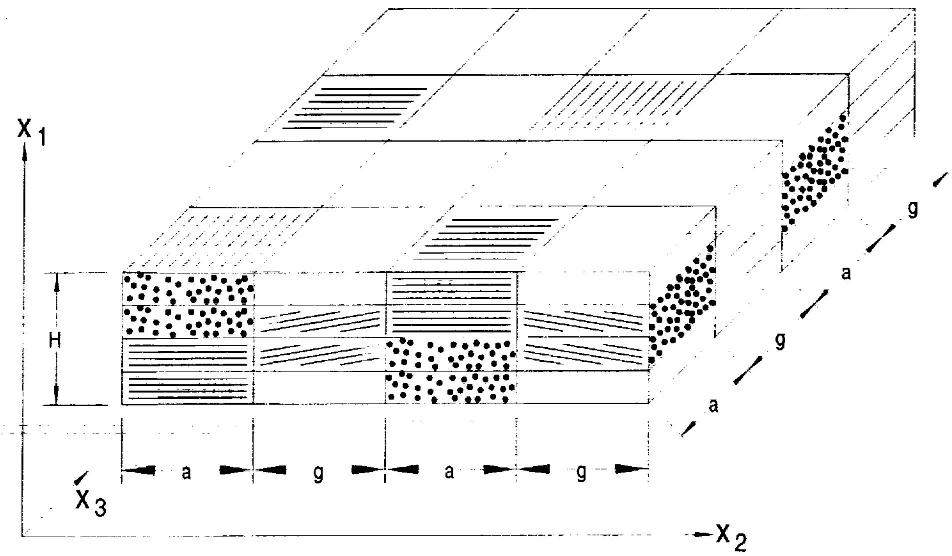

Fig. 2. MAC/GMC repeating unit cell used to represent a plain weave composite.

(1992), use will be made of the effective infiltrated fiber yarn properties given by these authors. These properties, which were determined via use of a composite cylinder assemblage model, are given in Table 1, along with the properties of the pure epoxy matrix material.

Table 1. Elastic properties provided by Naik and Ganesh (1992) for the infiltrated fiber yarns and the epoxy matrix.

Material	V_f	E_A (GPa)	E_T (GPa)	G_A (GPa)	G_T (GPa)	ν_A
epoxy	–	3.5	3.5	1.3	1.3	0.35
e-glass/epoxy	0.70	51.5	17.5	5.80	6.60	0.31
graphite/epoxy	0.80	311.00	6.30	4.40	2.10	0.25

Dasgupta et al. (1996) did not provide the properties of the infiltrated fiber yarns in the 35% plain weave e-glass/epoxy composite that they modeled. These authors employed the Mori-Tanaka method to determine the properties from the fiber and matrix constitutive properties. In order to compare MAC/GMC results with the results of Dasgupta et al. (1996), the fiber and matrix properties employed by these authors were homogenized using MAC/GMC to obtain the effective properties of the e-glass/epoxy infiltrated fiber yarns. A 26×26 MAC/GMC repeating unit cell (IDP 13, see Arnold et al. (1999)) was used for this purpose, and the resulting infiltrated yarn properties, along with the fiber and matrix properties are given in Table 2.

Table 2. Elastic properties provided by Dasgupta et al. (1996) for the e-glass fiber and the epoxy matrix and the properties of the infiltrated e-glass/epoxy fiber yarns determined via MAC/GMC.

Material	V_f	E_A (GPa)	E_T (GPa)	G_A (GPa)	G_T (GPa)	ν_A
epoxy	–	3.45	3.45	1.26	1.26	0.37
e-glass	–	72.4	72.4	29.67	29.67	0.22
e-glass/epoxy	0.65	48.3	14.5	5.06	5.09	0.264

The dimensions of the repeating unit cell (defined as a, g, and H in Fig. 2) were determined by first selecting a and then selecting g in order to yield the correct overall fiber volume fraction of the composite (given the infiltrated fiber yarn fiber volume fraction). Then, for the 42% e-glass/epoxy and the 41% graphite/epoxy, H was selected to yield the same quarter-cell aspect ratio [(a + g)/H] as the geometry employed by Naik and Ganesh (1992). Dasgupta et al. (1996) did not provide the dimensions of their 35% plain weave e-glass/epoxy composite, thus, for comparison with their results, H was selected to yield the same quarter cell aspect ratio as that employed by Naik and Ganesh (1992) for their e-glass/epoxy composite. Table 3 provides the unit cell dimensions; units are arbitrary. Note that the height of each through-thickness layer was taken as ¼ of the overall unit cell height, H (see Fig. 2). Accordingly, the angle of inclination of the fibers was taken as $\arctan(\pm H/2g)$ in the appropriate subcells.

Table 3. Repeating unit cell dimensions.

Material	a	g	H
42% e-glass/epoxy	1.00	0.67	0.50
41% graphite/epoxy	1.00	0.95	0.78
35% e-glass/epoxy	1.00	0.857	0.554

Given the above information, the effective elastic properties of the repeating unit cell shown in Fig. 2 can readily be determined using MAC/GMC's transversely isotropic elastic material constitutive model to represent the subcells. This model admits an arbitrary plane of transverse isotropy, thus enabling appropriate representation of all subcell materials present in Fig. 2. For more details on this procedure, see Example N in Arnold et al. (1999). Effective elastic properties for the plain weave e-glass/epoxy and graphite/epoxy composites predicted via this one step homogenization process are presented and discussed in Section 3.

An alternative two step approach, as mentioned previously, has been suggested by the work of Tabiei and Jiang (1999) and can be easily employed within the context of the MAC/GMC framework. Assuming the effective behavior of the infiltrated fiber yarns is known, a two step homogenization process wherein homogenization is performed through the thickness of the woven reinforcement prior to homogenization in the plane of the weave can be conducted. Examining the exploded view of the plain weave composite repeating unit cell employed previously (Fig. 3), it is clear that six unique types of through-thickness subcell groups exist. These six groups are shown in Fig. 4. Group 1 consists of subcells containing fibers oriented at 0° and 90° to each other in the plane of the weave. Groups 2, 3, 4, and 6 consist of two subcells of inclined fibers sandwiched between two pure matrix subcells. Finally, Group 5 contains only pure matrix subcells.

These six subcell groups are now homogenized independently via MAC/GMC. That is, the effective elastic properties of each group shown in Fig. 4 are determined by analyzing the group as if it were a triply periodic repeating unit cell. Clearly, Group 5 will have effective elastic properties identical to those of the epoxy matrix. The homogenized material represented by Group 1 is orthotropic, while those represented by Groups 2, 3, 4, and 6 are monoclinic. The effective stiffness matrices for Groups 1 – 4 and 6 are given in the Appendix for the two e-glass/epoxy composites and the graphite/epoxy composite. Note that both stacking sequences of the 0° and 90° subcells in Fig. 3 result in identical effective properties.

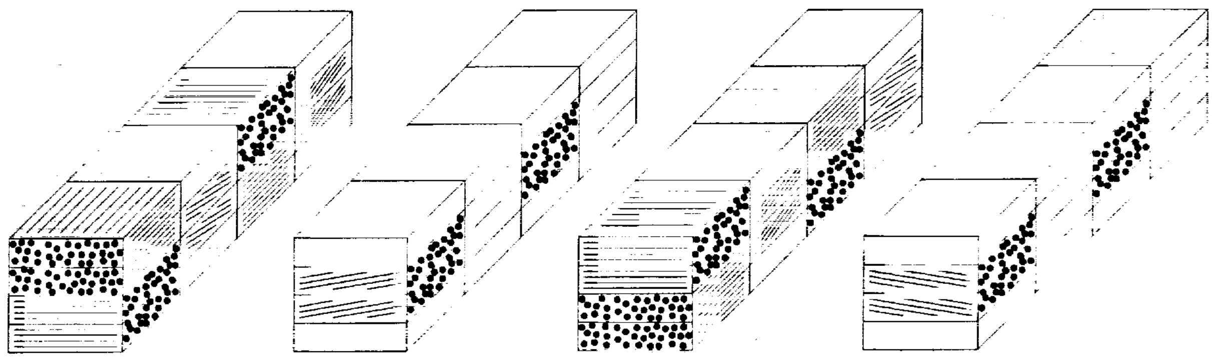

Fig. 3. MAC/GMC repeating unit cell for a plain weave composite – exploded view.

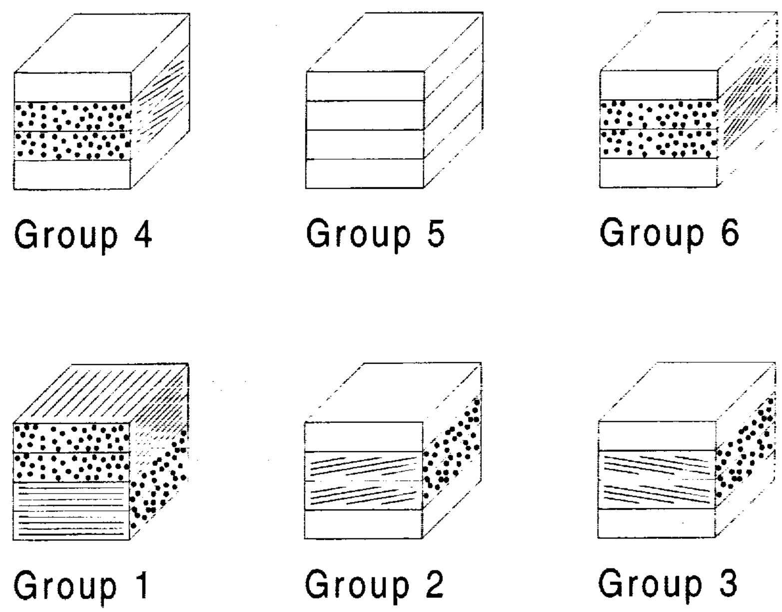

Fig. 4. Unique through-thickness subcell groups in the MAC/GMC repeating unit cell for a plain weave composite.

The second step in determining the effective elastic properties of the plain weave composite involves homogenizing the properties determined for the subcell groups in the plane of the woven reinforcement. This step was also performed using MAC/GMC and the corresponding repeating unit cell is shown in Fig. 5 where the numbers refer to the group numbers identified in Fig. 4. Clearly, by employing the effective material properties determined in step one, as shown in Fig. 5, the unit cell shown in Fig. 2 has been represented in a post through-thickness homogenization condition. It should be noted that MAC/GMC does not contain a monoclinic elastic material constitutive model in its libraries. The availability of user definable subroutines, however, made possible the use of the effective stiffness matrices given in the Appendix as direct input for the subcells in lieu of the typical engineering constants. Results generated for the plain weave e-glass/epoxy and graphite/epoxy composites are presented and discussed in Section 3.

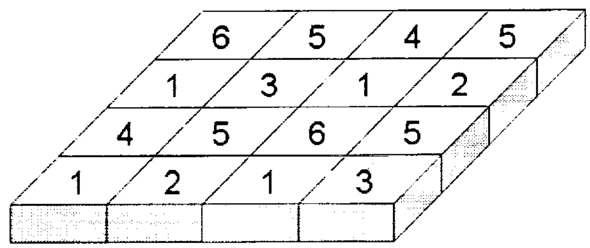

Fig. 5. MAC/GMC repeating unit cell for a plain weave composite after through-thickness homogenization.

3. Results and Discussion

Figures 6 – 11 provide the predicted in-plane elastic properties of the 42% e-glass/epoxy and 41% graphite/epoxy woven composites. The MAC/GMC results are labeled as "1 step" and "2 step" in these figures. "1 step" refers to predictions made via homogenization of the repeating unit cell shown in Fig. 2 without first homogenizing through the weave's thickness. "2 step" refers to utilization of the procedure described in Section 2 whereby homogenization is first performed through the thickness of the weave prior to the in-plane homogenization. All other results presented in Figs. 6 – 11 were taken from Naik and Ganesh (1992). These authors presented the slice array model (SAM) and two versions of the element array model (EAM), one in which the in-plane homogenization occurs first in parallel and then in series (PS) and the other in which this homogenization occurs in the reversed order (SP). The EAM in-plane homogenization is performed via use of iso-stress (series) and iso-strain (parallel) assumptions in the two in-plane coordinate directions. The order in which these directional homogenization schemes are applied gives rise to the two distinct EAM models (PS or SP), which, as indicated in Figs. 6 – 11, yield different predictions. For details on the EAM and SAM models, the reader is referred to Naik and Ganesh (1992).

Naik and Ganesh (1992) also provided additional simple model results to which their more refined EAM and SAM results were compared. These simple models are the modified mosaic parallel model (MMPM), which is an extension of the mosaic model developed by Chou and Ishikawa (1989), the modified Kabelka model (MKM), which is an extension of the model developed by Kabelka (1984), and the original Kabelka (1984) model. In addition, an experimental in-plane elastic modulus was provided by Naik and Ganesh for the e-glass/epoxy composite.

Examining Figs. 6 and 7, it is clear that utilization of the two step homogenization procedure with MAC/GMC rather than the traditional one step procedure significantly affects the in-plane elastic modulus predictions. For the plain weave e-glass/epoxy composite, the predicted modulus has increased from 13.4 GPa to 18.1 GPa, a change of 35%. The increase is even more dramatic for the graphite/epoxy composite, from 8.53 GPa to 17.4 GPa, or 104%. This greater increase is clearly due to the greater degree of transverse isotropy exhibited by the graphite/epoxy yarns compared to the e-glass/epoxy yarns (see Table 1). As mentioned previously, the low predicted in-plane elastic modulus associated with the one step MAC/GMC procedure is due to the lack of coupling between normal and shear stresses and strains in GMC. A manifestation of this lack of shear coupling is that each normal stress component is constant in rows of subcells along the stress component's direction. That is, in Fig. 2, σ_{22} is constant in rows of subcells along the x_2-direction while σ_{33} is constant in rows of subcells along the x_3-direction. Thus, if a single compliant subcell is present in series with many stiff subcells, that compliant

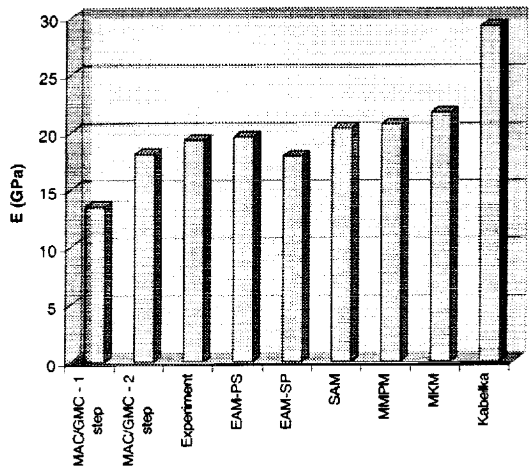

Fig. 6. Predicted/experimental in-plane elastic modulus for plain weave 42% e-glass/epoxy.

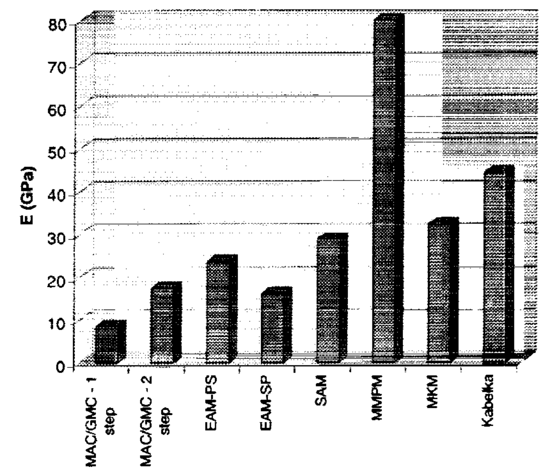

Fig. 7. Predicted in-plane elastic modulus for plain weave 41% graphite/epoxy.

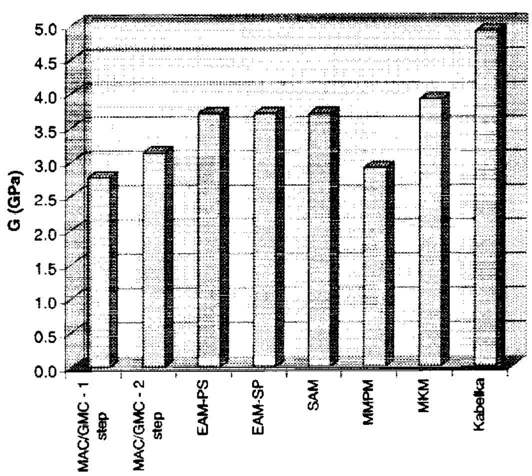

Fig. 8. Predicted in-plane shear modulus for plain weave 42% e-glass/epoxy.

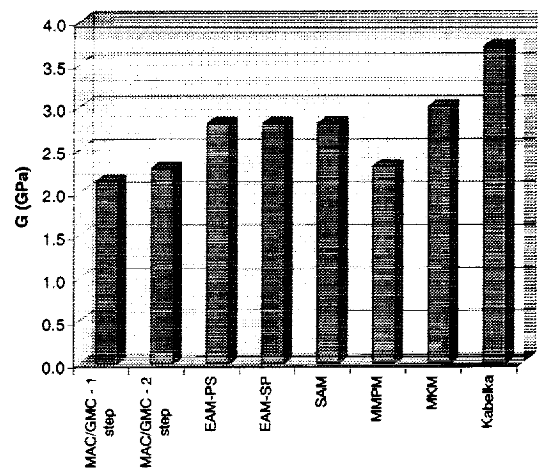

Fig. 9. Predicted in-plane shear modulus for plain weave 41% graphite/epoxy.

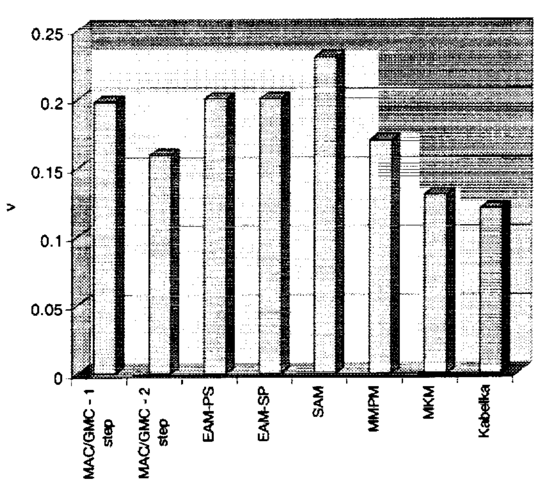

Fig. 10. Predicted in-plane Poisson ratio for plain weave 42% e-glass/epoxy.

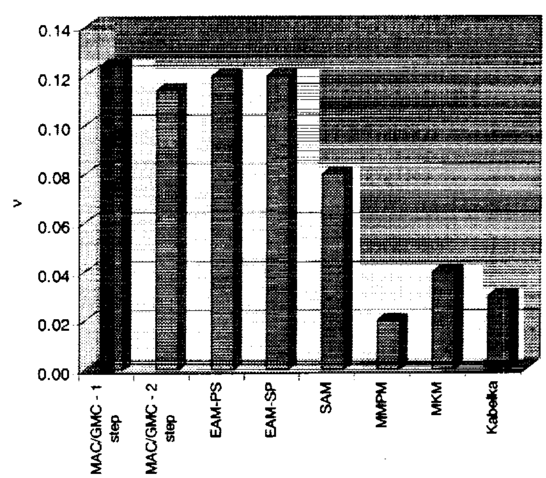

Fig. 11. Predicted in-plane Poisson ratio for plain weave 41% graphite/epoxy.

subcell must carry the same (appropriate component of) stress as the stiffer subcells. This then causes the entire row to have an unrealistically low stiffness, like a chain with a highly compliant link, as no stress can be transferred via shear to adjacent rows of subcells. This lack of shear coupling has a significant impact on the ability of the one step MAC/GMC procedure to predict accurately the in-plane modulus of woven composites as all rows of subcells contain compliant matrix only subcells or transversely-oriented composite subcells (see Fig. 3). Since the repeating unit cell lacks any complete subcell rows with continuous fibers, the one step approach underpredicts the in-plane modulus of the woven composite.

By homogenizing through the weave's thickness, the properties of the subcell groups (Fig. 4) are linked or "smeared" together. Then, in step two (see Fig. 5), two rows of subcells exist in both in-plane directions that do not contain any highly compliant subcells. This allows the two step MAC/GMC procedure to predict significantly more realistic in-plane elastic moduli for woven composites. This is illustrated via comparison with the other results given in Figs. 6 and 7. The two step MAC/GMC prediction for the in-plane elastic modulus compares well with the refined EAM and SAM models for both composites, and compares well with experiment for the plain weave e-glass/epoxy composite. Particularly encouraging is the fact that the two step MAC/GMC elastic modulus prediction falls between the EAM-PS and EAM-SP predictions for both woven composites. It should be noted that the EAM models employed 2500 individual geometric elements while the present MAC/GMC predictions were performed with a total of 64 subcells.

Examining Figs. 8 – 11, it is clear that the two step MAC/GMC homogenization procedure gives rise to higher in-plane shear moduli and lower in-plane Poisson ratios compared to the one step procedure. It appears that the MAC/GMC shear modulus predictions are improved via use of the two step procedure as they are in better agreement with the EAM and SAM model predictions. The Poisson ratio predictions of the one step MAC/GMC procedure are actually in better agreement with the EAM and SAM models than the corresponding two step MAC/GMC predictions.

Table 4 presents a comparison between MAC/GMC and the results of Dasgupta et al. (1996) for the 35% plain weave e-glass/epoxy composite. These authors employed a three-dimensional finite element unit cell model to predict the properties of the woven e-glass/epoxy composite. Dasgupta et al. (1996) also provided the experimental results given in Table 4. Recall that since Dasgupta et al. (1996) did not provide the dimensions of the composite, the geometry of the MAC/GMC repeating unit cell is approximate.

It is clear from Table 4 that the predictions of MAC/GMC have again been significantly improved through the utilization of the two step approach compared to the one step approach. As before, the in-plane modulus rises significantly (by 49%) resulting in much better agreement with experiment. Further, as before, the in-plane Poisson ratio has decreased significantly, but we now see that this decrease provides significantly better agreement with experiment. Thus it

Table 4. Comparison of elastic property predictions and experiment (Dasgupta et al., 1996) for 35% plain weave e-glass/epoxy.

	E (GPa)	ν
Experiment	18.8	0.14
MAC/GMC – 1 step	11.4	0.183
MAC/GMC – 2 step	17.0	0.144
Dasgupta et al. (1996)	19.7	0.14

appears that the EAM models' Poisson ratio predictions (Figs. 10 and 11), which agreed well with the MAC/GMC one step prediction, may not be as accurate as those made using the MAC/GMC two step approach.

In Table 4 it is also clear that the three-dimensional FEA predictions performed by Dasgupta et al. (1996) are in better agreement with experiment than the MAC/GMC two step predictions. This is to be expected as this FEA employed a significantly more accurate geometric representation than that employed in this study (see Fig. 2). Utilization of a more refined unit cell geometry might improve the MAC/GMC predictions further.

4. Summary/Conclusion

A two step homogenization procedure has been outline that enables the accurate prediction of woven PMC elastic properties with MAC/GMC. Previously, woven PMCs could not be accurately modeled using the GMC approach due to the lack of shear coupling inherent to the model. For woven MMCs, this lack of shear coupling was not prohibitive as the effects of matrix inelasticity and fiber-matrix debonding tended to dominate the woven MMCs' response. Via utilization of an independent through-thickness homogenization step, as suggested by Tabiei and Jiang (1999), MAC/GMC can now accurately model the response of the more common woven PMCs.

The results presented herein indicate that the two step MAC/GMC homogenization procedure predictions compare favorably with results from several previous models for woven composites and experiment. Rather than representing a significant achievement in and of themselves, these results serve as a proof of concept for this new MAC/GMC procedure for modeling woven composites. The next step will involve fully coupling this two step procedure with the embedded approach used previously to model woven MMCs (Bednarcyk and Pindera, 2000a,b), and incorporating these capabilities into NASA's MAC/GMC software package. This will, in effect, result in a multi-scale model for arbitrary woven and braided composite materials and structures, owing to MAC/GMC's interface with FEA. This multi-scale approach can be visualized as shown in Fig. 12. Via continuous localization and homogenization, the stress and strain fields in the fiber and matrix constituents can be tracked throughout the woven composite and structure during time dependent thermo-mechanical loading on the global (structure) scale. This will then allow employment of arbitrary visco-elasto-plastic constitutive models, damage models, and local failure criteria on the scale of the individual constituents.

It should be noted that the plain weave composite model developed by Tabiei and Jiang (1999) that introduced the concept of an independent through-thickness homogenization step also was linked with FEA. However, these authors' model localized only to the level of the infiltrated fiber yarns. Thus the constituent level fields were not available and micro scale constitutive, damage, and failure models could not be incorporated. Further, the work of Tabiei and Jiang (1999) considered only one particular woven composite architecture. Since the periodic composite microstructure admitted by MAC/GMC is arbitrary, the procedure outline herein can be employed for any type of woven or braided composite.

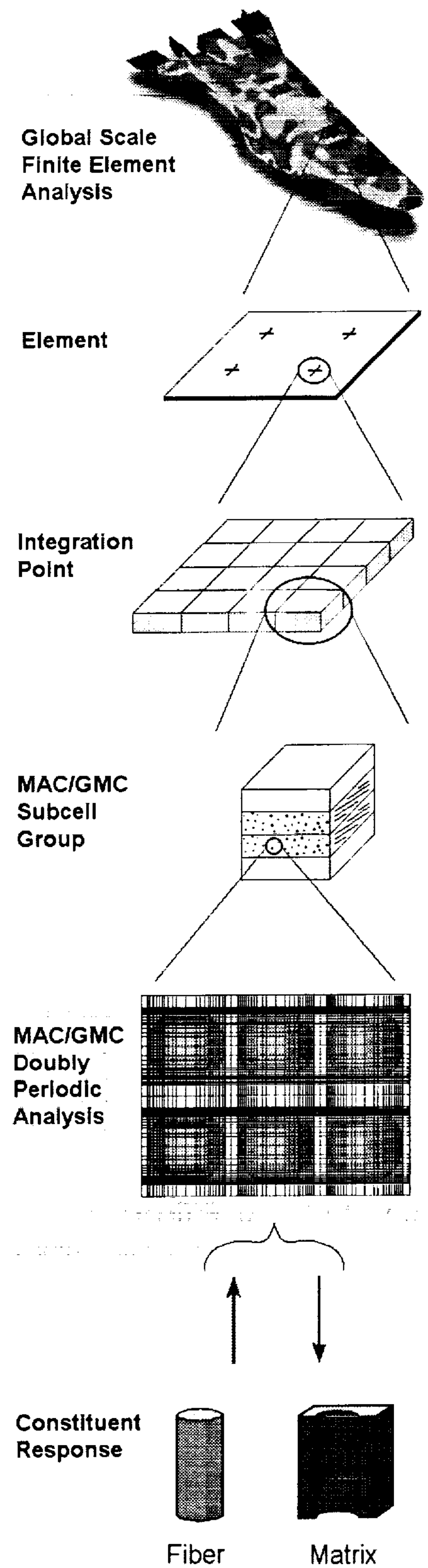

Fig. 12. Illustration of a multi-scale approach to modeling woven composite materials and structures.

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Appendix

Effective stiffness matrices for the subcell groups shown in Fig. 4. Units are GPa.

Group	42% e-glass/epoxy	41% graphite/epoxy
1	$\begin{bmatrix} 21.0 & 8.34 & 8.34 & 0 & 0 & 0 \\ & 39.0 & 8.93 & 0 & 0 & 0 \\ & & 39.0 & 0 & 0 & 0 \\ & & & 5.80 & 0 & 0 \\ & \text{sym.} & & & 6.17 & 0 \\ & & & & & 6.17 \end{bmatrix}$	$\begin{bmatrix} 8.43 & 3.70 & 3.70 & 0 & 0 & 0 \\ & 160. & 3.20 & 0 & 0 & 0 \\ & & 160. & 0 & 0 & 0 \\ & & & 4.40 & 0 & 0 \\ & \text{sym.} & & & 2.84 & 0 \\ & & & & & 2.84 \end{bmatrix}$
2	$\begin{bmatrix} 8.89 & 4.91 & 4.04 & 0 & 0 & 0.0395 \\ & 22.3 & 4.96 & 0 & 0 & 1.77 \\ & & 12.9 & 0 & 0 & 0.0231 \\ & & & 3.59 & -0.0437 & 0 \\ & \text{sym.} & & & 2.16 & 0 \\ & & & & & 2.19 \end{bmatrix}$	$\begin{bmatrix} 7.18 & 4.88 & 3.45 & 0 & 0 & 0.288 \\ & 30.1 & 3.34 & 0 & 0 & 5.22 \\ & & 6.98 & 0 & 0 & -0.0988 \\ & & & 2.60 & 0.281 & 0 \\ & \text{sym.} & & & 1.69 & 0 \\ & & & & & 2.21 \end{bmatrix}$
3	$\begin{bmatrix} 8.89 & 4.91 & 4.04 & 0 & 0 & -0.0395 \\ & 22.3 & 4.96 & 0 & 0 & -1.77 \\ & & 12.9 & 0 & 0 & -0.0231 \\ & & & 3.59 & 0.0437 & 0 \\ & \text{sym.} & & & 2.16 & 0 \\ & & & & & 2.19 \end{bmatrix}$	$\begin{bmatrix} 7.18 & 4.88 & 3.45 & 0 & 0 & -0.288 \\ & 30.1 & 3.34 & 0 & 0 & -5.22 \\ & & 6.98 & 0 & 0 & 0.0988 \\ & & & 2.60 & -0.281 & 0 \\ & \text{sym.} & & & 1.69 & 0 \\ & & & & & 2.21 \end{bmatrix}$
4	$\begin{bmatrix} 8.89 & 4.04 & 4.91 & 0 & -0.0395 & 0 \\ & 12.9 & 4.96 & 0 & -0.0231 & 0 \\ & & 22.3 & 0 & -1.77 & 0 \\ & & & 3.59 & 0 & 0.0437 \\ & \text{sym.} & & & 2.19 & 0 \\ & & & & & 2.16 \end{bmatrix}$	$\begin{bmatrix} 7.18 & 3.45 & 4.88 & 0 & -0.288 & 0 \\ & 6.98 & 3.34 & 0 & 0.0988 & 0 \\ & & 30.1 & 0 & -5.22 & 0 \\ & & & 2.60 & 0 & -0.281 \\ & \text{sym.} & & & 2.21 & 0 \\ & & & & & 1.69 \end{bmatrix}$
6	$\begin{bmatrix} 8.89 & 4.04 & 4.91 & 0 & 0.0395 & 0 \\ & 12.9 & 4.96 & 0 & 0.0231 & 0 \\ & & 22.3 & 0 & 1.77 & 0 \\ & & & 3.59 & 0 & -0.0437 \\ & \text{sym.} & & & 2.19 & 0 \\ & & & & & 2.16 \end{bmatrix}$	$\begin{bmatrix} 7.18 & 3.45 & 4.88 & 0 & 0.288 & 0 \\ & 6.98 & 3.34 & 0 & -0.0988 & 0 \\ & & 30.1 & 0 & 5.22 & 0 \\ & & & 2.60 & 0 & 0.281 \\ & \text{sym.} & & & 2.21 & 0 \\ & & & & & 1.69 \end{bmatrix}$

Group	35% e-glass/epoxy
1	$\begin{bmatrix} 18.7 & 7.82 & 7.82 & 0 & 0 & 0 \\ & 35.4 & 7.19 & 0 & 0 & 0 \\ & & 35.4 & 0 & 0 & 0 \\ & & & 5.06 & 0 & 0 \\ & \text{sym.} & & & 5.08 & 0 \\ & & & & & 5.08 \end{bmatrix}$
2	$\begin{bmatrix} 8.64 & 4.61 & 4.26 & 0 & 0 & 0.0223 \\ & 21.8 & 4.53 & 0 & 0 & 1.82 \\ & & 11.5 & 0 & 0 & -0.104 \\ & & & 3.18 & -0.00186 & 0 \\ & \text{sym.} & & & 2.07 & 0 \\ & & & & & 2.13 \end{bmatrix}$
3	$\begin{bmatrix} 8.64 & 4.61 & 4.26 & 0 & 0 & -0.0223 \\ & 21.8 & 4.53 & 0 & 0 & -1.82 \\ & & 11.5 & 0 & 0 & 0.104 \\ & & & 3.18 & 0.00186 & 0 \\ & \text{sym.} & & & 2.07 & 0 \\ & & & & & 2.13 \end{bmatrix}$
4	$\begin{bmatrix} 8.64 & 4.26 & 4.61 & 0 & -0.0223 & 0 \\ & 11.5 & 4.53 & 0 & 0.104 & 0 \\ & & 21.8 & 0 & -1.82 & 0 \\ & & & 3.18 & 0 & 0.00186 \\ & \text{sym.} & & & 2.13 & 0 \\ & & & & & 2.07 \end{bmatrix}$
6	$\begin{bmatrix} 8.64 & 4.26 & 4.61 & 0 & 0.0223 & 0 \\ & 11.5 & 4.53 & 0 & -0.104 & 0 \\ & & 21.8 & 0 & 1.82 & 0 \\ & & & 3.18 & 0 & -0.00186 \\ & \text{sym.} & & & 2.13 & 0 \\ & & & & & 2.07 \end{bmatrix}$

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13. ABSTRACT ***(Maximum 200 words)***

NASA's Micromechanics Analysis Code with Generalized Method of Cells (MAC/GMC) is used to predict the elastic properties of plain weave polymer matrix composites (PMCs). The traditional one step three-dimensional homogenization procedure that has been used in conjunction with MAC/GMC for modeling woven composites in the past is inaccurate due to the lack of shear coupling inherent to the model. However, by performing a two step homogenization procedure in which the woven composite repeating unit cell is homogenized independently in the through-thickness direction prior to homogenization in the plane of the weave, MAC/GMC can now accurately model woven PMCs. This two step procedure is outlined and implemented, and predictions are compared with results from the traditional one step approach and other models and experiments from the literature. Full coupling of this two step technique with MAC/GMC will result in a widely applicable, efficient, and accurate tool for the design and analysis of woven composite materials and structures.

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