ROUTINE THREE -DIMENSIONAL ANALYSIS OF WOVEN COMPOSITES

John D. Whitcomb and Xiaodong Tang

Department of Aerospace Engineering, Texas A&M University
College Station, TX, 77843-3141, U.S.A.

SUMMARY: It is now possible to perform 3D finite element stress analysis of woven composites on desktop computers. However, to avoid drowning in the various complexities involved in assembling models requires specialized tools and techniques. This paper discusses tools and techniques used by the authors to expedite the analysis of a variety of weaves. The discussion will focus on mesh generation, periodic analysis, and data management and interpretation.

KEYWORDS: woven composites, stress analysis, mesh generation, visualization.

INTRODUCTION

Unlike typical tape laminates, woven composites consist of interlaced fiber bundles that are subsequently impregnated with resin. Some of the possible interlace patterns for two-dimensional weaves are shown in Fig. 1. Although these weaves are referred to as two dimensional, the microstructure is obviously three-dimensional. Analysis of woven composite structures requires a global/local strategy [1]**.** A typical finite element based strategy is shown schematically in Fig. 2. Suppose one wishes to analyze an integrally woven stringer-stiffened panel. There are too many microstructural details to model each one discretely. Instead, micromechanics is used to determine effective engineering properties. Fiber/matrix unit cell models can be used to calculate effective properties of the impregnated fiber tows. Models of representative regions of a weave can be used to determine effective layer properties. These properties are used in a structural analysis. Results such as strains, stresses, and nodal forces, from the global analysis can be used to perform a local failure analysis. If excessive local failure is predicted, either the structure or the material would be redesigned and the process repeated. The challenges presented in Fig. 2 are not unique to woven composites, but some aspects are considerably more challenging than for conventional tape laminates because of the complex microstructure. This paper focuses on the challenges related to performing the micromechanics analyses required to obtain effective engineering properties and detailed local stress distributions for a woven composite. The plain weave has been studied extensively using analyses ranging from modified laminated plate theory [2, 3] to detailed three-dimensional analysis [4 - 7]. Most of the literature on the more complex weaves is limited to the simpler analyses, like modified laminated plate theory. While the simpler analyses tend to predict some of the properties fairly well, full 3D finite element analyses give much more insight into load transfer inside the weave and the failure mechanisms. There are several obstacles to 3D analysis.

Perhaps the biggest ones are mesh generation, identification of the smallest possible analysis region, derivation of appropriate boundary conditions and data management and interpretation. The objective of this paper is to discuss strategies for addressing these obstacles. Because of limited space, details cannot be given. Accordingly, the goal is to sensitize the reader to the need for specific types of tools if analysis of woven composites is to be routine.

The following will begin with a discussion of finite element mesh generation. Then identification of the basic building block (unit cell) and derivation of appropriate boundary conditions will be discussed. Finally, data management and interpretation will be discussed.

FINITE ELEMENT MESH GENERATION

Recent years have brought considerable progress in automated mesh generation for arbitrary geometries. However, the meshes tend to be quite large. An alternative is to develop special purpose mesh generators for woven composites. Rather than jumping immediately to the task of mesh generation, it is helpful to first generate solid models of just the tow architecture (like that shown in Fig. 1). These models are quite simple to generate by extruding a specified cross-section along a piecewise-defined path. Figure 3 shows the parameters that describe the towpath. The path is a combination of straight and sinusoidal sections. It also shows that the extruded tow is described using ordinary 20-node hexahedral elements. This was done so that the resulting model could be visualized using a plotter designed for ordinary finite element meshes. By translating, adjusting the phase, and rotating, it is possible to generate the models shown in Fig. 3 with a very simple code.

The solid model is useful for identifying the minimum region that must be analyzed. These models are also useful for identifying the bounding surfaces that will be used to define the elements in the “real” model (i.e. a complete analysis model containing warp tows, fill tows, and matrix pockets). After viewing a few of these solid models of the tow architecture, it becomes apparent certain regions are identical in different weaves. Figure 4 shows finite element models for three weaves. Some of the identical "building blocks" in the different weaves are marked. Although one has to invest some time in developing meshes for these blocks, many of them are useful for more than just one weave.

Assembling building blocks together to create a model for a specific weave can be a little treacherous without the right tools. The main problem is assuring that the nodes match up on adjacent blocks. For example, the 4-harness mesh in Fig. 5a was pieced together using building blocks. It contains compatibility errors that are not apparent using conventional rendering. The errors are not apparent until an unconventional rendering technique was used. The errors show up because the hidden line removal technique used in Fig. 5c was based in part on hiding element faces that match up perfectly with other faces. Incompatible faces do not match, so they are visible.

PERIODIC ANALYSIS

The finite element model requires boundary conditions that make it behave as though it was buried inside an infinite periodic array of unit cells. If one is willing to analyze the entire unit cell, the boundary conditions for the analysis model are given by

$$u_i\,(x_\alpha + d_\alpha) = u_i\,(x_\alpha) + (\partial u_i / \partial x_\beta\,)\,d_\beta$$

where d_β is a vector of periodicity. This vector is a vector from a point in one unit cell to an equivalent point in another unit cell. Figure 6 shows unit cells for different weaves. It should be mentioned that there is more than one choice for the unit cell, as can be seen in Fig. 7 for 8-harness satin weaves. Regardless of the unit cell chosen, if the correct boundary conditions are imposed, the results are the same (Fig. 7). Typically, there are symmetries that can be exploited, which results in a much reduced computational workload. The boundary conditions generally consist of multi-point constraints between points on a single plane or two different planes. These can be fairly complex and non-intuitive, as shown in Fig. 8 for an 8-harness satin weave model. Reference [8] describes a systematic approach for deriving the boundary conditions based on equivalence of coordinate systems. By identifying strategic coordinate transformations, such as mirroring about planes or rotations about lines, one can obtain constraint conditions on planes. Using the procedure in reference [8] automatically identifies constraints on constitutive relations (that permit or prohibit the proposed equivalence transformation) that are not so obvious when using adjectives like "symmetric" or "anti-symmetric" to describe the configuration. In earlier work by the first author, the derivation of boundary conditions was somewhat ad hoc and consequently time consuming and sometimes hard to justify. The technique described in reference [8] eliminates much of the difficulty. It should be mentioned that imposing multipoint constraints can increase the bandwidth of the equation tremendously. Consequently, iterative solvers using sparse storage are often needed for large models.

DATA MANAGEMENT AND INTERPRETATION

Finite element analysis generally involves very large data sets for both problem specification and the results. Two of the areas that have been simplified in our work are mesh generation and specification of boundary conditions. Mesh generation has been simplified by specifying the mesh parametrically in terms of very limited data, such as the undulation wavelength, cross-section shape, and tow volume fraction. Hence, meshes for parametric studies can be generated in a few minutes. Of course, for a new type of weave, the basic building blocks must be identified and the process will take longer. Aside from the mesh itself, the next most complex data is the collection of multi-point constraints. For large models, this can involve thousands of constraints. Since the constraints involve points in two regions in a single plane or two planes, a utility was written that expresses the constraints in terms of planes rather than individual nodes on the planes. This simple utility transforms the constraints from a huge, unreadable (and unwieldy) collection to a concise statement that is very readable.

Interpretation of the results from finite element analysis (or any three-dimensional analysis) is challenging. However, there are some characteristics of the analysis of weaves that are worthwhile mentioning here. First, a three-dimensional analysis was assembled to determine the detailed stress distributions. Figure 9 shows typical stress contours for an 8-harness satin weave. The stresses are those in the material coordinate system, so σ_{22} for the fill tow is roughly the same stress component as σ_{11} for the warp tow. The stress distribution is obviously very complex. There are plenty of details! Even with graphical postprocessing there is the potential for information overload.

Very high stresses in tiny regions might not be of much physical significance or at least not trustworthy if the gradients are significant compared to the fiber diameter (not tow size). Also, if the high stresses are due to ostensibly innocent characteristics of the assumed tow architecture, one must investigate whether the predictions are real or artifacts of the modeling. Although it is now possible to quickly produce predictions like those in Fig. 9, more work (experimental and analytical) is needed to properly interpret the results. One technique that has been considered for improving understanding of the stress distributions is to examine the volume distribution of the stresses. Figure 10 shows the volume distribution of the six stress components for 4- and 8-harness satin weaves for a subdomain that is very similar geometrically in the two weaves. Such results help identify similarities between weaves and quantify how large of a volume is highly stressed.

CONCLUSIONS

Although 3D micromechanics analysis presents many challenges, much of the difficulty in the past has been a lack of robust strategies. It has been about a decade since the first author struggled to perform 3D analysis of a plain weave. Today, 3D analysis of a wide variety of weaves can be routine. However, one of the most important lingering questions is how to properly interpret the massive amount of information that is obtained. More experimental and analytical work is needed to answer this question.

ACKNOWLEDGEMENTS

The material is based upon work supported by the AFOSR under Grant No F49620-98-1-0149. Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of the AFOSR.

REFERENCES

1. Srirengan, K., Whitcomb, J.D., Chapman, C., 1997, “Modal Technique for Three-Dimensional Stress Analysis of Plain Weave Composites,” *Composite Structures.* Vol. 39, N0. 1-2, pp. 145-156.
2. Ishikawa, T. and Chou, T.-W., 1982, “Elastic behavior of woven hybrid composites,” Journal of Composite Materials 16, 2-19.
3. Naik, N. K., 1994, “Woven Fabric Composites,” Technomic Publishing Co.
4. Whitcomb, J.D., 1991, “ Three Dimensional Stress Analysis of Plain Weave Composites,” ASTM STP 1110.
5. Paumelle, P., Hassim, A. and Léné, F., 1991, “Microstress analysis in woven composite structures,” La Recherche Aérospatiale 6, 47-62.
6. Dasgupta, A., Agarwal, R.K., 1992, “Orthotropic thermal conductivity of plain-weave fabric composites using homogenization technique,” Journal of Composite Materials 26, 2736-2758.

7. Chapman, C.D., Whitcomb, J.D., 1995, “Effects of Assumed Tow Architecture on the Predicted Moduli and Stresses in Woven Composites,” Journal of Composite Materials 29, 2134-2159.

8. Whitcomb, J.D., Chapman, C.D., Tang, X., “Derivation of Boundary Conditions for Micromechanics Analyses of Plain and Satin Weave Composites,” Submitted 8/98 to *Journal of Composite Materials*.

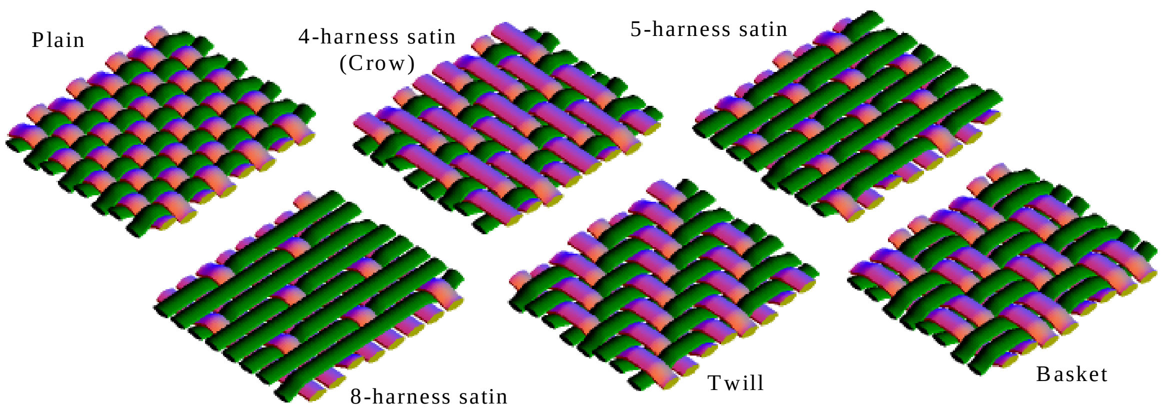

Fig. 1: Schematics of woven composites (without matrix pockets).

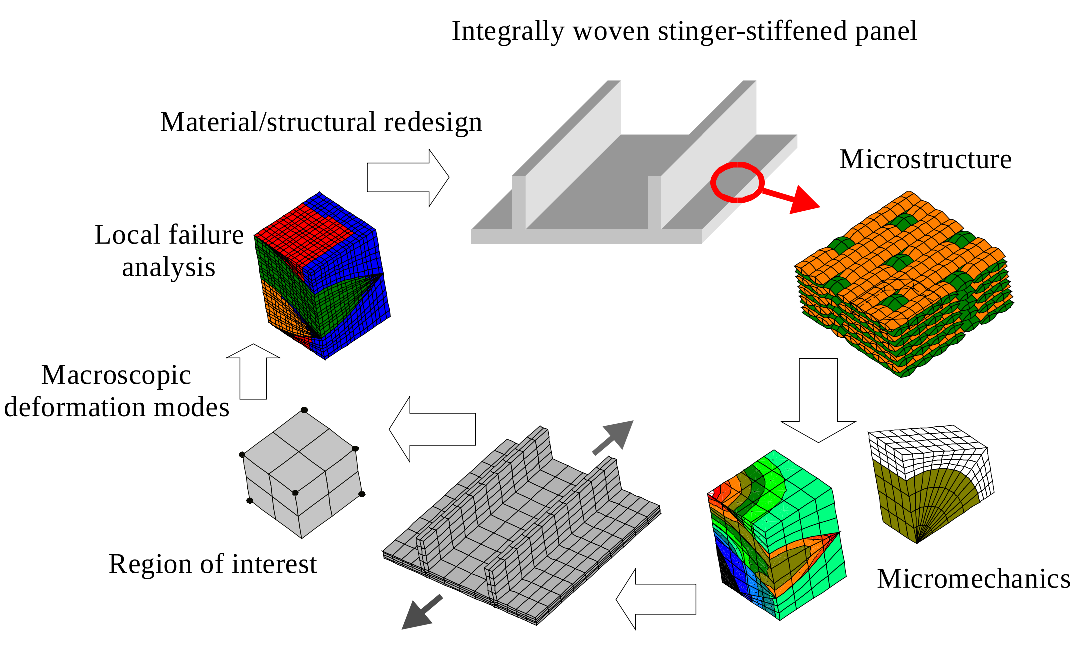

Fig. 2: Finite element based global/local strategy for woven composite structures.

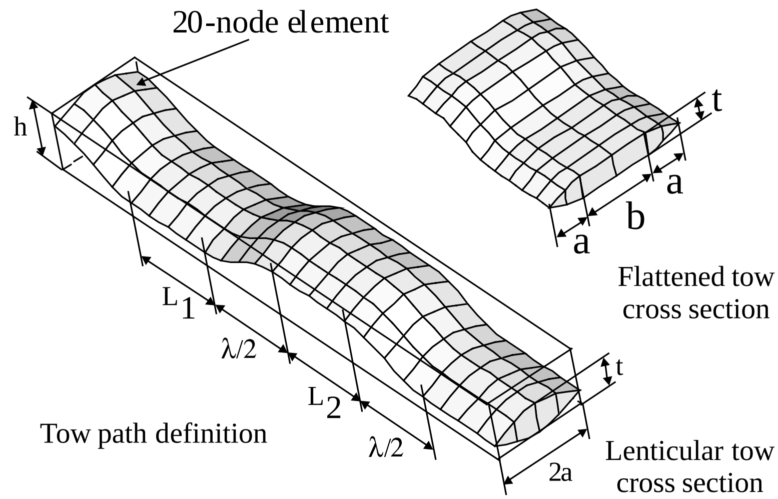

Fig. 3: Description of tow geometry.

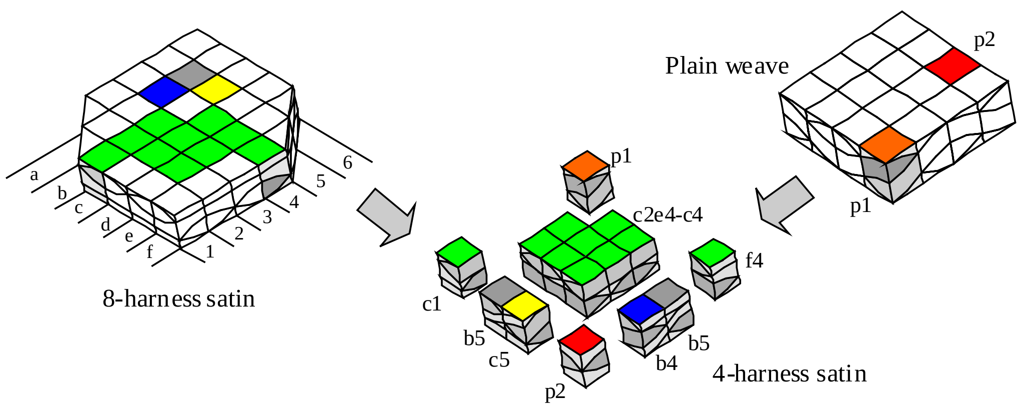

Fig. 4: Building block strategy for woven composites.

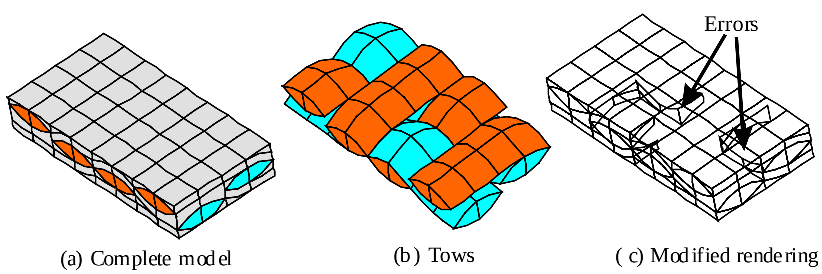

Fig. 5: Visualization of mesh errors.

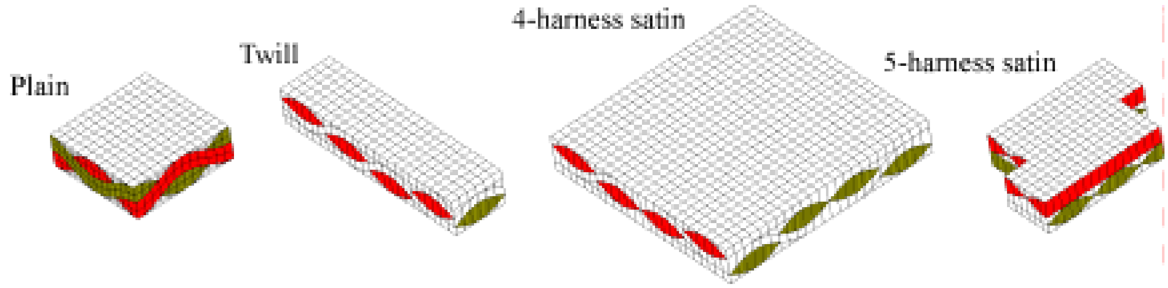

Fig. 6: Unit cells for different weaves.

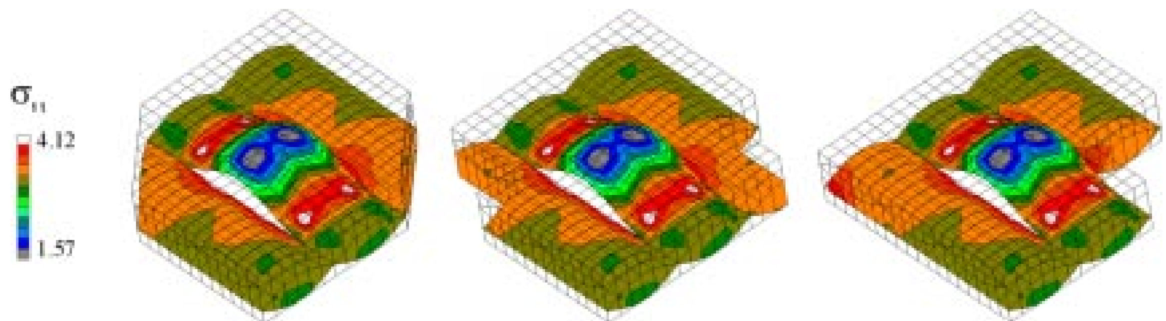

Fig. 7: Stress contours for analyses using three different definitions of the unit cell.

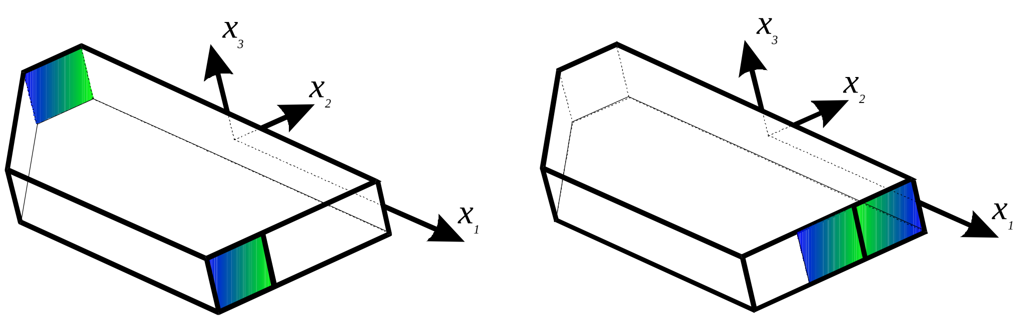

Fig. 8: Paired regions for multipoint constraints for 8-harness satin weave.

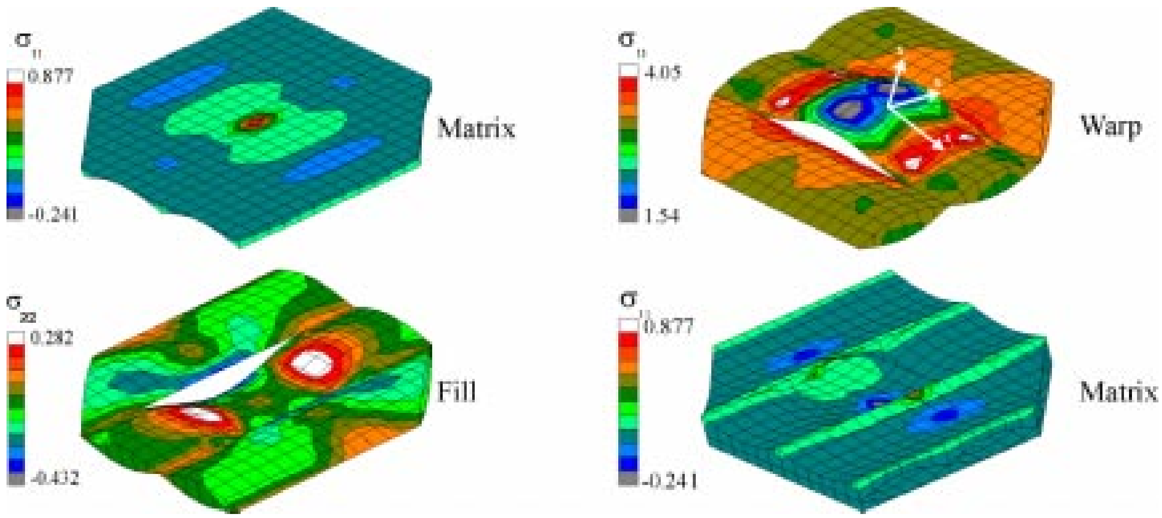

Fig. 9: Stress contours for eight harness satin weave (WR=1/3).

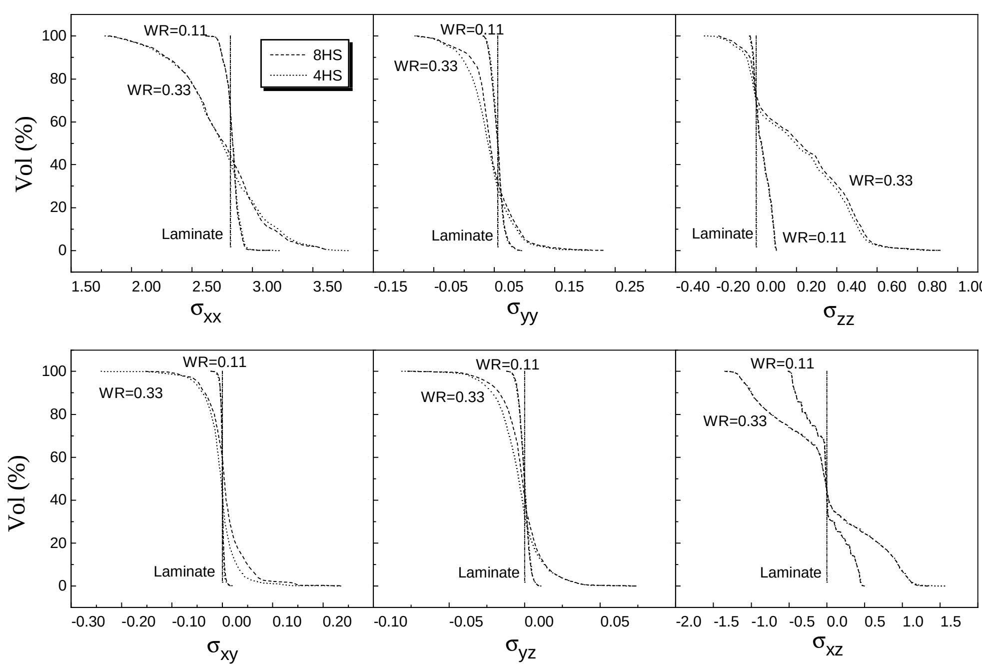

Fig. 10: Volume distribution of stresses for weaves.