



# Failure Analysis of Fiber Reinforced Injection Moldings Using a Composite Lamina Failure Approach

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**MA5600-P** - This class will demonstrate how the use of experimental test data of several tensile specimens of varying fiber orientation can help determine an adequate failure criterion for a given reinforced thermoplastic. This criterion can then be utilized to better predict failure of complex part designs with widely varying fiber orientations. Data for a 30% glass-reinforced PEEK material will be shown as an example of this approach to orthotropic failure analysis.

## Learning Objectives

At the end of this class, you will be able to:

- Demonstrate the importance of orthotropic structural analysis for good design
- Show the need for further structural research of fiber reinforced materials
- Demonstrate how the lamina failure approach plays a key role in predicting injection molded strength
- Better predict the strength of any fiber reinforced injection molded part design

## About the Speaker

*Robert (Bob) Sherman is the senior computer-aided engineering (CAE) analyst for RTP Company at their headquarters in Winona, Minnesota. In 1999, Bob started the CAE group, which is utilized as a support service for RTP company customers. Bob has a BS in engineering from Purdue University, and a solid background in both structural and injection molding analysis. His industry experience includes six years with Bell Helicopter Textron (Ft. Worth, Texas), followed by nine years with McDonnell Douglas Astronautics Company (St. Louis, Missouri). From there, Bob took a job with Moldflow Corporation (Kalamazoo, Michigan) as a customer support engineer, and quickly became the North American support manager. Bob also worked five years for Bluegrass Plastics Engineering, a molding analysis consulting firm. In addition to publishing several papers and presenting at several Moldflow® User Group meetings, Bob is one of the co-authors of **Successful Injection Molding**.*

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## Introduction

Injection molded structural components are a critical point in their evolution where good predictability of their properties of paramount importance. Of course a components property prediction is directly dependent upon the complex fiber orientation created during the injection molding process. Not only is it important to get the orientation behavior correct as it varies across a complex geometry part, it is also important to have the correct distribution of orientation through the part thickness. Good prediction of bending strengths requires the correct distribution through the thickness where simple tension and compression loads only require good average orientation predictions.

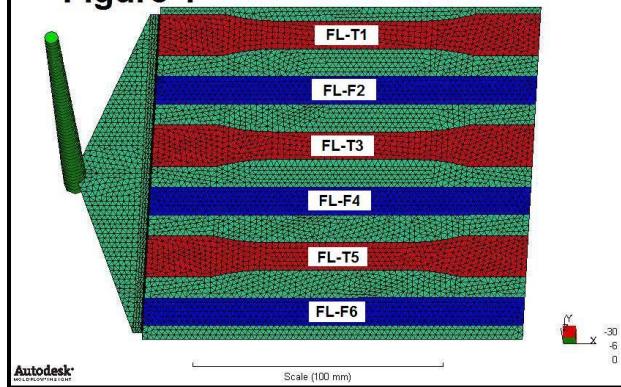
The introduction of the RSC (Reduced Strain Closure) factor in the latest release of Autodesk Moldflow® Insight should provide a means to obtain better correlation of the fiber orientation with actual molding behavior because it introduces an attempt to better predict the slower development of the steady state orientation that was predicted before this release. It is expected however that the recommended default value when utilized (0.05) may not be suitable for all materials, which presents a problem for the user. Some work was done earlier in the year with a 30% GF reinforced nylon 66 and what was learned there was utilized in directing this investigation into a 30% GF reinforced PEEK compound.

## An Approach to Validation of Orientation

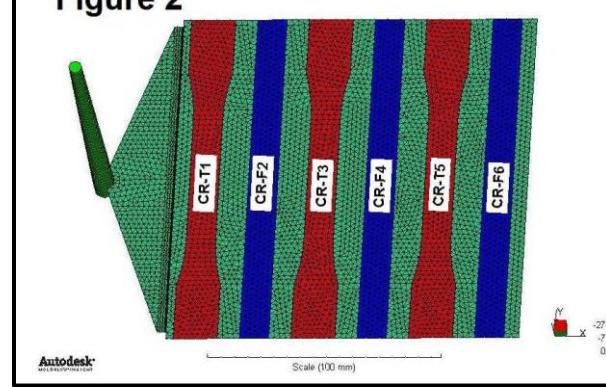
Most organizations utilizing CAE software do not have the necessary sophisticated equipment available or the time to validate fiber orientation numerically through microscopy and/or other means more exact means. So in order to gain confidence in the orientation predictions, other less direct and more expedient approaches must be considered. What we have initially investigated @ RTP Company, is utilizing the micro-mechanical predictions of modulus of the material molded in different thickness test panels in different directions to compare with the experimental values gathered in testing of those same specimens. It is expected that this will allow a better determination of what RSC factor to utilize with a given material since the RSC factor is expected to vary by material and type and level of fibrous reinforcement.

With the intention of eventually validating bending behavior in addition to tensile behavior, the test panels were cut into both flow and cross-flow tensile and flexural specimens in two different thickness test panels. Since the test panel has centerline symmetry the tensile and flexural specimens were alternated as shown in *Figures 1 & 2*.

**Figure 1**



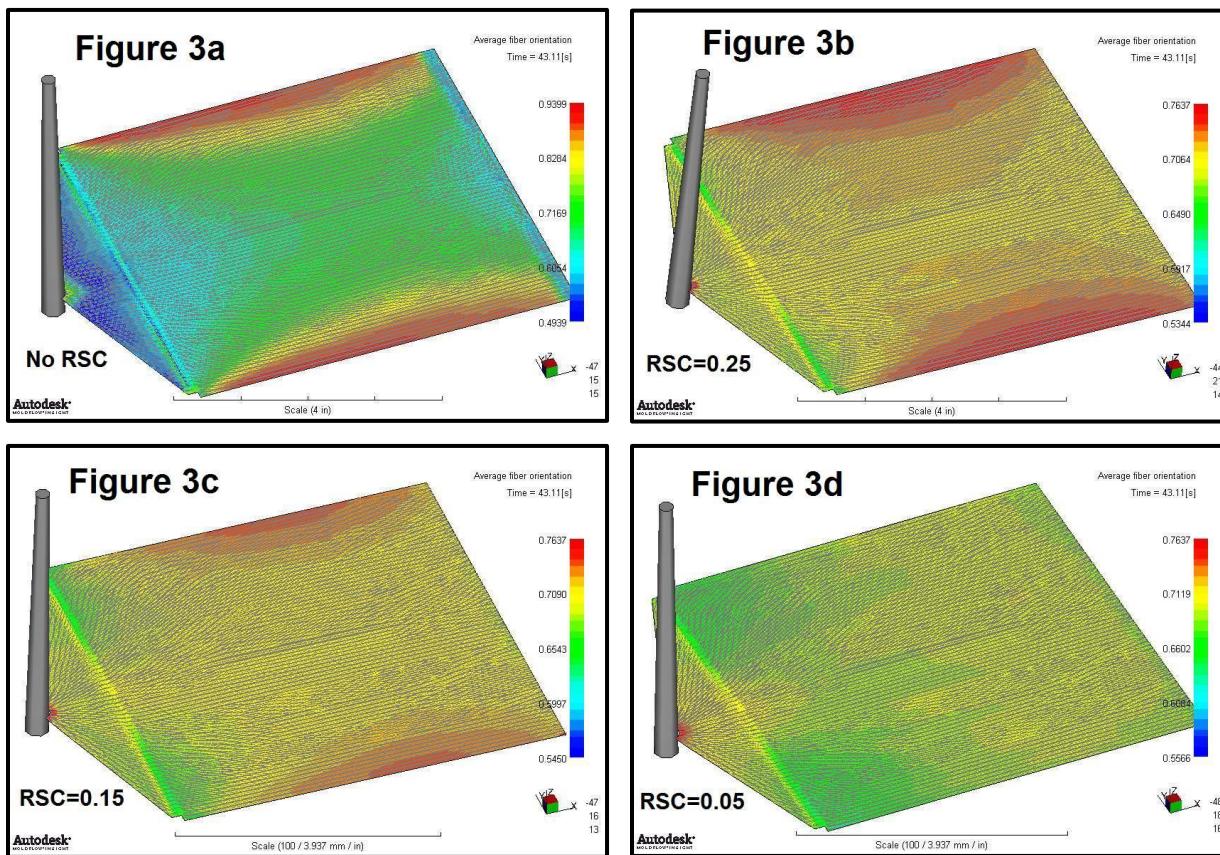
**Figure 2**



In addition to the experimental data collected from the flow and cross-flow specimens from the molded test panels, data from molded tensile bars was utilized as an initial “screening” of the RSC factors effects upon tensile modulus predictions. In addition to the RSC factor, fiber aspect ratio was also investigated for improved correlation of the modulus predictions. In both the panel specimens as well as molded tensile bars, 5 replicates were tested of each unique geometry and/or orientation.

## The Influence of the RSC Factor

For all the years of the development and improvements in the fiber orientation technology, the values predicted have been for “steady state” flow and have been predicted as though they instantaneously reach that state throughout the part. But in fact it has been known that the steady state behavior does take time to develop. The RSC factor attempts to introduce the corrections for that phenomenon. When I first began working with utilizing the RSC factor (off by default), I was surprised at the significance of its effect. **Figures 3a through 3d** show the average orientation results for a 6 inch X 6 inch (152.4 mm X 152.4 mm) test panel mold without the RSC factor, then with an RSC equal to 0.25, 0.15, and 0.05 respectively. The difference in orientation predictions between no RSC factor and the “suggested” value is rather dramatic. The relatively strong variation in orientation behavior across the panel width is reduced significantly by the introduction of the RSC factor, especially at the “suggested” setting of 0.05.

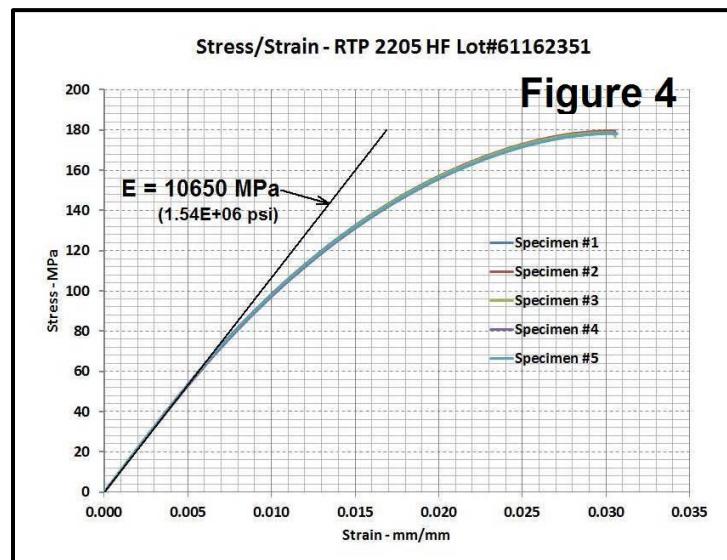


Previous work had been done with predictions of a 30% glass reinforced nylon material that showed similar effects upon the orientation with the implementation of the RSC factor. Predictions of modulus for that material indicated that the orientation variations across the width of the test panel were too strong without the RSC factor, but not strong enough with the RSC factor implemented when compared to experimental measurements. Initial indications from the PEEK material would seem to show the same trends.

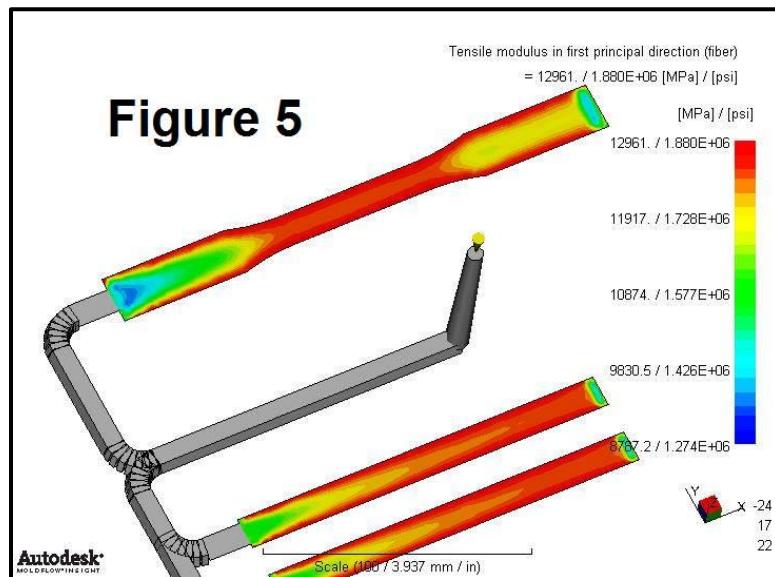
## Molded Tensile Specimen Data

**Figure 4** shows the stress/strain data of the molded tensile bars tested for the RTP 2205 HF material. For all of the testing as well as software predictions, the modulus is evaluated based on a 0.5% secant value. Tangent moduli are very sensitive to measurement errors and instrumentation problems in addition to being impractical for computational use. Low level secant moduli are a more realistic representation of engineering materials.

The quality assurance test mold was utilized to predict the properties of RTP 2205 HF utilizing the standard processing conditions for this material. All



predictions from the software utilized a secant modulus for the base high flow resin that this material is compounded from. This information was obtained directly from the material supplier and input into the analysis in the mechanical properties section of the data. A sample result is illustrated in **Figure 5**.



## Molded Tensile Specimen Results

Simulation with the model shown in **Figure 5** was performed utilizing the previously mentioned secant modulus data for the PEEK resin used in this material. The initial variations of RSC were limited to the low range based primarily on the experience gained from working with the RTP 205 data. There also is another factor that influences the orientation significantly that until now hadn't been considered as a variable because the orientation in general was already "over-predicted." That factor is the reinforcement aspect ratio (AR) which for almost all short fiber reinforced materials has been set at a default value of 25.

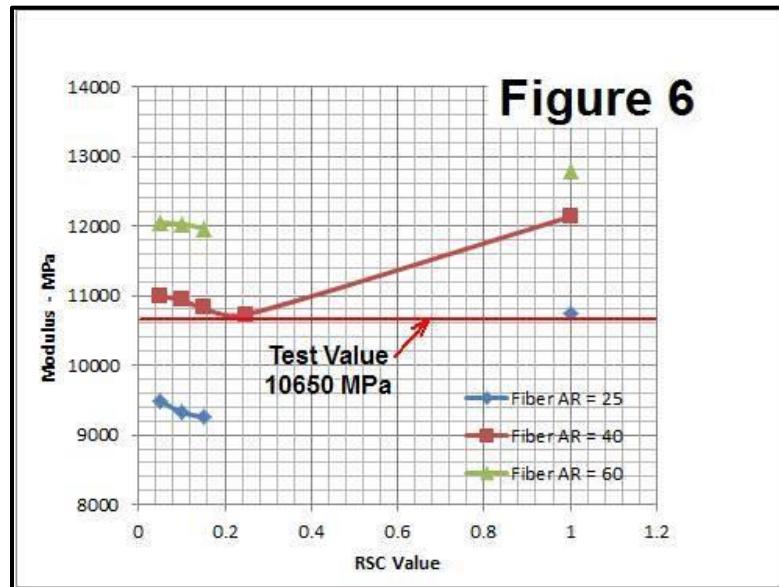
Unfortunately fiber AR can be quite variable due to molding conditions, gate size, etc. However it is felt that when molded well, an aspect ratio of 25 should be about a minimum value, so it was added as a variable in this study also. **Figure 6** shows a plot of the results of the predicted modulus value averaged over the extensometer gage region for the molded tensile specimens with different RSC factors and AR values. For the molded tensile specimen, the fiber AR of 25 without the RSC factor implemented provides a very good prediction of the modulus, but with the RSC implemented the fiber AR of 40 seems to provide better predictions of the modulus. The fiber AR of 60 over-predicts the modulus regardless of the RSC value implemented.

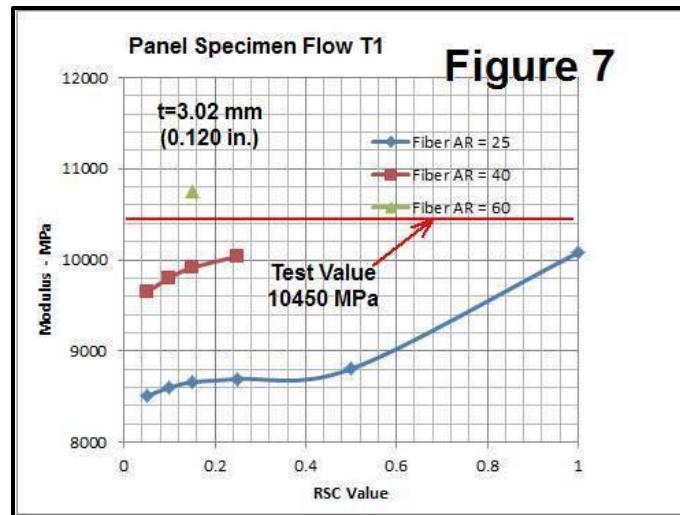
prediction of the modulus, but with the RSC implemented the fiber AR of 40 seems to provide better predictions of the modulus. The fiber AR of 60 over-predicts the modulus regardless of the RSC value implemented.

## Flow Direction Panel Tensile Specimen Results

In conjunction with the predictive analysis of the molded tensile bars, extensive variations of parameters were also studied for the panel moldings at the 3.05 mm thickness. The testing of the cut specimens from these panels produced consistent stress/strain behavior for each of the panel locations, with the exception of the T1 (also T6 by symmetry) position. Problems with the extensometer settings for those 5 specimens were experienced and not noticed until all five specimens were tested. That data point seems to be the only one in question, the other data showed to be very consistent.

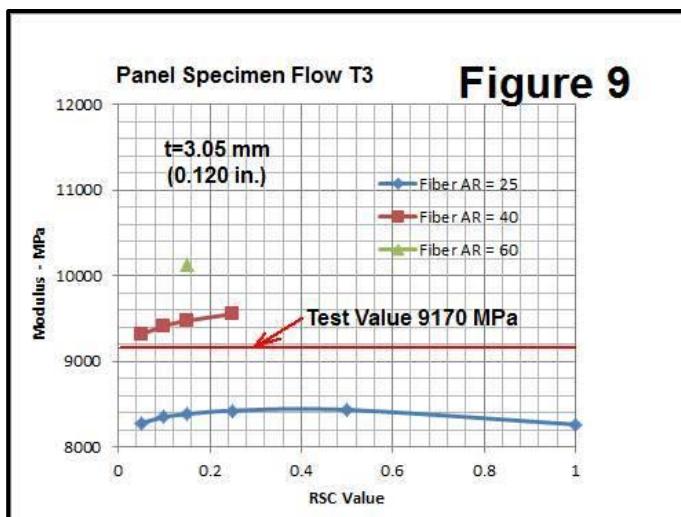
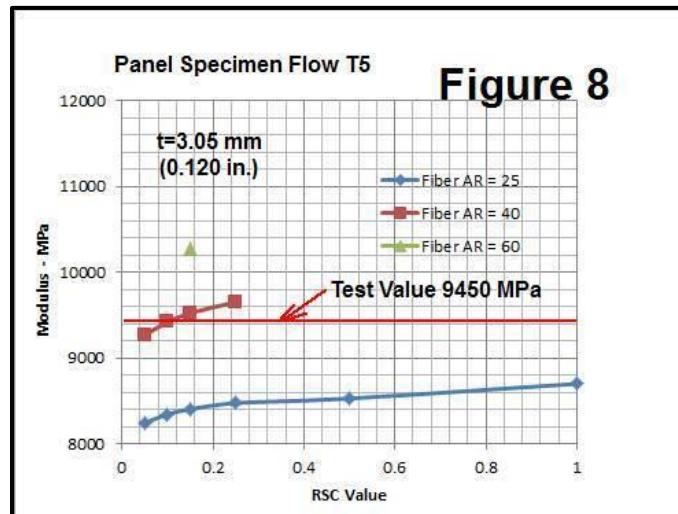
**Figure 7** shows the predicted tension modulus in the flow direction (principal average fiber orientation direction) for the T1 specimen location. This shows variation with the RSC value implemented as well as fiber aspect ratio.



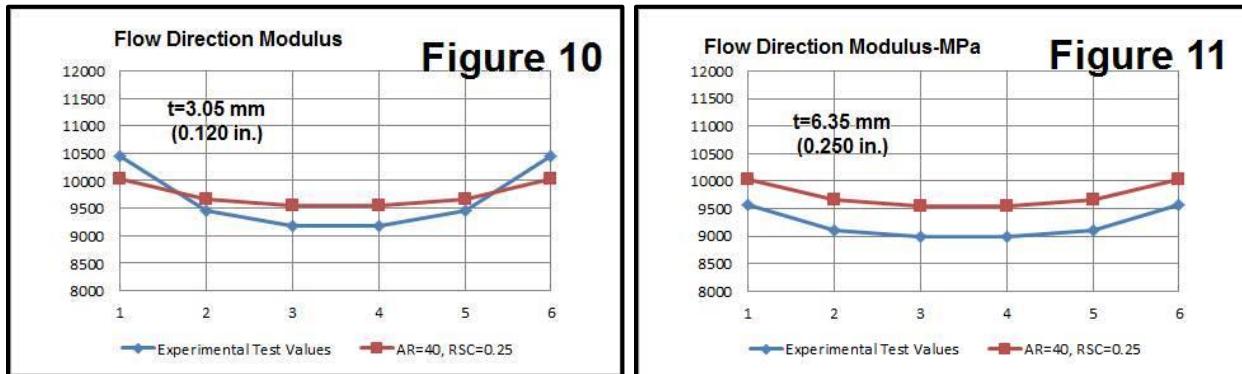


The results for the panel location T5 (which is also T2 by symmetry), is illustrated in **Figure 8**. The experimental testing of this location was solid and the correlation seems to be better for the fiber aspect ratio of 40 and relatively low values of the RSC factor (as expected).

The results for panel location T3 (also T4 by symmetry) are shown here in **Figure 9**. These results seem to show reasonable correlation with low RSC values and the fiber AR of 40.



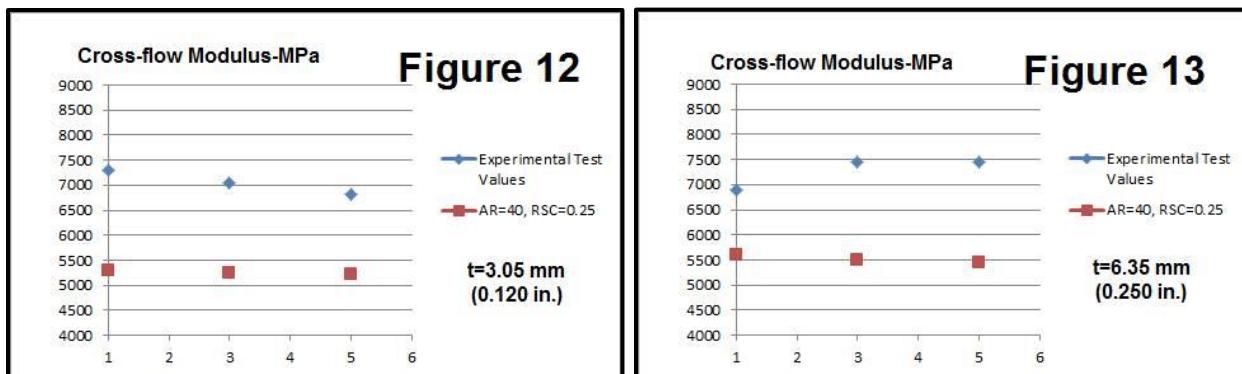
**Figures 10 & 11** summarize the results for the flow direction predictions in both the 3.05 mm as well as the 6.35 mm thickness. Notice that the variation modulus across the width of the thicker panels seems to be well modeled, just shifted in magnitude. It is expected that this would also be truer of the thinner panel moldings if the problems with testing of the edge specimen location were not encountered.



## Cross-flow Direction Panel Tensile Specimen Results

To sum it up in a few words, the cross-flow results were disappointing! I don't have any good explanation for it, but the transverse moduli seem to be significantly under-predicted across the board with the utilization of the RSC factor. In the previous work with a 30% GF PA66 very good correlation with the cross-flow predictions were obtained for the 3.05 mm thickness panel specimens while significant under-prediction of the modulus was seen with the 6.35 mm thick cross-flow specimens. For this study with a PEEK material poor correlation was obtained for both thickness specimens. Predictive analysis was not performed for all of the same fiber aspect ratios and RSC factors with the panel model for cross-flow specimens as the only difference in the panels are the location of boundary elements for the specimens cut from the panels. The results from the flow direction analyses was inspected for the cross-flow moduli variations and other fiber AR's and RSC factors provided very little in the way of better results.

**Figures 12 & 13** illustrate the cross-flow modulus predictions for the fiber AR of 40 and RSC factor of 0.25 compared to the experimental test results.



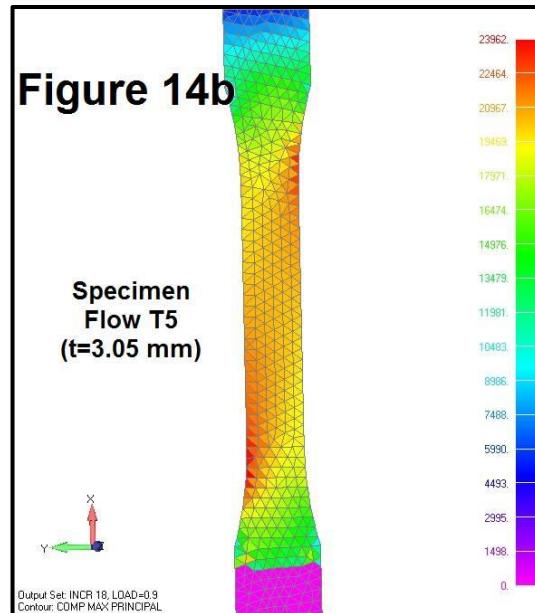
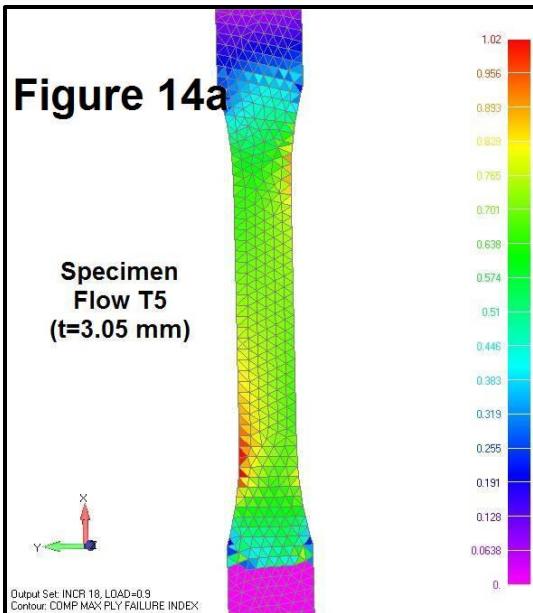
## Stress Analysis Utilizing NASTRAN Composite Elements

Midplane shell models are very convenient for doing property validation of stiffness and strength for several reasons. First is their quick run-time because of the finite difference/finite element analysis combination. Secondly their properties can more easily be examined and compared. And the final reason is that these models are easily transferred to composite element properties for use in the structural analysis programs. We have successfully utilized Moldflow's internal stress analysis for years for both research as well as customer models. However there is no easy way to evaluate the stress levels from a failure criteria standpoint.

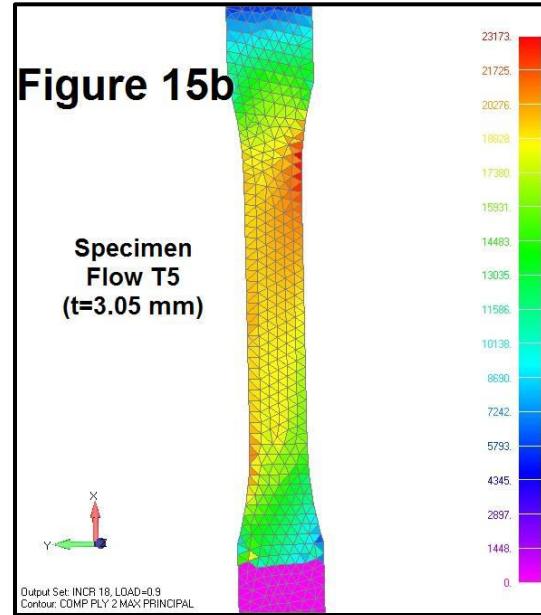
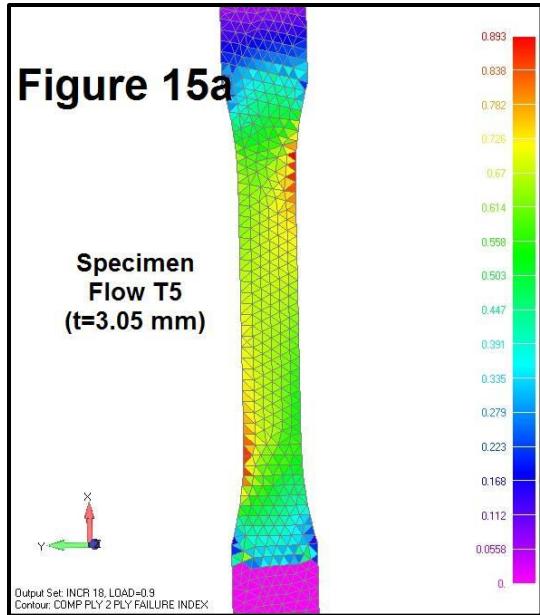
Utilizing the structural interface for NASTRAN, we have investigated failure analysis as composite laminate structures and utilized the failure analysis criteria options built in to this program (specifically NEi NASTRAN). Utilization of successive ply failure options in this program was intended to be implemented on these results, but we were not able to properly interface the models to add the necessary stiffness factors with our crude FORTRAN program. This will eventually happen (probably with outside assistance) and also investigate failure in bending using test specimens from this program. Key missing information (allowable stresses) has to be added to material property cards with the previously mentioned FORTRAN program to utilize the ply failure calculations in NASTRAN. But it provides the only means by which to review and complex geometry and evaluate critical stress areas.

By deleting the extraneous panel elements from the models, structural analysis models can be generated with anisotropic properties for any of the twelve test specimen orientations or positions. The treatment of the laminate ply stress information in the results allows some easy inspection to quickly trouble-shoot critical stress areas. **Figures 14a & 14b** show some results for the flow direction panel specimen T5.

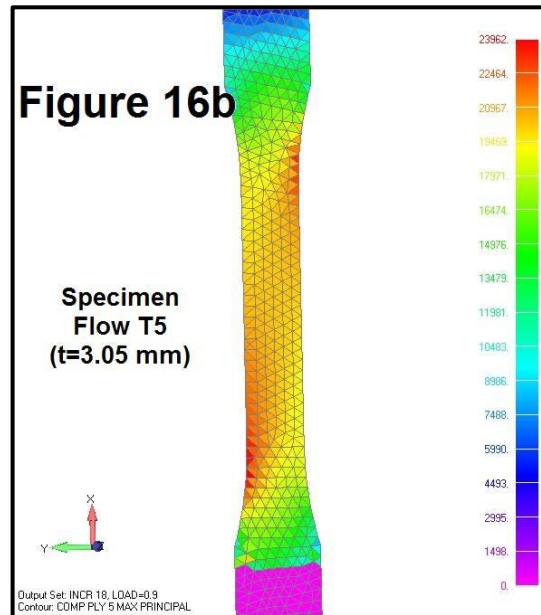
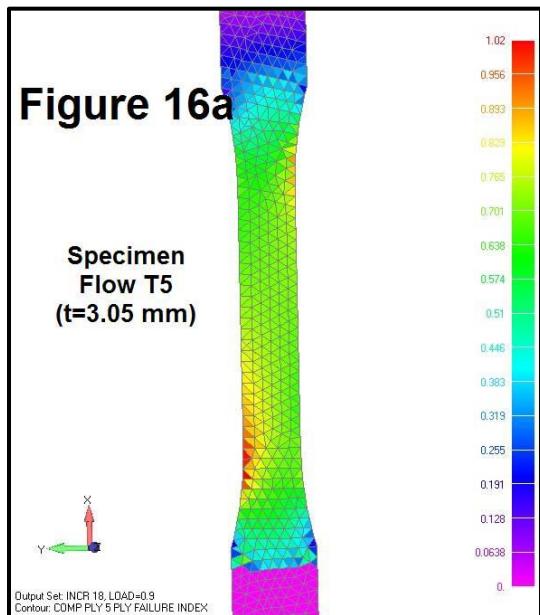
**Figure 14a** illustrates the maximum failure index over the entire model and all laminate plies. This allows a quick determination of the critical stress area(s). **Figure 14b** shows the maximum principal stress value (also through all laminates).



The fiber orientation analysis was performed with 20 laminates through the panel thickness. **Figures 15a & 15b** show the same results (ply failure index and maximum principal stress) for laminate ply #2.



**Figures 16a & 16b** show the same information for laminate ply #5. Notice that even though the stress levels may be similar, the failure indexes are different because of variations in fiber orientation and strength allowables.



This brief look at the stress analysis capabilities of a composite lamina approach should give some idea of the power of these capabilities once the anisotropic information is transmitted to this kind of analysis. The importance of the lamina approach may not seem so important when analyzing a simple tensile specimen, but even for a tensile specimen the ply failure capabilities allow pinpointing of the critical stress area and laminate. With complex part geometry, complicated fiber orientation and bending loads introduced into an anisotropic analysis, the value of this approach can be quickly realized.

## **Concluding Remarks**

Obviously there is plenty of room for more work to be done in the area of improved fiber orientation correlation. Utilizing modulus predictions as was done here may be an overly simplistic approach, but it still has potential to simplify some of the work needed to increase the confidence in fiber orientation and mechanical property predictions. The biggest hole in the new results coming from the implementation of the RSC factor seem to be the significant reduction in distinct orientation transvers to the flow direction which can be seen visually as well as microscopically.