COST 526

"Automatic Process Optimization in Materials Technology"

(APOMAT)

Half-Yearly Report

To be sent to **V.Tesch@access.rwth-aachen.de** until **February 28, 2004**

1. Reporting Period	**28.2.2005 – 15.10.2005**
Project title	Optimisation of properties and dimensional stability of composites by controlled fibre placement
Project leader	Dr. Martyn Wakeman
Organization	Laboratoire de Technologie des Composites et Polymères (LTC) Ecole Polytechnique Fédérale de Lausanne (EPFL) CH-1015 Lausanne, Switzerland
Main collaborators involved	Dr. Niklas Jansson, Dr. Martyn Wakeman

2. Funding Situation

Amount of money received specifically for COST 62 000+59 000=121 CHF (received 2002-06-24, 2003-09-03)

Other resources partially used for the project kEuros

3. International Collaboration

(mention group and type of work done in collaboration during the reporting period)

Participation in the APOMAT conference in Morschach + final project report

☑ YES

☐ NO

4. Industry participation

(mention name of companies and work done in collaboration during the whole project)

The project will to some extent be carried out in collaboration with DaimlerChrysler, Research and Technology, Ulm, Germany

5. Meetings, visits, exchange of	**Location, date**

scientists, short-term scientific missions	

6. Progress within the reporting period

(Not exceeding 3 pages, including tables and figures)

The aim of this research project is to develop the techniques and tools necessary to optimise the amount, material and location of the tow in order to reach the maximum mechanical performance in relation to weight or cost of structures manufactured by using integrated processing. One important building block includes the development and validation of finite element modelling strategies to allow efficient but accurate stress and stiffness analysis of fibre-tow reinforced thermoplastic structures. Efficient and accurate finite element analysis forms the basis and is a prerequisite for a subsequent successful coupling with the to-be developed optimisation tools and routines.

As a starting point detailed 3D finite element analyses have been performed and shown to compare favourably with available experimental data. However, one conclusion that can be drawn from the results of the detailed 3D modelling is that the effects of stable cracking in the matrix (experimental observation) and the non-fatal transverse failure of the tow (from the simulations) are very hard to incorporate in a finite element analysis. That means that the advantage of a good resolution of the stress state in the detailed 3D models is counteracted by the inability to model the progressive damage occurring in the structure. Hence, in an attempt to decrease the complexity and computational cost of the finite element models substantially with only a minor loss of accuracy, 2D models have been developed.

Two different 2-D models have been developed and tested, the beam and the composite shell model. In both models, the matrix is represented by shell elements whereas the tow is modelled either by beam elements or composite shell elements. In the latter, the area covered by tow is meshed with layered shell elements where the tow is an orthotropic layer in the middle with matrix layers top and bottom. The models has been evaluated in both tension and flexure against a detailed 3-D analysis and against experimental data.

The first main conclusion that can be drawn from the comparison between experiments and simulations is that the modelling of the compressive behaviour need further attention. In the 3-point flexure test, compressive failure is predicted to occur already at a mid-point deformation of 7-8 mm. However, in the miscroscopy examinations of the flexure specimens, no signs of buckling failure could be found even for a maximum displacement of 16.5 mm. The second conclusion is that the results from the 2-D models compare favourably with the ones from the 3-D model. Hence, it is fully viable to use the more effective 2-D models for the optimisation simulations.

To test the routines in the commmercial finite element program Ansys to optimization of tow reinforced structures a test problem, in form of a U-beam reinforced with cross-ribs was chosen. Design variables were the thicknesses of the bottom and sides of the U, the thickness of the ribs and the amount of tow in the top and bottom of the side walls and in the top of the ribs. Of the algorihtms available in Ansys, the so called sub-problem approach was used. This is a response surface method where the optimization problem is solved by a gradient based algorithm. It has the advantage that the gradients don't have to be numerically calculated for each iteration but can be obtained from the response surface. The method also allows for general non-linear behaviour of the structure which is desirable for the current type of structures.

Several optimisation runs were performed to test the influence of starting point, number of initial runs before commencing the actual optimization and the number of design variables. It turned out that neither the number of design variables nor the number of initial simulations had a clear influence on the convergence behaviour of the optimization. It should be noted though that enough simulations were always performed to form the response surface. Another result, as described already in the manual, is that the results from the optimization algorithm are dependent on the starting position. This has the implication that one has to perform the optimization several times, and more times for more design variables, to be reasonable sure that a good solution has been found. This can prove expensive as the solution algorithm performs one FE model evaluation for each iteration.

The work in the current reporting period has been directed towards testing a pure approximation based optimization. For this, the optimization program iSIGHT was used in conjunction with Abaqus on the problem in Figure 1. The beam consists of four different materials with different thicknesses in different areas. All the areas have one layer of glass mat thermoplastic (GMT, PP and 30% Mf glass fibres), all areas except the ribs have one layer of 4/1 Twintex© fabric and one layer of ±45 1/1 Twintex© fabric. UD tows are placed with different thicknesses in the radius between the bottom plate and the walls, in the flange radius and in the flanges. Design variables are the thicknesses of the different layers, nine all in all. The 'Abaqus' finite element model is based on the composite shell approach, i.e. the tow reinforcement is represented by one layer in the shell elements.

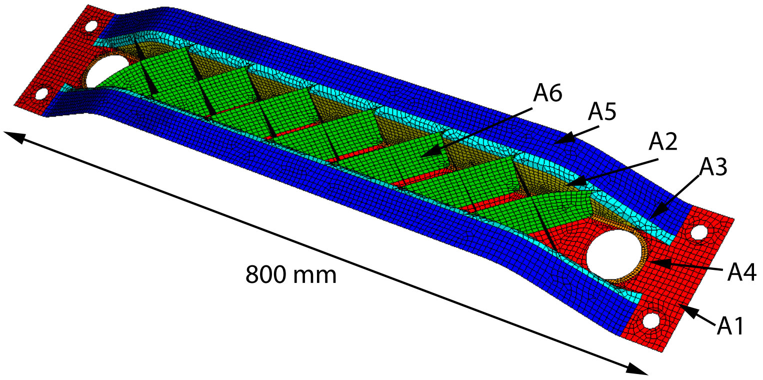

Figure 1 Geometry of the beam with the areas of different thicknesses indicated

In this work the Optimized Latin Hypercube technique is used to generate the simulation data to feed the approximations. 150 simulations were run, up to 110 has been used for the approximations and 30 used for checking the errors in the approximations. The approximations tested are the polynomial with and without term selection (up to fourth order with quadratic cross-terms), radial basis functions and Kriging. In Fig. 2 the mean error is shown for the four most accurate approximations, the Kriging, Radial basis, the quadratic polynomial and the selective fourth order polynomial. Interestingly, the full quadratic polynomial performed better than the higher order polynomials. It can also be noted that as expected the selective term approach yields a better and more reliable fit than the full polynomials. Both the Kriging and the Radial basis function are local interpolation functions and give a very robust fit which seems to improve steadily with more sample points without levelling out. Clearly though the Kriging has the by far best accuracy but it should be mentioned that the approximation fitting took more than two hours for the 90 and more than four hours for the 110 sampling points which could render the approximation too computationally expensive for larger data sets.

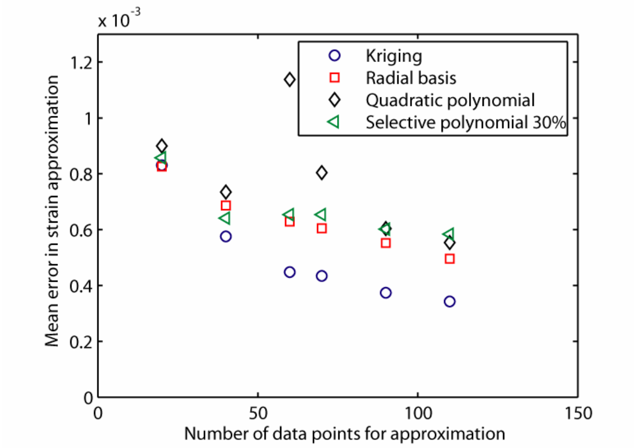

Figure 2 Mean strain error from the Kriging, radial basis, quadratic and term selection polynomial approximations.

For the optimization on the Kriging surrogate model, the Multi-Island Genetic Algorithm was used. Several different optimization runs were made with the 1/1 weave, the UD tow in the bottom plate and the UD tows in the flanges and flange radius removed together with the corresponding constraints. The best solution was found when all materials were used, a similar solution was also obtained using discrete thicknesses. As many of the constraints are close to their limits, it was concluded that the optimization routine is successful in finding a good solution on the complex design space. A verified solution was found by running the simulation code, updating the approximation and re-running the optimization in three loops until convergence was obtained.

7. List of publications

a) Published

Below are publications that have been generated within the IPPC project, which as mentioned, is related to the APOMAT project:

MECHANICAL ANALYSIS OF MULTI-MATERIAL COMPOSITES MANUFACTURED BY INTEGRATED PROCESSING
P.-O. Hagstrand, M. D. Wakeman, F. Bonjour, P.-E. Bourban and J.-A. E. Månson
Mechanical Analysis of Thermoplastic Polymers Reinforced with Robotically Placed Continuous Fibre Tows
P.-O. Hagstrand, N. Jansson, M. D. Wakeman, F. Bonjour and J.-A. E. Månson
Proceedings of the 14th International Conference on Composite Materials (ICCM-14)
San Diego, California, USA, July 14-18 2003.

Finite Element Modelling and Testing of an Injection Moulded Generic Tow Reinforced Structure
N. Jansson, P.-O. Hagstrand, M. D. Wakeman and J.-A. E. Månson
Composites: Part B, 2005; 36: 487-495

Optimization of Properties and Dimensional Stability of Composites by Controlled Fibre Placement
N. Jansson, M. D Wakeman, J.-A. E. Månson
First Invited COST 526 Conference APOMAT for Automatic Process Optimization in Materials Technology
Morschach, Switzerland, May 30-31 2005.

b) Submitted for publications

Optimization of Hybrid Thermoplastic Composite Structures Using Surrogate Models and Genetic Algorithms
N. Jansson, M. D Wakeman, J.-A. E. Månson
Submitted to Composite Structures

c) In preparation