High Precision Composites Moulding Prediction of Distortion Using Analytical Methods

PRECIMOULD

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PUBLISHABLE SYNTHESIS REPORT

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Partners:	British Aerospace, Advanced Composites Group, Saab AB, ISRIM Scarl, CASA, FEA and University of Twente		
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Project Manager:	Ian Leaver (BAE Systems)		

Approved for and on behalf of the PRECIMOULD consortium by:

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1 SUMMARY

- **<u>Five Project keywords</u>**

  - PRECIMOULD
  - COMPOSITE
  - DISTORTION
  - MANUFACTURING
  - ANALYSIS

- **Abstract of the results & benefits of the project.**

Advanced composite materials are one of the main keys to lightweight, energy efficient structures for Next Generation Aircraft. Unfortunately, there is a serious technical and economic barrier to their cost effective application in areas where accuracy is critical, due to the uncontrolled and largely unpredictable distortion which occurs during the moulding stage.

There are many factors affecting this phenomenon, but the net result is often several remakes of tooling to attempt to correct for distortion or spring back, a high scrap rate (often over 40%) and costly assembly problems, since composites are elastic and cannot be bent to shape.

The purpose of this research project is to: -

- develop an analytical method and associated database for predicting distortion phenomena
- to create a materials and processing model to ensure that the production moulding process can be specified and controlled to achieve consistent high precision and reduce scrap rates to less than 5%.

The overall aim is to reduce time to market for prototypes and production mouldings, with right first time, predictable component accuracy saving typically three to six months lead time. Also to achieve repeatable, high accuracy in series production mouldings to avoid scrap, reduce rework and achieve closer fit of assemblies. The target is to reduce factory floor costs of producing composite parts by at least 30%. (BAe has conducted tests on assembly cost savings which concur with this figure). This will, in turn, make the composites option commercially more viable to other transport sectors and to general industry.

2 THE CONSORTIUM

The project brings together a number of highly skilled and highly motivated partners from five EEC countries, covering FE software development, prepreg material manufacture, composite tool manufacture, component moulders and users in aerospace, communications and space sector industries.

Additionally, two research organisations with specific complementary skills in composites numerical analysis and characterisation support the industrial players.

BAE SYSTEMS

BAE SYSTEMS is a major aerospace and engineering group employing some 44,000 people, with annual sales exceeding £8 billion, of which 89% are overseas. The company is one of the world's leading defence and aerospace companies and is a pioneer and leader of major international collaborative programmes involving 27 nations.

The company has customers in more than 70 countries, including collaborative links with governments and industry worldwide.

BAe has a wide portfolio of products provided by the manufacturing divisions of the Company and the joint venture operations it has undertaken throughout Europe. The scope of BAe's commercial activities are considerable, however, the core businesses of the Company are in two areas: Commercial Aerospace and Defence.

In the commercial aircraft market, BAE SYSTEMS is a major partner in the two leading consortia of Airbus Industrie and Aero International (Regional).

The Military Aircraft sector of the business designs, develops and manufactures a wide range of military and training aircraft and associated products in collaborative partnerships across Pan European Consortia. The Eurofighter aircraft is the major current development for this side of the business.

BAE Systems have great experience in the development and manufacture of composite structures at its Samlesbury site and its prime role in Precimould is to carry out the task of Project Co-ordination in which it has skills developed over many Pan European projects.

FEA Ltd.

FEA's business is the development and supply of the LUSAS analysis software.

FEA's role in this project is to be responsible for software development. They will lead Work Package 4 (Development of Composite Thermal Software Codes), Work Package 5 (Enhancement and Integration of Fibre Distortion Module into FEA package and validation), Work Package 6 (CADIFE Interface Tool), and Work Package 9 (Integration of Mathematical Models into the FEA Software).

As well as being the original developers of LUSAS FEA software they have many years of experience with various CAD and other engineering software. They will bring to the project access to their LUSAS FEA software.

ACG Ltd.

ACG have 245 staff and have been at the forefront of advanced composite materials processing and development for the past 20 years. They pioneered the development of Formula 1 Grand Prix carbon fibre chassis and many other leading edge applications. Their novel low energy cure prepregs have found application in both tooling and components.

Facilities include advanced component moulding equipment, autoclave, vacuum bagging equipment, resin blending and automated hot melt, unidirectional and woven prepregging lines and associated test equipment.

ACG's role in this project is to provide research resources and skills on all aspects of prepregs and processing technology, as well as to provide innovative prepreg materials skills, advanced composite tooling design and analysis of the needs of aerospace users.

EADS CASA

Since being set up in 1923, the Spanish aeronautical sector's leading company, Construcciones Aeronáuticas S.A., has constantly developed a technological and productive capacity that enables it to compete in international aerospace markets for design, manufacture and maintenance contracts.

CASA's commercial department is efficiently oriented towards export markets which account for more than 80% of the company's business. The company remains competitive by investing about 15% of annual turnover in research and development.

CASA's workforce is made up of more than 7,000 highly qualified workers with long experience in the aeronautical industry. The company carries out continuous training in order to attune staff to the most modern technological advances and new manufacturing processes.

CASA is firmly established in the aeronautical market in the civil and military fields and concentrates on the following areas: aircraft, maintenance and space.

Since the company was founded, CASA has been designing, manufacturing and commercialising aircraft. We have given wings to more than 50 countries and to the world's leading aerospace companies.

More information: www.casa.es

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ISRIM

ISRIM is a non-profit making RTD organisation on advanced materials with both public and private shareholders. ISRIM is organised into integrated departments in order to follow the life cycle of a material.

ISRIM's role in this project is to participate in Work Package 1 and assume leadership of Work Package 2, to determine thermomechanical parameters affecting distortion.

ISRIM have collaborated or led BRITE projects involving the preparation and characterisation of composite materials. They have also studied the correlation between the production processes and properties of the composite material obtained. Facilities include autoclave, pultrusion, injection moulding apparatus and thermochemical and mechanical testing apparatus.

University Of Twente

University of Twente is one of three technical universities in the Netherlands.

Within the Department of Mechanical Engineering, the major research interests of the Chair of Engineering Design in Plastics (EDP) include design, manufacture and performance assessment of structures or products made from fibre reinforced plastics, composites and polymers.

Warpage/distortion, internal stresses and orientation are assessed and correlated with the manufacturing process conditions both experimentally and by numerical simulations. The Chair of Technical Mechanics (TM) has substantial expertise in numerical stress analysis, including in-house developed FE software relevant to sheet forming and polymer melt processing.

Twente's role in this project is to undertake Work Package 5 drape modelling and Work Package's 7 and 8 measuring and predicting internal stresses in composite panels. (Twente represent state-of-the-art in using the layer removal technique for composite panels to do this task).

SAAB AB

Saab AB is a manufacturer of aerospace products such as military aircraft, civil aircraft components and satellite components. Numbers of employees in the Saab Group are approximately 14 500. As regards civil aircraft products, Saab is a subcontractor to both Boeing and Airbus and has been a manufacturer of commuter aircraft in the 30-50 passenger range. Saab is also producing the fighter aircraft Gripen, the first fighter aircraft in the fourth generation. This aircraft includes much of the new technology such as carbon fibre composites and fly-by-wire systems.

Saab has more than 60 years of experience in the field of aircraft production and about 20 years experience in composite deign and manufacturing.

The Saab contribution to the project will be material characterisation, theoretical modelling of' 'spring back' phenomena and validation of experimental software by manufacturing composite parts.

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3 TECHNICAL ACHIEVEMENTS

The technical activities within the project were broken down into 3 main subsets or groups.

Group one relates to the **Scientific Group** of work packages and was technically led by ACG.

Group two relates to the **Software Group** of work packages and was technically led by FEA.

The final group, group three relates to the **Validation group** of work packages and was technically led by CASA.

This section of the report is therefore written outlining the achievements attained by each of the above groups.

THE FOLLOWING REPORT HAS BEEN COMPILED BY:

THE ADVANCED COMPOSITE GROUP (ACG)

AS PART OF THE PRECIMOULD SYNTHESIS REPORT.

THE FOLLOWING SECTION RELATES TO:

THE SCIENTIFIC GROUP OF WORKPACKAGES

3.1 Scientific Group

3.1.1 Moulding Distortion Effects

The distortion of Composite components and mould tools in their manufacture can be attributed to many interrelated factors. The objective of the Scientific group was to define, quantify and generate data to allow prediction of the individual factors.

In doing this the phenomena were classified into two general groups:

Group 1: Primary Distortion Criteria. These are the physical and chemical material factors, which occur irrespective of the moulding environment.

Cure Process Polymerisation 'Shrinkage' and CTE strains
Material Inplane Modulus Coupling – Complex geommetries
Form Tool CTE effects

Group 2: Process Specific phenomena. These arise directly from the processing conditions. They involve interactions between composite part and tool and non-equilibrium conditions (gelation occurring outside the process dwell and process temperature not readily achieving its dwell value).

Non-Equilibrium Process Conditions – Thermal & Cure transients
Manufacture pressure related - Fibre 'Wash' (preferential compaction at bag face) & Male and Female former consolidation.
Surface interaction stresses between curing composite and Tool

3.1.2 Materials Database

The PRECIMOULD FE based analytical software predicts the corrected tool geometry to invert the distortion effects. That prediction relies on a non-linear visco-elastic material modeller developed in the software group. The governing material parameters for distortion were identified and the data base fields defined for the material modeller.

Those fields include critical engineering mechanical properties, thermal properties, parameters for cure kinetics & chemorheology analysis and direct distortion measurements.

The Database has 5 categories: Pattern Data, Laminate Data, Resin Data, Fibre Data and Core Data.

3.1.3 Test Works

3.1.3.1 Test Methodology

The Test Methodology was set to encompass the diversity of materials and process techniques commonly employed by the advanced composites community, to allow the proving of a general analytical solution. The test programmes incorporated:

i) The common epoxy thermoset resins and ultra high temperature thermosets, covering the full range of process temperatures.

ii) A full range of Fibre moduli, weave architecture and lay-up configuration including panel constructions of both monolithic and sandwich form.

iii) Autoclave, Vacuum pressure and Resin Transfer Moulding process techniques.

3.1.3.2 Database

The database was fully populated to the Test Methodology. Test procedures were developed to measure the properties directly used in process simulation and novel methods written for quantifying process dimensional changes, which are generally in the tens of micro-strain order of magnitude.

3.1.3.3 Simple Geometry Validation

Verification tests based on the out of plane distortions in simple curvature components were also set and completed. This was to establish the relationship between dimensional changes in prime material axis (measure on flat plates) to curved geometry spring warpage. They also provide test cases for Precimould Software formal validation procedures.

3.1.3.4 Evaluation of Process Specific Phenomena

The extensive database generated satisfies all the input required to predict Primary Criteria effects and Non Equilibrium Process Conditions (Process Specific Phenomena). Test works were undertaken to asses the significance of Manufacturing pressure related effects and Surface interaction stresses. The processing conditions where these will have an important effect on accuracy were identified. Analytical or semi-empirical solutions can be employed here.

THE FOLLOWING REPORT HAS BEEN COMPILED BY:

FINITE ELEMENT ANALYSIS LTD. (FEA)

AS PART OF THE PRECIMOULD SYNTHESIS REPORT.

THE FOLLOWING SECTION RELATES TO:

THE SOFTWARE GROUP OF WORKPACKAGES

3.2 Software Group

3.2.1 Software development

Advanced composite materials are one of the main keys to lightweight, energy efficient structures for Next Generation Aircraft. The purpose of this research project was to develop an analytical method and associated materials database for predicting the distortions that can occur when manufacturing such composite materials using hot curing.

Continuous fibre reinforced thermoset laminates that undergo hot curing exhibit deformations due to thermal and cure shrinkage. During this process residual stresses will develop in laminates due to the mismatch of thermal expansion along and across the fibres, cure shrinkage of the thermoset resin and the change from cure to room temperature. These deformations and residual stresses lead to undesirable shape distortions when the cured components are released from the mould. Currently the tool designer accommodates for these distortions by trial and error and experience. It is desirable to be able to predict these distortions, reducing trial and error time and wastage of material when producing a new component.

The software development work undertaken in the PRECIMOULD project has resulted in an integrated package which caters for the transfer of geometry from a CAD system right through to the computer simulation of a curing (and post curing) process. This package, which also includes a draping module for predicting fibre directions and volume fractions along with an inverse analysis facility, is available in version 14 of the commercial finite element program LUSAS. These new facilities will enable the user to simulate the curing process in the following manner:

- Read the CAD model geometry of the part and tool into the LUSAS Modeller pre-processor via an IGES transfer file. Using the tools available in Modeller merge and trim surfaces so that the original solid geometry is recreated.
- Create a finite element model of the tool and part. At this stage the draping module available in Modeller can be used for draping a composite material onto an arbitrary shaped surface.
- Assign resin and fibre properties to the features in the model. These properties can be extracted from a database of composite material properties, which is directly accessible from within Modeller.
- Specify a time-temperature profile for the autoclave or RTM curing cycle along with changing boundary conditions to simulate removal of the part from the tool or mould.
- Carry out a coupled thermo-mechanical analysis which takes into account the effect of internal heat generation, changes in viscosity, amount of chemical and thermal shrinkage to predict the amount of distortion after the curing cycle is complete.

- Carry out an inverse analysis after examining results in the LUSAS post-processor and export the revised geometry for the tool to a CAD system.

A final predictive High Precision Moulding tool has been developed which provides a complete package for predicting the distortion that is likely to occur during the curing process of thermoset laminates through to the export of the predicted tool shape geometry to a CAD system. To facilitate this a CAD interface has been provided via an IGES transfer file. Sewing algorithms have been developed within Modeller so that the original solid geometry can be recreated. The LUSAS program provides an easy to use interface for setting up the finite element model with convenient access to a database of some of the currently available resin and carbon fibre composite materials.

The draping program predicts the changing angles between warp and weft which occur when a fabric is draped onto a doubly curved surface. A geometrical method has been used to model the draping process whereby the shape of the product is defined by algebraic expressions. By projecting a square mesh onto the surface the final deformed fabric shape is predicted. The draping program provides fibre skew angles and volume fractions for each finite element at each layer of the composite material.

A unidirectional and woven fabric material model have been integrated into the LUSAS Solver program which possesses the capability to solve non-linear transient, thermo-mechanical coupling and contact problems. Both thermal and structural 3D continuum composite elements are available, formulated using algorithms which provide efficient solutions to large problems. The equations governing curing kinetics, viscosity and the chemical shrinkage/degree of cure relationship have been implemented in a general manner to provide the user with as much flexibility as possible in controlling the evolution of these effects for differing materials and cure cycles. The degree of cure, heat of reaction, chemical shrinkage and viscosity profiles can be plotted for any point in the model as an aid to validate the results obtained.

To further supplement the modelling of the part and tool along with the curing process, a library of additional loading, element and material types is available in the LUSAS finite element system along with curved contact and thermal surface algorithms.

THE FOLLOWING REPORT HAS BEEN COMPILED BY:

Construcciones Aeronauticas SA (CASA)

AS PART OF THE PRECIMOULD SYNTHESIS REPORT.

THE FOLLOWING SECTION RELATES TO:

THE VALIDATION GROUP OF WORKPACKAGES

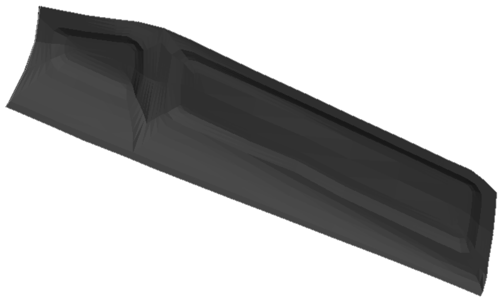
3.3 Validation Group:

The final phase of PRECIMOULD was based on the validation of the experimental scientific work performed in the first phase and the software code developed in the second phase, through real aeronautical parts. BAE Systems, in partnership with SAAB, and CASA, were taking main responsibilities for this work. This phase is divided in two main work packages:

3.3.1 WP10: Verification of HPM Software Tool.

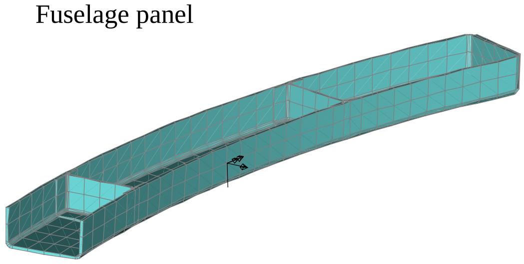
Scope. The scope of this work-package is to apply the software developed in the previous work packages to real parts. These parts will be later manufactured on WP11 to correlate the analytical distortions here obtained with the real one obtained in the parts manufactured.

Validation parts: Two main aeronautical parts were used for validation purposes:
BAE Systems selected a C-Spar manufactured by RTM on a closed steel mould.
CASA selected a fuselage panel manufactured by classical hand lay-up technology. Moulds made of steel and composite were analysed by CASA for the study.



Fuselage panel

Cleated C-Spar



The main tasks performed for CASA and BAE Systems were:

Part Model simulation: Both companies required to make this work outside LUSAS, developing an automatic translator

Process simulation: This task was specially complicated for the RTM process and some simplifications were needed.

Materials constant determination. Two approaches were made:

a) using a semi-empirical method, obtaining a so called Coefficient of Proccess Expansion (CPE).

b) Using the viscoelastic approach using the software capabilities developed for LUSAS.

Tuning and testing of the software. This task took several iterations with FEA with suggestions for debugging the software.

Strain analysis: for the two aircraft components and in the case of CASA also for the composite moulding tool.

SAAB made use of traditional FEA packages (ABAQUS), using only a thermo-mechanical approach, for comparison with the results obtained by BAE Systems.

3.3.2 Main results achieved:

The individual results can be found in the respective documents. A summary with comparison with the results obtained in the real parts will be given later.

Further work required.

- Improvement of the LUSAS CAD Interface
- Incorporation of the possibility for correcting the material orientation.
- Upgrade the process conditions.
- Enhance the material database, specially the inconsistency of nomenclature and units and limited flexibility of the user interface.

3.3.3 Wp.11 Build Large Scale Mould Tools And Validate/Demonstrators.

Scope: The scope of this work package was the manufacturing of real parts to verify the software results obtained in the previous work packages and the assessment of results.

3.3.3.1 Task performed:

BAE Systems manufactured up to three RTM Cleated C-Spars. A tool model was created, from reverse analysis, using the Precimould software. Tool model were later checked. The pieces were manufactured and lately checked. The results obtained were assessed.

CASA manufactured four hand-lay Fuselage panels. Two of them on an existing tooling made of Ni, and two of them on a new corrected tool made of steel.
The pieces were manufactured and lately checked.

3.3.3.2 Main conclusions:

From the comparison between predicted and real deformations:

The mode of deformation predicted by the LUSAS Precimould analysis in these trials was found to be correct, but the magnitude of spring predicted by the analysis was found to be less than that measured on the demonstrators

It is considered that the accuracy of the results for this trial fall outside the normally accepted AERONAUTICAL tolerances for these type of parts and further work to understand the errors and sensitivities need to be addressed. The analysis shows sufficient promise to merit further development work and research.

4 EXPLOITATION & FOLLOW UP ACTIONS

PRECIMOULD Technology Developed

From the outset PRECIMOULD was an ambitious Project. Its primary objective has been to provide a general solution to the Moulding distortion problem, through the development and validation of a complex analytical material modeller operating within a complicated fully coupled transient Finite Element approach. This goal has been achieved for the prediction of Primary and transient cure Distortion criteria. That success has been brought about by the forwarding of understanding and development of Technologies at every stage of:

'phenomena identification → measurement → modelling → coding → solving → validation'

What has been learnt at each stage has a significant contribution itself to solving the problem.

Characterisation of Distortion Effects.

At the onset of the project there was an awareness of primary and secondary process distortion phenomena but no real appreciation of the relative significant or limits of each effect. The extensive test works completed (across the European research and Aerospace community) incorporating the full boundaries of advance composite processing, has resulted in an extensive and in depth characterisation of Primary Distortion criteria and Process specific phenomena.

Database for Process Engineering

The measurement of geometrical changes under processing (which occur at a level of 0.01% strain) brought a unique challenge. In the project new test methods and procedures have been written for direct distortion measurement on generic moulded shapes. Extensive Data has been generated for specialised cure and rheology modelling, and also for critical elastic and thermal properties. All data has been compiled into a powerful database capable of supporting any Engineering process analysis.

Analytical Models

PRECIMOULD project has incorporated thermo-elastic, visco-elastic, cure (heat of reaction), rheological and dynamic gelation modelling. The thermo-elastic model is a basic tool for the Design Engineer to predict woven fabric 3 dimensional elastic properties. The extent of cure and rheological capabilities are fundamental tools for the Process Engineer to optimise production (for instance deciding on the stacking and scheduling of jobs in a large autoclave).

Improving Part Accuracy – Design Against Distortion

From a basic approach taking:

- the understanding achieved in the project
- distortion measurements
- database generated
- simple analytical tools developed

the fundamentals of reducing part inaccuracy have been significantly advanced by PRECIMOULD. More importantly the foundations have been set for design against distortion rather than purely predicting it i.e. by following rules such as matching tooling and component CTE, minimising thermal and cure transients during cure and identifying the resin gelation point in the process cycle.

The application of PRECIMOULD FE solution

Operation of the full PRECIMOULD FE system is complex; bringing all parts of the Project together in the 'solution' creates a readily accessible high functionality in the software, suited to a development operator. The pre-processing has not been optimised for the general user.

In considering the likely end users we see the importance of applying the fundamental technologies developed in PRECIMOULD:

Consultant FE Analysts: Many analysts consider structural composite a complex novelty. A thorough understanding of the composite moulding process is necessary to build the PRECIMOULD FE model and an advanced knowledge to verify the solution. Currently this understanding is not in place.

Manufacturing Process Engineers: Even within the Aerospace environment historically manufacturing has not recruited Engineers with good analytical capabilities – in discussion, this software is perceived to be 'high level' and for effective application requires highly skilled Engineers with both analytical and processing expertise.

It can be seen a good process engineer is unlikely to have the analytical capabilities to run and interrogate the output of the software, where as a good Analyst will not have the materials knowledge to ensure quality input and output.

Realising the full potential of PRECIMOULD

Addressing the lack of knowledge in the fundamentals of process distortion is the key to realising the full potential gains from this project. It will both bridge the gap between Stress Analyst and Manufactures and provide the essential 'hand calculated' first approximation to verify this complex solution. The fundamental science completed in the project provides the basis for that.

It is important that the software solution is also developed to a more ‘user friendly’ form where there is the option to access increasing levels of functionality. The sensitivity of the solution will require further exploration to provide a proper basis for a balance between ‘time spent generating a model/solution’ and ‘accuracy of the results’.

Partners, in particularly the University of Twente will assist in the dissemination of knowledge by publication of project output in scientific journals and through seminars.