SIXTH FRAMEWORK PROGRAMME

PRIORITY [4]

[Aeronautics and Space]

ITOOL

Integrated Tool for Simulation of Textile Composites

Contract no.: 516146

Publishable Final Activity Report

Period covered: from 01.04.2004 to 30.09.2008

Date of preparation: 15.10.2008

Start date of project: 01.04.2004

Duration: 42 months

Internal reference: E.45046

Revision: issue 1

Project coordinator name: Dr. Peter Middendorf

Project coordinator organisation name: EADS Deutschland GmbH

Content

1 Original project data

1.1 General project data

Title: Integrated Tool for Simulation of Textile Composites

Acronym: ITOOL

Contract Nr.: 516146

Starting Date: 01/03/2005

Duration: 42 months

Total Cost: 3754097 €

EU Contribution: 2619913 €

Web-site: http://www.itool.eu

The project website will be kept online beyond the end of the project, dated 30.09.08.

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Project logo:

1.2 Abstract

The overall aim of ITOOL is to ***increase the usage of textile preforming for composites in Aeronautics applications***. It is well-known from related projects that preforming offers a ***potential cost savings of 20-30%*** in materials and processing compared with prepreg technology. But a still ***missing prerequisite*** for taking advantage of this potential are ***adequate design and analysis methods*** and especially ***validated simulation tools***. The technical approach of the project covers this aspect by ***development of an integrated solution***, simulating the ***manufacturing and processing chain*** as well as the ***loading stage*** to get reliable results also for 3d fibre architectures. Focus is laid on ***braiding, weaving and stitching technologies*** including also Non Crimp Fabrics. The resulting types of preforms will be analysed on different approximation levels (micro / meso / macro modelling) to take inhomogeneous fibre distribution and waviness into account.

To fulfil the objectives within a limited time (and cost) scale, the ***linking and integration of different stand-alone solutions*** in the tool chain is proposed thus creating an ***open flexible interface for fluent data exchange and communication.*** The alternative to develop new multi purpose software would be prohibitively costly.

The main value is therefore gained for the user of textile composites. ITOOL can set up a ***standard for testing, modelling and simulation*** with minimized interference and without data loss and by this reply to the market demands. Further impact of the enhanced simulation capabilities will be a distinct ***reduction of at least 20% in necessary testing effort*** as well as a ***lead time reduction of more than 15%***.

The ***proof of this concept*** will be performed for different ***application examples in Aeronautics*** and summarized in ***guidelines***, ***design rules*** and ***educational tools***.

1.3 Objectives

Textile preforming of composites offers the potential of significant ***cost savings of 20-30%*** in comparison to prepreg tape layering due to cheaper materials (dry fibre rovings, yarns or fabrics), easier storage conditions and the possibility of automation of the preforming process. These advantages open ***new markets*** for textile preforming, especially in ***low-cost composite applications***.

To enable development engineers to make use of dry fibre textiles, ***reliable simulation tools and design principles*** are needed. But in contrast to conventional, unidirectional reinforced composites, textile reinforcement results in ***3d fibre architectures*** so that standard analysis procedures like 2d rules of mixture, in-plane strength criteria and classical laminate theory are no longer valid.

For textile preforming it is also important to consider the manufacturing of the textile preform since the shaping operation will cause fibre reorientations, distributions, frictional and prestressing forces which will have a strong influence on the resulting textile properties. The technical approach of ITOOL is therefore a ***simulation along the process line*** with a ***virtual manufacturing chain*** incorporating the preform manufacturing, draping and impregnation process followed by the external loading of the finished component.

The scientific objective of ITOOL is to close the gap between missing knowledge and proved advantages of dry fibre textiles by ***development of an adequate integrated simulation tool*** for textile preforming technologies including ***braiding, advanced engineering textiles, weaving and stitching***. Reliable simulation tools and design methods provide the enabling prerequisites for an increased use of these materials in Aerospace (and other) industries.

From the technical point of view, special focus will be laid on 3d reinforcement by the use of structural stitching to ***improve mechanical properties*** of composites in the thickness direction (damage tolerance +80%, fracture toughness +75%, weight specific energy absorption +75%).

The mechanical behaviour will be analysed on three different approximation levels called ***3M (micro / meso / macro) mechanics***:
on the microscale the different constituents are always modelled separately,
on the mesoscale fibre and matrix properties are homogenized locally,
on macro level the micro or mesoscale models are homogenized in a coarser way to lower the computational effort.

As there are already ***stand-alone solutions*** for several parts of the simulation in use, the approach of ITOOL is mainly the ***linking and integration*** of these tools to ensure a ***fluid interaction and data interchange*** with minimum friction and without critical data loss. Furthermore the ***user interference*** should be ***minimised***. This approach will enable a flexible and adaptable solution, which may be extended to include alternative technologies such as Liquid Composite Moulding and impregnation simulation.

The ***proof for this integration concept*** will be performed for different ***application fields*** of textile preformed composites ***in Aerospace***: typical stiffened skin sections, integral joining technologies and a braided propeller fan. The evaluation also includes the interface and the related flow of data as the quality of results in comparison with tests. The achievement of reliable simulation data will lead to a further ***20% saving of testing effort*** and to a ***lead time reduction of approximately 15%*** due to a decrease of product development iteration loops. Greater optimisation of structural parts via validated simulation tools will be possible.

In parallel to the development of the integrated simulation tool the second aspect of the project is to ***build up physical understanding*** of textile preformed composites behaviour to ***increase their usage***. Therefore ***design rules*** for the use of dry fibre textiles should be extracted and made easily available for the design engineer in a guideline. In addition, an ***educational tool*** based on e-learning concepts will be developed and disseminated.

By achieving the above-mentioned objectives, ITOOL can provide the basis of a ***standard*** for the design, analysis and testing of ***textile preformed composites in Europe***.

1.4 Partners

The **consortium** comprises three aerospace companies, one SME, one software supplier, two research organisations and six universities to reflect applications, scientific and research partners of the project. All of the partners are experienced in either textile composites preforming, simulation or both of them and have in many cases already worked in previous national or European projects. A summary of participating companies and institutes is given below in table 1.

Table 1: ITOOL participants

Partic. Role[1]	Partic. no.	Participant name	Participant short name	Country	Date enter project[2]	Date exit project
CO	1	EADS Germany	EADS-G	D	Month 1	Month 42

[1] CO = Coordinator, CR = Contractor

[2] Normally insert “month 1 (start of project)” and “month n (end of project)” These columns are needed for possible later contract revisions caused by joining/leaving participants

CR	2	Alenia Aeronautica S.p.A.	ALA	IT	Month 1	Month 42
CR	3	Cranfield University	CRAN	GB	Month 1	Month 42
CR	4	Dassault Aviation	DAS	F	Month 1	Month 42
CR	5	German Aerospace Center	DLR	D	Month 1	Month 42
CR	6	EADS France Innovation Works	EADS F IW	F	Month 1	Month 42
CR	7	ESI Software	ESI	F	Month 1	Month 42
CR	8	University of Stuttgart	IFB	D	Month 1	Month 42
CR	9	University of Aachen	ITA	D	Month 1	Month 42
CR	10	University of Leuven	KUL	B	Month 1	Month 42
CR	11	INSA University Lyon	LAMCOS	F	Month 1	Month 42
CR	12	SISPRA	SISPRA	E	Month 1	Month 42
CR	13	University of Zaragoza	ZARA	E	Month 1	Month 42

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1.5 Project Work packages and work package interdependence

Covering the whole development chain, the project starts with ***WP1 “Material Characterisation / DataTool”*** *where* the requirements for the DataTool used in other parts of ITOOL is researched. Materials, used in the validation examples, are analysed and their properties needed for the validation examples are stored in the DataTool. In parallel, ***WP2 “3M Mechanics”*** provides models compatible with and ready to be integrated in structural analysis tools developed on Macro level. It also contributes to the description of the textile geometry, to the development of textile process models and stiffness/failure/impact models. ***WP3 “Process Simulation”*** develops a `virtual manufacturing´ chain for the production of textile reinforced plastics. ***WP4 “External loading behaviour”*** investigates the complete structure of textile reinforced plastics and aims to integrate macroscopic structural deformation, stress and failure modelling into ITOOL. ***WP5 “Integration”*** takes care of the interaction between these different WP solutions. The interaction is defined properly for each component and described in such a way, that data interchanging is made with minimum friction and without critical data loss. User interference is also minimized by the use of a Graphical User Interface (GUI). Using three different test cases, ***WP6 “Industrial validation / Test”*** validates the whole simulation chain by a comparison between the manufacturing and the process simulation as well as between the mechanical testing and external loading analysis. Finally, ***WP7 “Design guidelines / Standardisation”*** provides general design guidelines, design diagrams and “rule-of-thumb” design procedures to allow textile engineers as well as composite engineers to take basic decisions at a very early phase of the development and to allow a rough estimation concerning the performance of a structure.

The workflow and interaction of work packages within the ITOOL project is depicted in the chart below (figure 1).

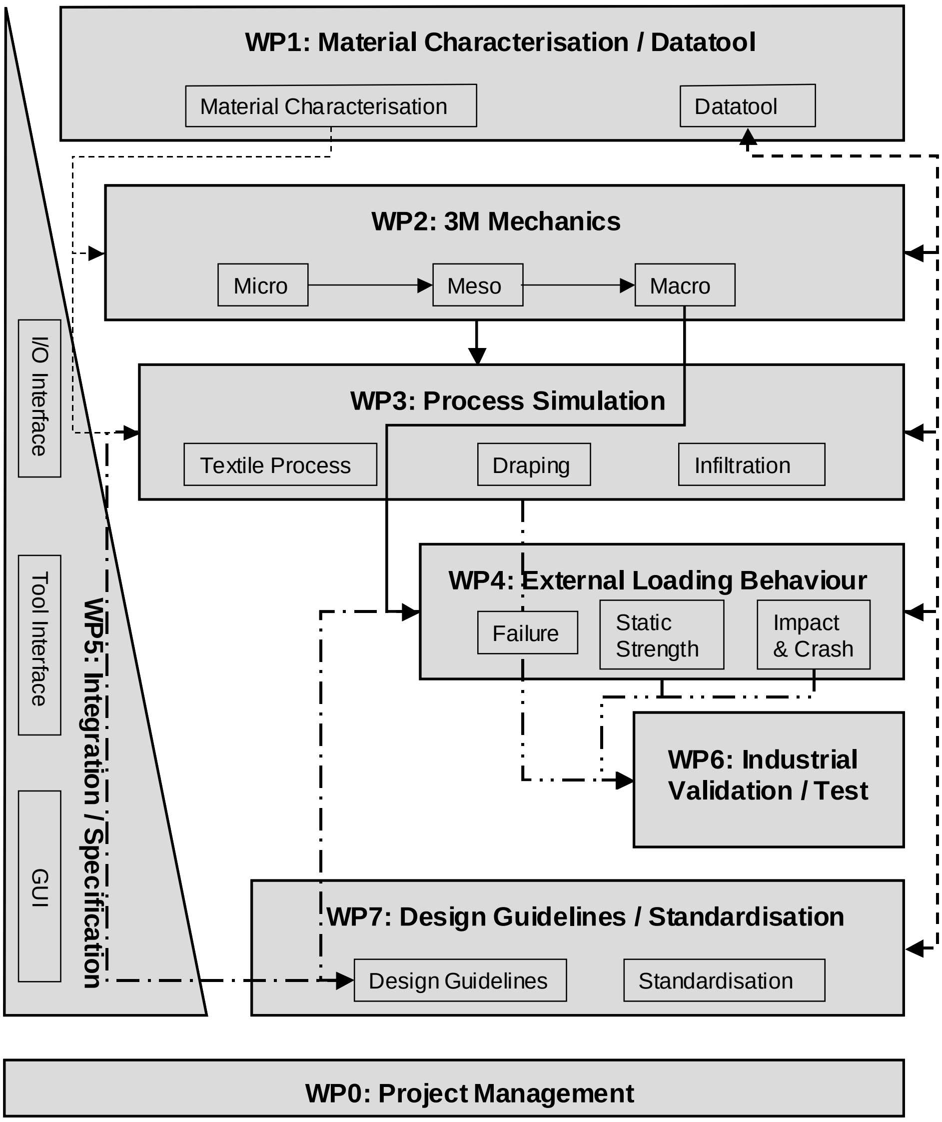

Figure 1: Work flow diagram

1.6 Project organisation structure

The project structure was organised according to ISO standard to ensure fluent communication between partners. A ***site manager*** which is responsible for the project contributions was appointed for each partner. A ***work package leader*** was responsible for the work in each work package. On a regular base (each six month) the technical am management status of the project was discussed during a review meeting and have been reported in technical reports.

A graphical overview of the project organisation structure is shown in figure 2.

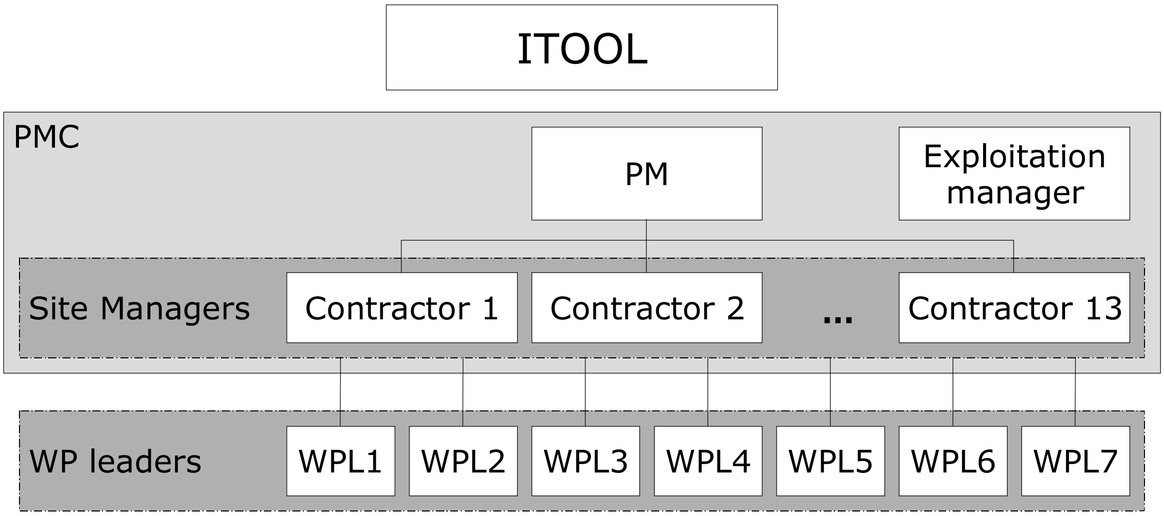

Figure 2: Overview of ITOOL project management structure

1.7 Main advantage of the ITOOL approach

The advantages of the ITOOL approach against the up to now standard approach are listed in table 2.

Table 2: comparison between standard and ITOOL approach.

Standard approach	***ITOOL approach***
A significant amount of experimental testing is required to characterise new materials	Many of the material properties can be simulated and validated by a limited amount of experimental work.
The selection of the textile reinforcement is limited to the existing products on the market	Engineers can virtually design optimised textile architectures for a specific application
Uniform permeability's re used to perform an infiltration simulation. For the draping process no or at maximum kinematic draping algorithms are used which doe not take into account the mechanical properties of the textile	A mechanically based draping algorithm predicts the textile deformation during the draping process. Based on these results and a detailed geometrical description of the deformed textile a local permeability is predicted for an infiltration simulation.
Only the average behaviour of the textile reinforced composite is know from the experimentally investigations	The multi-level modelling approach allows a detailed physical understanding of the phenomena that occur in a textile reinforced composite part.
Stand alone solution are used to perform different steps in the design process of a (textile) composite part. Often problems arise when transferring the results between different simulation steps	The integration approach of the ITOOL project ensures a fluent transfer without critical data loss between the different stand-alone software tools.
No universal methods and standard exist for textile reinforced composites due to the complexity and variability of these materials.	The ITOOL project has set a first important step towards development of methods and standards.

1.8 Main project motivation

Many projects show that textiles and textile reinforced composites have advantages in terms of cost and effort against prepreg technologies. The main differences which have been observed are listed in table 3. Moreover, when it comes to the analysis, there is no universal approach to handle of textile reinforced composites as summarised in table 4. It can hence be concluded that there is a need for a new and integrated set of tool that enable a detailed analysis of textiles and textile reinforced composites.

Table 3: motivation for textile preforming

Prepreg	***Preform***
resin pre-impregnated unidirectional tapes or fabrics (high material cost)	cost-effective dry fabrics (braids, weaves, NCF)
storage limited by resin (6 months at –18°C)	storage limited by fibre sizing (2 years at ambient conditions)
labour-intensive stacking of single layers with defined orientation	assembly by stitching or binders (high potential for automation even for complex shapes)
2D fibre architecture	option for 3D reinforcement by stitching
Autoclave processing	reliable and cost-effective infiltration with non-autoclave techniques or RTM

Table 4: Analysis options for composite materials

Prepreg	***Preform***
2D fibre architecture	3D fibre architecture
nearly ideal fibre alignment	fibre misalignment due to draping + influence of infiltration process
micro / macro models established for determination of • stiffness (unit cell models, CLT) • strength (failure criteria → WWFE) • continuum damage evolution	no universal (numerical) modelling approach, only single solutions • structure and properties of the composite material are dependent on the manufacturing process • simulation along the process chain • based on 3M mechanics (micro / meso / macro)
numerical implementation mainly for layered shell elements	

2 Work performed and results

The summary of the performed work and the gained results during the ITOOL project follows the work package and task structure defined at the project start and was described in annex I of the consortium agreement. Due to a six month extension of the project this annex was updated including a reschedule of several deliverables and milestones.

The following sections provide an overview of the planned work, aims and objectives within the different work packages and discusses the obtained results.

2.1 WP1: Material Characterisation / DataTool

The aim of this work package is to collect all the information that may be relevant for any simulation within the ITOOL framework. Related to this task is the creation of a comprehensive database (DataTool) to store the obtained data. The characterisation of different types of materials and material properties is essential and includes mechanical, physical and geometrical properties for both dry textiles and infiltrated composites. Especially for new textile architectures it is important to have an appropriate model which is able describe the material. Therefore work package 1 was subdivided in three logical sub-tasks:

2.1.1 Task 1.1: Selection of relevant data

The objective of task 1.1 was to identify a set of relevant parameters which can be used within any kind of simulation which is related to textile and textile composites. A comprehensive study on different textile architectures and their corresponding composite was performed to identify the key parameters on mechanical, physical and geometrical level. Moreover parameters are identified on micro, meso and macro-scales. From this study a list is compiled which contains the relevant material parameters. For each of these parameters a testing method and a short test description are given.

Approximately 50 relevant parameters have been identified from the investigations in this task. These parameters are mainly geometrical properties of yarns and textile structures, mechanical properties of yarns, textiles and textile composites as well as deformability and permeability characteristics of dry textile. The identified parameters are listed in deliverable D1.1.1.

2.1.2 Task 1.2: Structure of the DataTool

Within the second task in work package 1, a structure for a database is developed. This database, which is named DataTool, will enable the storage of all relevant data identified in task 1.1 and will enable the different partners (or future users) to access this information. The structure of the DataTool does not only provide a way to store most important characteristics of a material, but also allows to add comments, link entries of different constituents or link the resulting property with its testing protocol.

The results of this task, described in deliverable D1.2.1, are used within work package 5 where the DataTool is developed and implemented in a software application.

2.1.3 Task 1.3: Collection of data

The third and final task of work package is the selection of relevant data. In this context the word relevant refers to the industrial validation examples which are defined in work package 6 (see section 2.6). Only for the selected materials used in the three validation parts and for the selected process or external behaviour of the part, the required material parameters are obtained.

The determination of the relevant parameters is done in three steps. First of all, a list of relevant data available from previous projects is compiled. This list contains references to data that may be relevant for the project. Second, data on experimental investigations on micro and meso scales are collected. This data is mainly used as input for the micro and meso-mechanical simulations by different partners. Finally, the data of experimental investigations on macro level are collected. This data is used for the validation of different simulations. All of the obtained values are finally listed three deliverables and are stored in the DataTool.

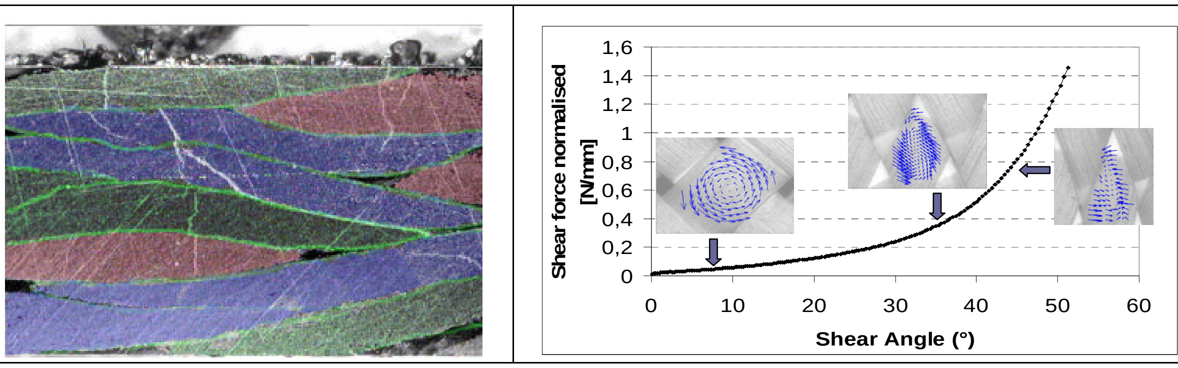

Figure 3: examples of collected data within task 1.2

2.2 WP2: 3M Mechanics

The aim of work package 2 is to develop geometrical models of textile reinforcements on the one hand and mechanical models of textile composites on different levels on the other hand. Using both the finite element method and approximate methods (e.g. method of inclusions) the local stiffness and damage information of materials is in this way predicted.

Three different structural levels are defined on which the models are defined: micro, meso and macro level. On micro (scale of 10 to 100 µm) level the individual fibres inside yarns or fibrous plies of the textile reinforcement are considered. The meso (scale 0.1 to 100 mm) level defines so-called unit cell of textile composites. Finally the macro (0.1 to 10 m) level defines the structural analysis level of a composite part.

The models developed and used in this work package constitute the core of the integrated design tool. They provide crucial information of variability of mechanical properties of the composite material over a part, accounting for anisotropy of the properties and damage initiation/propagation. Work package 2 provides models compatible with and ready to be integrated in structural analysis tools, developed on Macro level in WP5. It also contributes to the description of the textile geometry, to the development of textile process models (WP3) and to the stiffness/failure/impact models (WP4). It uses the materials characterisation data provided in DataTool in WP1.

More details about the work content and the results are summarised in the following task descriptions.

2.2.1 Task 2.1: Geometrical and mechanical models on Micro level

In this task the uneven fibre distribution in yarns and fibrous plies is characterised from experimental observations and generalised in geometrical models of placement of fibres accounting for irregularities of their distribution. The proposed models are implemented in the WiseTex software (figure 4).

In case of yarns or tows it is found that the fibrous content usually decreases towards the edge of a bundle/yarn. The proposed geometrical model of the uneven fibrous content allows accounting for the major features of the experimentally observed microstructure of multifilament stitching yarns or fibrous bundles in woven fabrics. The experimental investigation of stitching sites in non-crimped fabrics shows a considerable distortion of fibres and a significant decrease of the fibrous content near the stitching sites.

The failure and damage behaviour of fibre reinforced composites on micro-level is also investigated within this task. Parameters for failure criteria which are able to take into account three-dimensional loading as well as parameters for the continuum damage mechanics model of Ladevèze are characterised. The different damage and failure models are implemented in subroutines for finite element software.

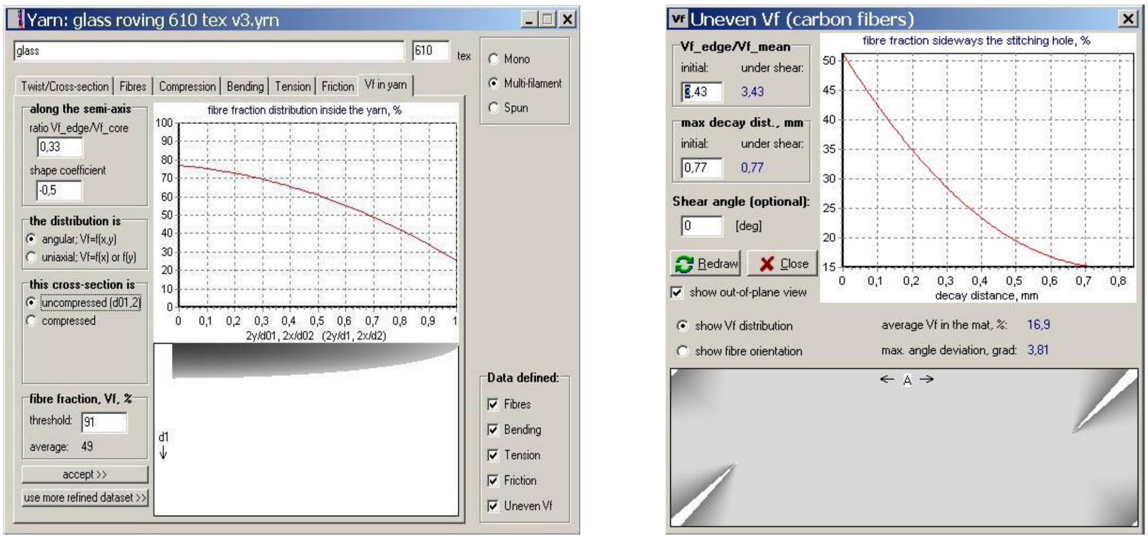

Figure 4: Graphical user interface of the new WiseTex modules for uneven fibre distributions in yarns (left) and fibrous plies (right)

2.2.2 Task 2.2: Geometrical models on Meso level

Geometrical models for both 3d-braids and 'structural' stitches are developed within this task. Samples of both textile architectures are manufactured and used for geometrical and mechanical characterisation. Based on geometrical measurements, models using the WiseTex description are developed (figure 5).

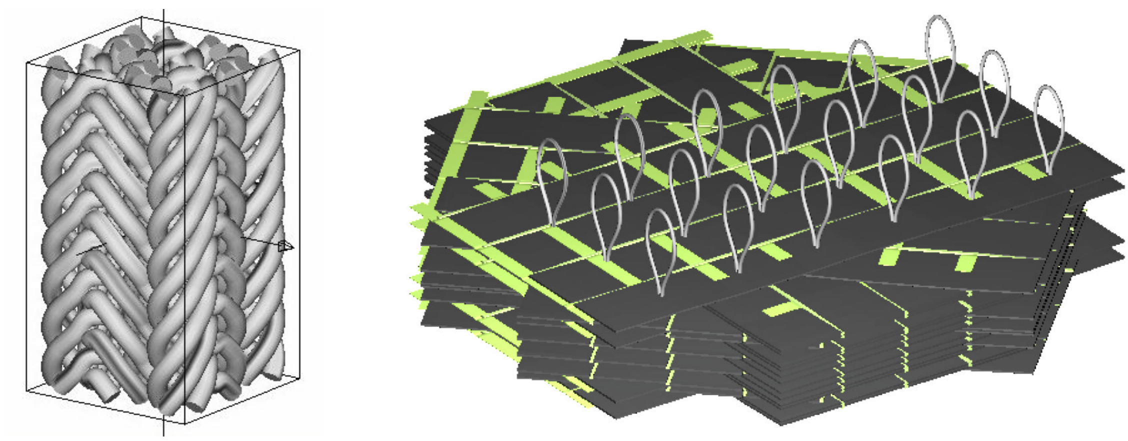

Figure 5: WiseTex geometrical models of a 3d-braid (left) and structural stitching (right)

2.2.3 Task 2.3: Homogenisation: Micro – Meso level:

Based on the damage models developed and implemented within task 2.1, the prediction of damage and decrease of mechanical properties associated to the damage are developed for meso-level. The obtained homogenised mechanical behaviour is compared to the experimental investigations.

Initial damage events are predicted at approximately the same level as observed with acoustic emission measurements. The non-linear stress-strain behaviour of simple test coupons, the strength and ultimate strain are other quantities that are compared for the purpose of validating the model. Moreover microscopic computer tomography investigations of samples at different load levels are used for the validation of the damage pattern.

2.2.4 Task 2.4: Homogenisation: Meso – Macro level

In task 2.4 the homogenisation approach in case of high non-uniformity of internal structure and of stress-strain field is investigated. For multiply composites, a unit cell of one ply is often considered as a representative volume element (due to the computational restrictions). The classical analysis assumes infinite mapping of the unit cell in the out-of-plane direction. However, the meso strain field can be very much perturbed by the free surface. Several evidences are found about the preferential role of the surface layers for the damage accumulation of carbon-epoxy textile composite. The role of the free surface is explored numerically on a representative test problem and advanced homogenisation approaches are developed to take into account the above mentioned problems.

The development of computational and modelling tools is also finalised in this task. A textile perform undergoes shear deformations when shaped into a 3D part. These deformations vary from point to point, changing the local properties of the composite part. The theoretical methods, implemented in software packages (WiseTex), allow calculation of the local stiffness in relation to the local deformation of performs, using meso-level description of the geometry of the unit cell of the reinforcement. The local deformation is predicted via simulation (QUIKFORM), and used together with the output of TexComp in FE packages (SYSPLY) as a material property data. The integrated model is implemented in a new version of SYSPLY software. It allows calculating for composites reinforced by woven or braided fabrics.

2.3 WP3: Process Simulation

Textile raw materials (yarns, tows, roving) lose in strength and stiffness due to friction and bending during processing and manufacturing. The change of these properties influence the draping behaviour of this textile and the mechanical performance of a reinforced part manufactured with the textile. Work package 3 focuses on the simulation of the textile production to get the key information about a pre-cured textile structure (fibre orientations, fibre material properties including fibre-fibre friction). Material data characterised in WP1 and geometrical models developed in WP2 provide input to build models containing this key information. The models are used for further processing. Two important applications where the model is used are selected: the draping behaviour of a textile structure over a predefined geometry and the impregnation behaviour of a resin into a textile reinforced part.

More details about the work content and the results are summarised in the following task descriptions.

2.3.1 *Task 3.1:* Development of concepts for a process simulation for NCF, sewing/stitching, 2D-braiding

Task 3.1 is split into three parts. First, an extensive analysis of textile and textile composite manufacturing processes is performed resulting in a list of key parameters and machine settings which have an influence on the textile material properties. For multi-axial multi-play fabrics, the shear behaviour is analysed. The influence of the stitching process on the deformability is investigated for several textiles.

Second, a ‘virtual manufacturing model’ is developed that takes into account the observed phenomena in the first task. As a result a virtual textile is available including all necessary information (fibre orientations, fibre material properties, fibre-fibre friction) required for further use in other tasks. The ‘virtual textile model’ is a meso-level model based on the meso-model of WP2. The third and final part of task 3.1 consists of validation of the developed models by compassion of experimental and simulated results.

2.3.2 *Task 3.2:* Drapability simulation

Material laws base on experimental observation are developed to represent the deformability behaviour of fabrics. In a semi-discrete approach which is used, the necessary data appears to be the biaxial tensile surfaces and the in plane shear curve. Both of these properties can be determined experimentally of by simulation of the textile deformability (Figure 6)

The developed material models are tested on a benchmark case which forces the draped fabric to significantly deform. Good agreement with experimental observations was obtained. Furthermore the data on the internal structure of the deformed fabric which is deaped on the benchmark part is used for injection simulation in task 3.3.

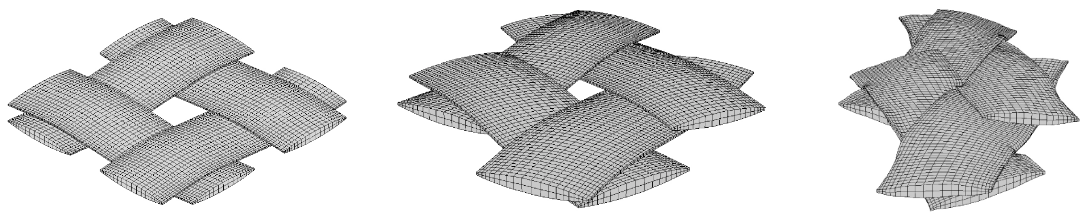

Figure 6: A plain weave textile in undeformed, 27° sheared and 54° sheared deformation.

2.3.3 *Task 3.3:* Mould filling simulation

The objective of this sub work package is to predict the flow of resin while it is infiltrating a textile reinforced part in the mould. Deformation of a textile structure can have a big influence on the permeability hence on the flow behaviour of the injection. A coupling between the draping simulation described in task 3.2 and this task is established.

The finite particle method (FPM) is adapted to perform the injection simulation as it provides solutions for compressible and incompressible flow problems and can be coupled to structural FE codes. An important feature regarding polymer composites manufacturing science is that chemical reactions, heat transfer, temperature dependent viscosity can be handled. To illustrate the potential of the code, the case of numerical permeability prediction of a fabric unit cell has been simulated and compared with existing experimental data.

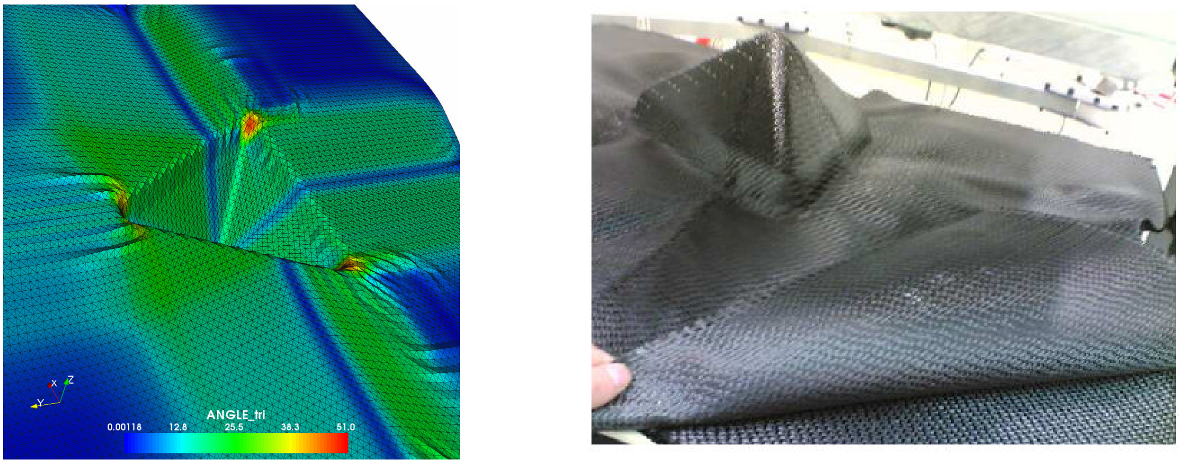

Figure 7: Draping simulation (left) and experiment(right) of a academic validation example.

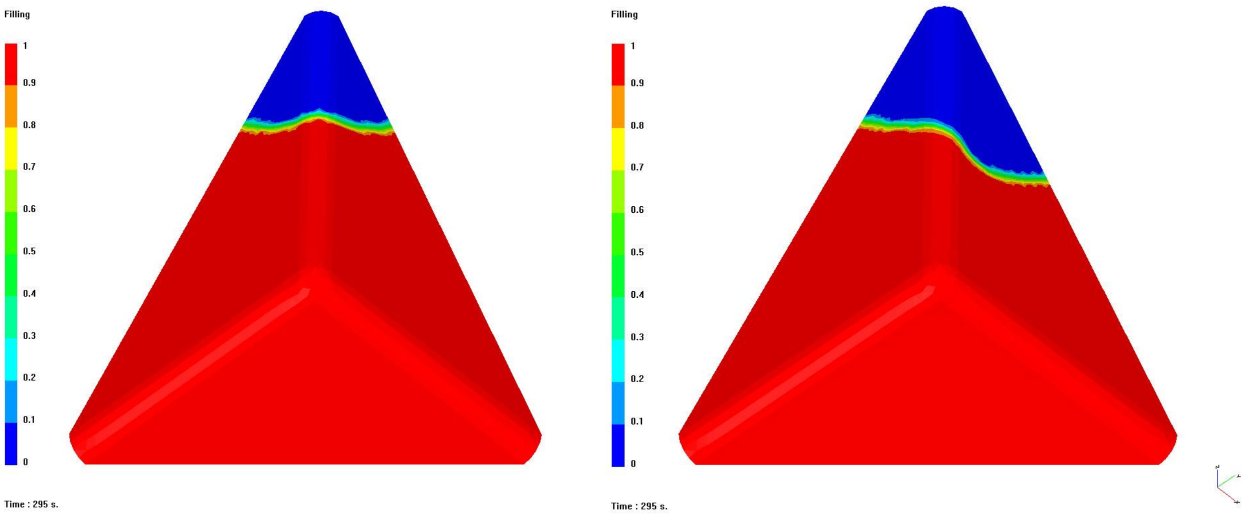

Figure 8: Comparison between the results of an infiltration simulation without (left) and with (right) taking into account draping results (figure 7).

2.4 WP4: External loading behaviour

This work package looks at the complete structure of textile reinforced parts and aims to integrate macroscopic structural deformation, stress and failure modelling into ITOOL. Global analysis methods which compute structural behaviour under external loads will be provided. The developed tools regard static stress, quasi-static failure, crash and dynamic impact computations.

The input properties for the calculations in this work package are extracted from the results of simulations in work package 2 and 3. From the draping simulation performed in work package 3, the fibre orientations are extracted and used for the definition of the mechanical properties. The mechanical properties are determined by meso-scale calculations of a textile reinforced unit cell and homogenisation algorithms.

More details about the work content and the results are summarised in the following task descriptions.

2.4.1 *Task 4.1:* Stress analysis and quasi-static failure criteria

In this task the stress and failure behaviour of tri-axial braids as well as unstitched and through thickness thick NCF reinforced composites is investigated. Multi-level models which are able to predict damage inside the material are set up for the tri-axial braids. The mechanical behaviour of a part manufactured with this material is simulated and tested against experimental investigations. A good comparison could be observed.

A special test rig, based on the Arcan test rig is developed to test through thickness properties of thick laminated structures. This test device is used to test unstitched and through thickness NCF reinforced composites. A failure envelope for out-off plain loading is deduced from the results and is used in macro-level part analysis.

2.4.2 *Task 4.2:* Impact and crash simulation

In task 4.2 the dynamic part of the external loading behaviour is investigated. Damage development under low to high strain rates is investigated experimentally (figure 9) and tool for simulation of the observed behaviour are implemented and validated. Both unstitched and 3D reinforced materials hare investigated.

The obtained material properties are used to simulate the bird impact behaviour of one of the industrial validation examples. Here delamination as well as in-plain failure modes are the focus of the work.

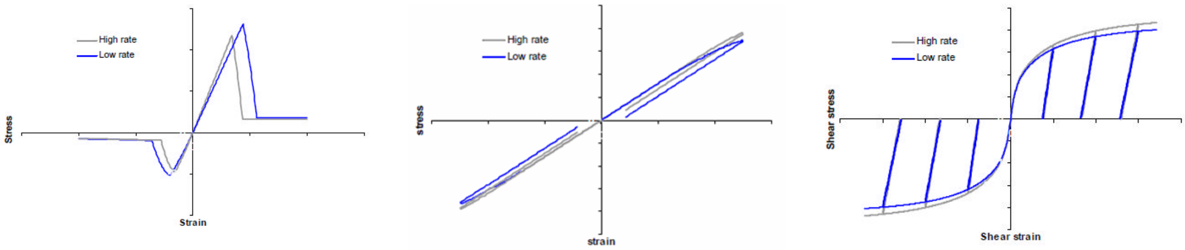

Figure 9: Comparison between constitutive laws at low and high strain rates for fibre (left), transverse (middle) and shear (right) loading.

2.4.3 *Task 4.3:* Assistance for WP6 activities

The relative new nature of the ITOOL developments would require the industrial validation partners to study and learn these tools for the validation of the ITOOL tool chain. This task was planned to provide support to the work package 6 activities and hereby reduce the time required to study the new tools. Manufacturing, testing, modelling and simulation activities are performed for each industrial validation partner.

2.5 WP5: Integration

The main concept of ITOOL focuses on an integrated solution. The integration of the different tools developed in the other work packages or from previous projects is handled in this work package. For a typical analysis of a textile reinforced composite part, two types of data can be determined. Already at the beginning of the proposal it was decided to separate these two types of data and develop different protocols to store them.

The case depended data is data which will change for each new part that is designed. Examples are part geometry and mesh or stacking sequences. This data is stored in generalised data transfer protocols which enable the different tools to exchange this data in this format.

Second there is the case independent data which can be reused for different designs (e.g. material properties). The so called DataTool is developed to store this data in a database like environment.

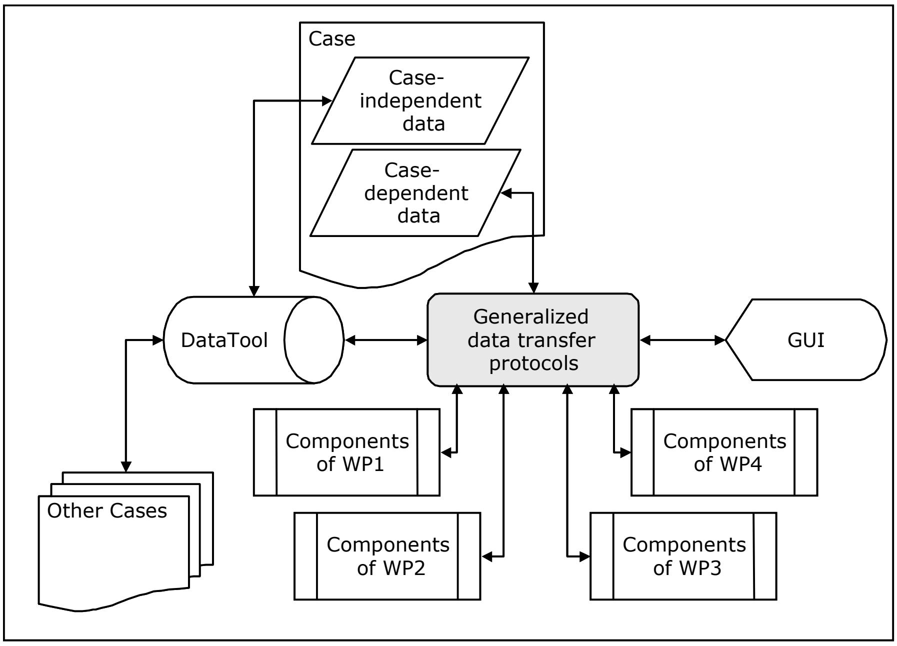

Figure 7.6.5.1 Schematic overview of the DataTool and the general data transfer protocol

More details about the work content and the results are summarised in the following task descriptions.

2.5.1 *Task 5.1:* **Evaluation of the different tools**

A detailed analysis of which data is or will be transferred between the different software tools is performed. Typically each tool that is to be used is analysed by determining all possible inputs an outputs and identifying possible interactions with other tools. As a result not only a list of parameters is compiled but also the data type and the data flow is mapped. The result of this investigation is used for the definition of the data transfer protocols of the case-dependent data and the DataTool for the case independent data.

2.5.2 *Task 5.2:* Data handling

The data transfer protocols (DTP) are carefully designed, using input from WP 5.1, to be able to transfer case dependent data between different tools. The DTP developments are based on the XML standard and are able to transfer the definition of a mesh (nodes, elements, edges and faces), load and boundary condition descriptions as well as results (fields). Different steps are defined in the DTP:

1. Mapping: This step enables the mapping of data between different meshes. For instance the results from a draping simulation may be stored in a highly distorted mesh whereas a good quality mesh is required for the later mechanical analisis.
2. Transfer: This steps enables the transfer of data between nodal and integration point quantities.

3. Variable scaling: This step enables the modification of units as different partners may be using other unit systems.

A second development within this task is a data format (DataTool) for storing the case independent data (typically material data). Also here it as chosen to develop a file format based on the XML standard. The data is divided in

1. Constituent: basic material used as an element to a global set. This can include epoxy resin, foam, Yarn.
2. Reinforcement: fibrous part in which the filaments are arranged in a particular way to achieve the desired result. This can include braided, stitched, woven fabrics, mats, rovings, UD.
3. Ply: Materials obtain by combination between reinforcement and a constituent. This can include UD fibre and epoxy resin, ceramic fibre and metallic matrix component of a laminate.
4. Laminate: A product made by bonding together ply or constituent like foam or honeycomb in order to form a single part.

2.5.3 *Task 5.3:* Design of the DataTool and a graphical user interface for ITOOL

A graphical user interface for both the data transfer protocols (figure 10 and figure 11) and the DataTool (figure 12). These tools enable the future users to easily handle the two developments of task 5.2 and ensure data integrity. Within the project mainly the features that are required for the industrial validation examples are supported. However, the tools are developed in such a way that they are expandable and can be easily enriched with new features.

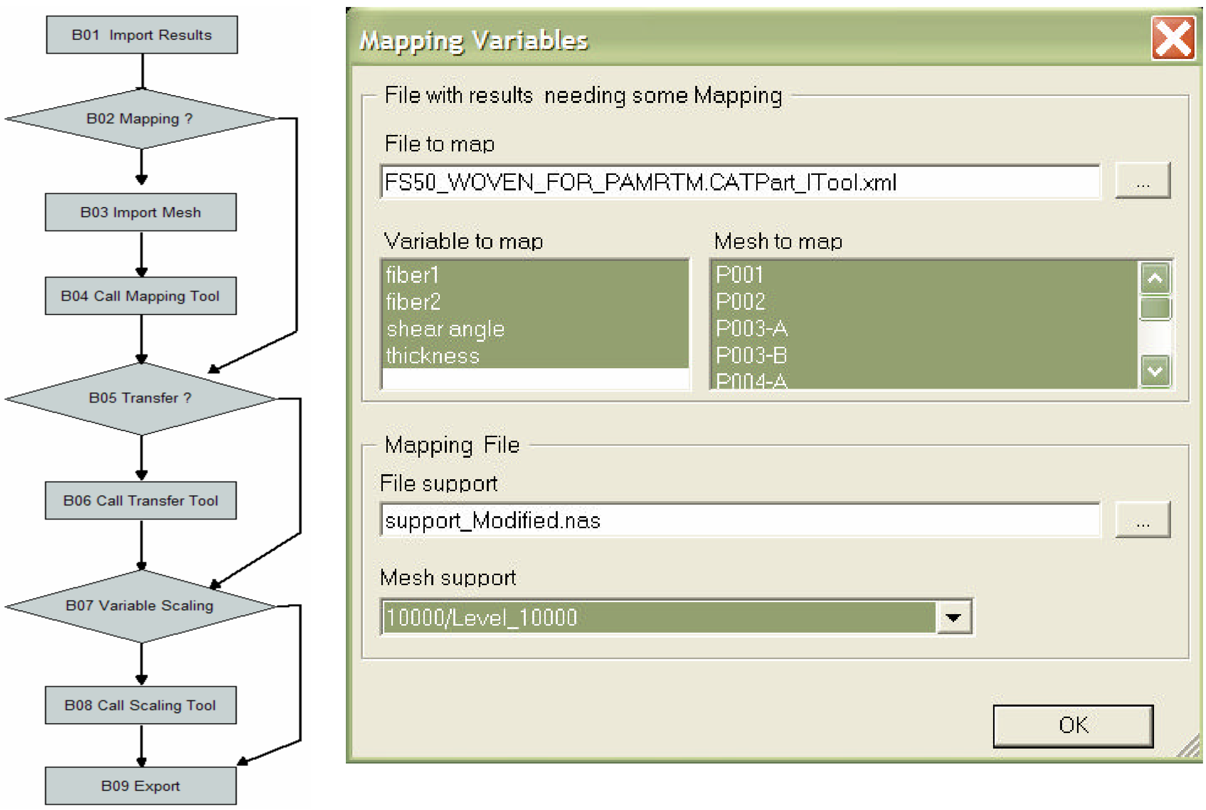

Figure 10: Left: A graphical representation of the steps in the data transfer protocols. Right:

graphical user interface of the mapping step in the data transfer protocols.

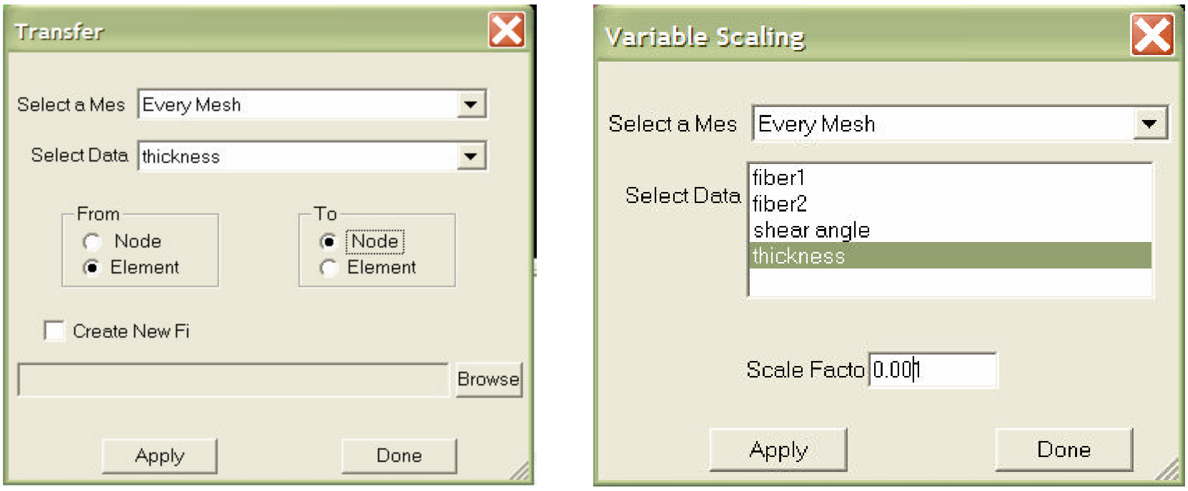

Figure 11: Left: graphical user interface of the transfer step in the data transfer protocols. Right: graphical user interface of the variable scaling step in the data transfer protocols.

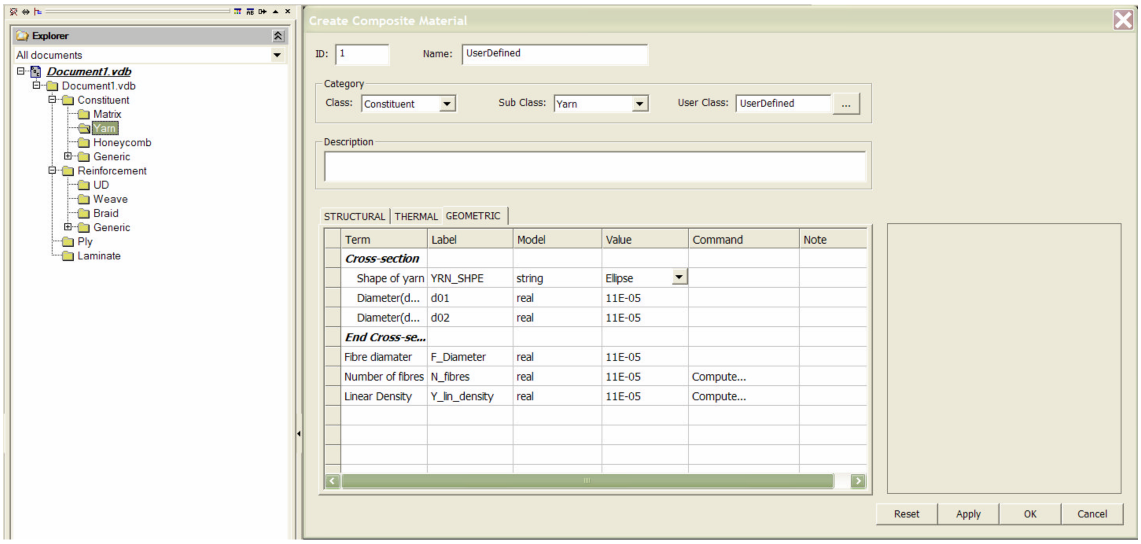

Figure 12: The graphical user interface of the DataTool

2.6 WP6: Industrial validation / Test

This WP6 intends to provide test cases for the "industrial" acceptance of the integrated simulation tool developed in the other work packages. The goal is to test the whole simulation chain, including the simulation of the textile production (creation of the "virtual" textile), the prediction of meso/macro properties, the drapability behaviour, the impregnation and FE-analysis of the finished composite part. A comparison between the manufacturing (including testing) and the whole process and mechanical simulation will be performed. The main technologies of textile production as braiding, stitched material including non crimp-fabrics and fibre placement will be investigated.

The goal of the defined test cases is to become the basis of an "industrial" acceptance methodology for future improvements or upgrades of the developed simulation tool.

More details about the work content and the results are summarised in the following task descriptions.

2.6.1 *Task 6.1:* Specification of test cases

In order to test different developments of the ITOOL project, the industrial partners have selected complementary examples. As soon as the project started the validation examples are defined and for each of them the following features are defined:
a description of the different parts to be manufactured (material, technology, structure…),
the kind of mechanical tests to be lead on the defined parts and
the ITOOL tool chain to be performed for each part (both process and mechanical simulations).

A graphical representation of the three validation examples is shown in figure 13.

Figure 13: Graphical representations of the three industrial validation examples

2.6.2 *Task 6.2:* Manufacturing of the parts and testing

Based on the information coming from 6.1 the activities in this task vary for each validation example. Basically three kinds of activities can be distinguished. First, a set of basic material tests each material used in the validation example is performed. This task is required to characterise the materials used in the validation examples. Second, the industrial validation parts are manufactured and different properties are determined during or after the manufacturing. This includes infiltration, draping and mechanical characteristics. Finally the mechanical performance of the parts is determined. Buckling and bird impact behaviour are investigated here.

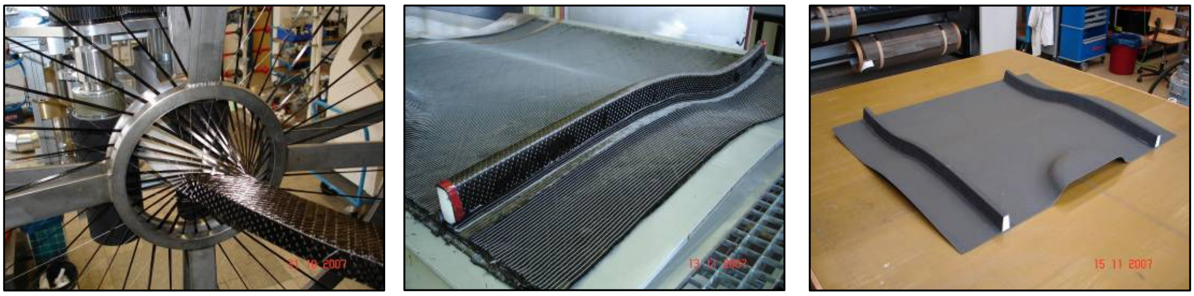

Figure 14: Manufacturing steps for the EADS-G validation example

In this task, the industrial partners are supported by other partners as previously described in section 2.4.3.

2.6.3 Task 6.3: Tool chain proof on defined test cases

The aim of task 6.3 is the testing of the whole simulation chain and validating it against experimental results. For each industrial partner the ITOOL chain is validated on three levels: First, simulations on the basic material test enable to validate developments issued from work package 2, 3 and 4.
Second, a feature of the part manufacturing process is simulated and validated against its experimental counterpart.
Finally, a validation of the mechanical performance prediction is validated.

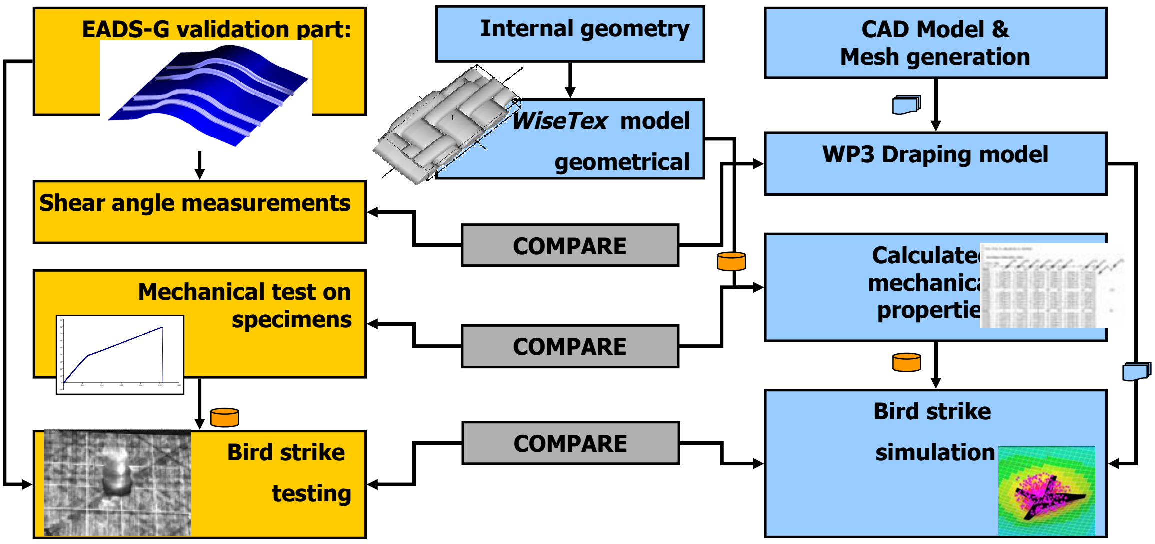

Figure 15: Graphical representations of the three industrial validation examples

2.6.4 Task 6.4: Cost benefit analysis

To evaluate the benefit of the ITOOL developments against up to now standard approaches, a cost-benefit analysis is performed. The analysis is based on the industrial validation examples and is performed on cost and effort levels. For all three validation examples the ITOOL approach has shown a benefit in both cost (between 4% and 60%) end effort (between 15% and 70%).

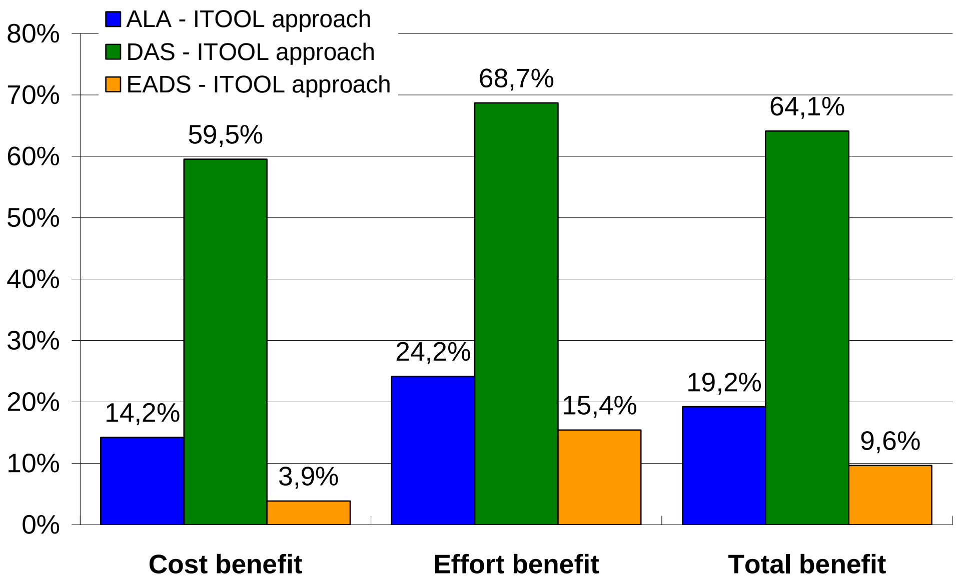

Figure 16: results of the cost benefit analysis for the three industrial validation examples.

2.7 WP7: Design guidelines / Standardisation

The optimum design and cost effective manufacturing of textile structural composites requires a lot of knowledge on the factors of influence. At the early phase of development the designer has to know
which basic textile process is the best for the specific structure,
which limitations have to be taken into consideration and
which detailed parameters lead to an optimum weight saving.

Work package 7 tries to generate design guidelines, design diagrams and "rules of thumb", based on the work done within the ITOOL project and are intended to help future engineers to design with textile reinforced composite materials.

More details about the work content and the results are summarised in the following task descriptions.

2.7.1 Task 7.1: Definition of structural elements

In order to structure the magnitude of information, characteristic sub-structures that can be manufactured using textile reinforced composites are identified. The sub-structures identifies are: shells and panels (flat, 2d curved or 3d curved), profiles, box structures, interfaces and joints, overlapping linear joints (riveted or bonded), fittings and cut-outs.

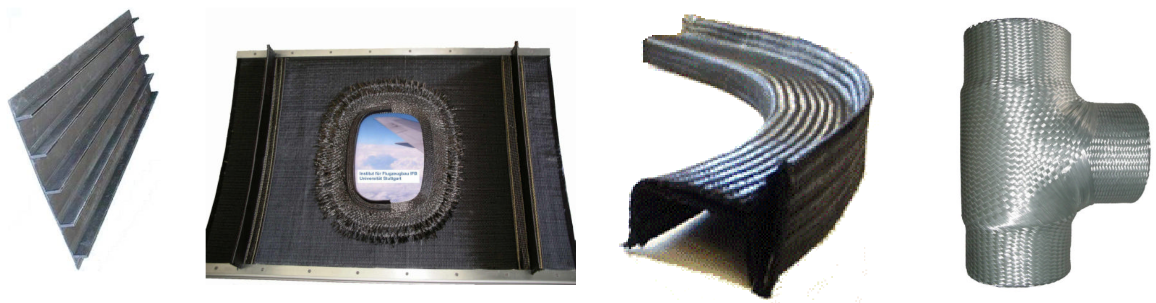

Figure 17: a selection of the identified structural elements. From left to right: panel with jointed profiles, cut-out, profile, joint element.

All characteristic elements that are used in the industrial validation examples are included for the further investigation in work package 7.3.

2.7.2 Task 7.2: Potential and limitations of textile processes

The state-of-the-art for the textile processes are investigated with the aid of literature studies and own experience of partners. The following processes, which are used in the industrial validation examples, are investigated: non-crimp fabrics, robot assisted braiding, stitching and textile fibre placement (embroidery). For each of them the possibilities and limitations are listed and described in deliverable D7.2.1.

2.7.3 Task 7.3: Development of design guidelines

The goal of task 7.3 is to show procedures how to design the basic elements which were proposed in task 7.1 with the processes described in task 7.2. The basis for the determination of optimum design is the use of optimisation techniques with gradient and generic algorithms. From the results of the optimisation calculations engineering design criteria and rules of thumb are deduced and summarised in deliverable D7.3.2.

2.7.4 Task 7.4: Evaluation based on realistic applications

The partners which manufactured the industrial validation parts tried to evaluate the design guidelines fro task 7.3 based on their part. The applicability of the rules is tested and remarks/comments are collected and described in deliverable D7.4.1.

2.7.5 Task 7.5: Standardization

Content of this work-package is to derive and generate the basis and philosophies for defining standards for test procedures and textile processes. Since textile composites offer a high degree of freedom in respect to fibre architectures and production methods the effort for material testing, accreditation, quality control and simulation is high for this kind of materials. Based on the experience within the ITOOL project and the evaluation of the produced tools and parts standards are proposed within this task.

2.8 List of deliverables

The list of deliverables is given in **Error! Reference source not found.**.

Table 5: Deliverables list WP1

Del. no	Deliverable name	Lead contractor
D1.1.1	Relevant Data	ITA
D1.2.1	Requirements for DataTool	ITA
D1.3.1	List of available data	ITA
D1.3.2	Data at mesoscopic and microscopic scale	ITA
D1.3.3	Complete data	ITA
D2.1.1	Model of fibre placement on micro-level	KUL
D2.1.2	Model of damage on micro-level with parameters identified from experiments	DLR
D2.2.1	Geometrical model of architecture of 3d braids implemented in FEA and WiseTex	ZARA
D2.2.2	Geometrical model and architecture of structural stitching implemented in WiseTex	KUL
D2.2.3	Validation of the geometrical models of 3D braids	ZARA
D2.2.4	Validation of the geometrical models of structural stitching	KUL
D2.3.1	Model of damage initiation and development on meso-level	KUL
D2.3.2	Validation of damage models on meso-level	EADS-G
D2.4.1	Theoretical formulation of homogenisation on meso-level for high non-uniformity of stress-strain fields	KUL
D2.4.2	Validation of the meso-mechanical stiffness models for high non-uniformity of stress-strain fields	KUL
D2.4.3	Computational tools implementing the 3M models and integrated with Macro-analysis	KUL
D3.1.1	Models of deformability of non-crimp fabrics, of the stitched reinforcements and of internal geometry of deformed stitched reinforcement	KUL
D3.1.2	Definition of the influence of different machine settings on the characteristics of a textile	ITA
D3.1.3	Geometrical description of the positions of fibres and stitches of different textiles including open and closed structures.	ITA
D3.2.1	Identification of meso-macro mechanical behaviour laws used in the fabric finite element approach developed for fabric forming simulations.	LAMCOS
D3.2.2	Specific meso-macro finite element for dry textile forming.	LAMCOS
D3.2.3	Report including modelling and validation of dry fabrics forming.	EADS-F
D3.3.1	First version of a numerical model for the prediction of permeability	ESI
D3.3.2	Numerical model of prediction of permeability	ESI
D3.3.3	Injection modelling and validation of deformed dry fabrics.	EADS-F
D4.1.1	Final version of software tools for quasi static failure	DLR

Del. no	Deliverable name	Lead contractor
D4.1.2	Final report on validation of homogenisation	EADS-G
D4.1.3	Final report on experimental validation tests and FE stress and failure analysis	DLR
D4.2.1	Preliminary version of software tool for dynamic failure analysis	CRAN
D4.2.2	Final version and final technical report on validation of software tool for dynamic failure analysis	CRAN
D4.2.3	Final technical report on crash simulation and failure studies	SISPRA
D4.3.1	Final report on supportive activities to WP6	DLR
D5.1.1	Analysis of the data used and produced during a composite analysis	ESI
D5.2.1	Data and transfer protocol	ESI
D5.3.1	GUI	ESI
D6.1.1	Test case definition	DAS
D6.2.1	Coupon testing	DAS
D6.2.2	Manufactured and tested “industrial” parts	DAS
D6.3.1	ITOOL tool chain proof	DAS
D6.4.1	Cost benefit analysis	DAS
D7.1.1	Basic elements requirements	IFB
D7.2.1	Performance catalogue	IFB
D7.3.1	Design guidelines	IFB
D7.3.2	Basis for handbook chapter	IFB
D7.4.1	Guideline Evaluation	IFB
D7.5.1	Standardization philosophies	IFB

3 Degree to which the objectives where reached

Objective: reliable simulation tools and design principles

Within the ITOOL project it was chosen to use integrate existing and newly developed tools which have been extensively tested against experimental benchmark cases. Also within the project a large amount of effort was put into experimental work for validation purposes.

Objective: simulation along the process line with a virtual manufacturing chain.

Taking into account the prediction of textile deformations during draping processes and linking the results from there simulations to predictions or permeability and mechanical properties a simulation along the process line is established. Moreover the tools are organised in such a way that other features that have not been taken into account during the project can easily be integrated.

Objective: development of an adequate integrated simulation tool

The integration of the existing and newly developed tools have led to reliable simulation tools and design principles which are able to handle composites reinforced with 3d fibre architectures. The linking and integration of exiting tools ensures a fluent interaction and data interchange with minimum friction and without critical data loss. Furthermore a graphical user interface is developed to minimise user interference.

Objective: consider braiding, weaving and stitching technologies

The performance of textiles and textile reinforced composites is analysed on three different approximation levels called 3M (micro / meso / macro) mechanics. This approach enables to consider many different kinds of textile architectures as all of them can be assembled from the basic building blocks. Newly developed tools enable geometrical and mechanical descriptions of braiding, advanced engineering textiles, weaving and stitching textile preforming technologies.

Objective: improve properties in the thickness direction with stitching technologies

Different though thickness reinforcement technologies where investigated. New modelling tools are developed that enable the analysis of such materials. Via optimisation algorithms ideal stitching configurations could be determined. These results where experimentally validated.

Objective: proof for this integration concept and benefit of cost and effort

The integration concept is validated for different application fields of textile preformed composites in Aerospace. Typical stiffened skin sections with integral joining technologies are evaluated. The use of the ITOOL approach has shown to provide a reduction of in 4% to 60% of costs and a reduction of 15% to 70% of effort for the industrial validation examples.

Objective: extraction of design rules for the use of textiles as composite reinforcement

Physical understanding of textile preformed composites behaviour is obtained during the project and is summarised in design rules. Many of the obtained results have been disseminated on conferences and in international journals.

4 Achievements of the project related to the state of the art

4.1 State of the art before project start

Most ***preforming technologies*** are well-known in the textile industry and have reached a ***high level of automation***. By this, ***a cost-effective manufacturing*** of fabrics and apparel has been established.

The idea of ***adapting the technologies of braiding, weaving and stitching*** for reinforcement of composites started in the 80's and was improved mainly in the late 90's. The ***problems to be solved*** have been ***fibre damage,*** due to the stiff and brittle fibre behaviour, ***friction, fibre waviness, drapability and infiltration*** and the minor decrease of in-plane ***mechanical properties*** of textile preformed composites in comparison with unidirectional prepregs.

Meanwhile ***dry fibre textiles have passed the prototype stage*** and are available for application. Many of the basics have been developed in National and CEC funded research projects such as INTEX, MULTEXCOMP or COBRAID. The main results of the related research activities are that:

textile structural composites have proven their ***high potential for automation and cost reduction*** in the manufacturing of high performance composites,

3d-reinforcements, especially realized by stitching, have proven a high potential for ***improve damage tolerance, structural integrity and energy absorption*** without significant reducing in-plane performance,

several ***series applications*** are in development making use of stitched textile preforms (for example Airbus A380 pressure dome, Boeing wing-structures and Mercedes SLR crash structures)

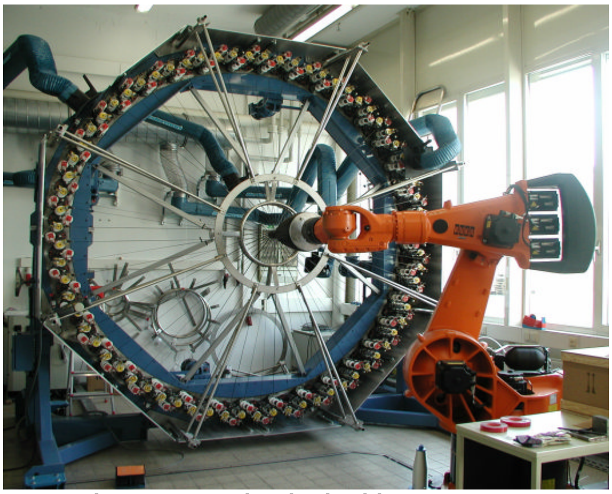

Figure 4.1.1: Circular braider at EADS-G

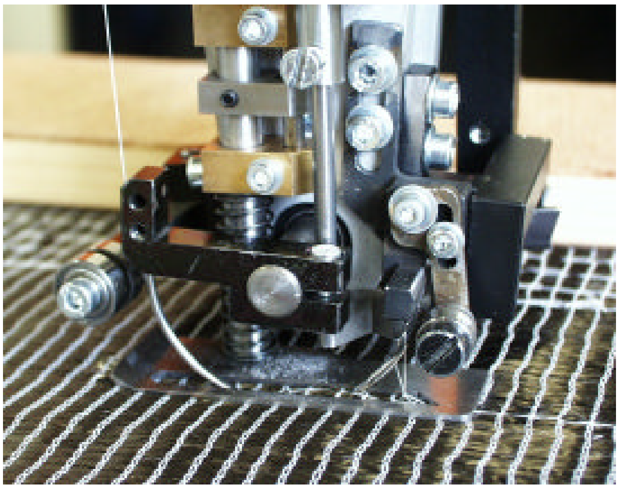

Figure 4.1.2: Stitching of a textile preform

However, ***only basic principles for simulation and calculation*** as well as only ***limited understanding of principles and mechanics*** of these techniques are available. Most of the theories and finite element implementations for composite materials are based on simple unidirectional homogenisation methods of fibre and matrix properties; strength prediction is done only plywise. For ***3d fibre architectures*** homogenisation of voxel-type representative volume elements (RVE) has shown promising results, whilst ***failure prediction*** is much more difficult due to nonlinearities like friction behaviour of cross-over points, complex 3d fibre-matrix interactions.

For parts of the regarded simulation chain, including manufacturing and loading stage, ***stand-alone solutions are already available*** resp. in development phase, e.g. PAM-FORM™ or WiseTex®. But, up to now, ***communication and data handling*** between these tools ***is not harmonised*** so that a fluent exchange of data is not possible.

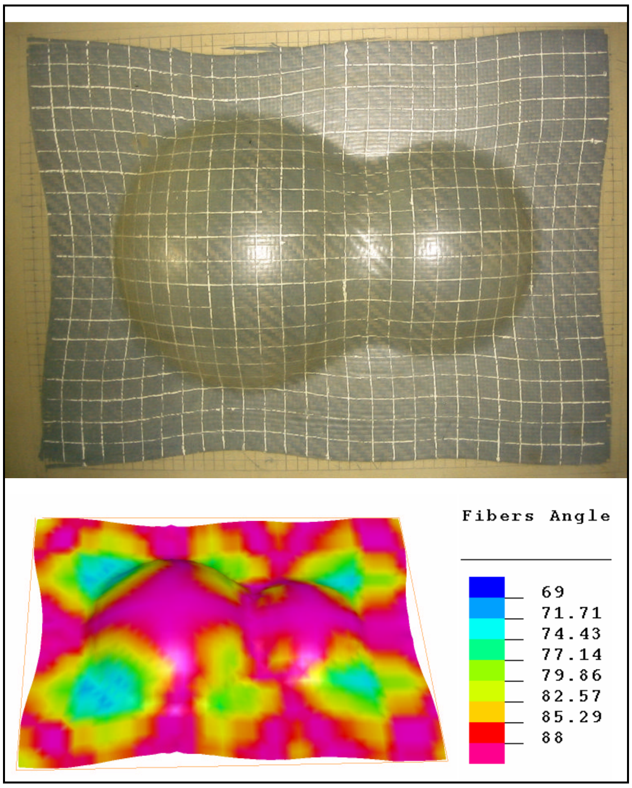

Figure 4.1.3: Simulation of fibre reorientation due to draping process

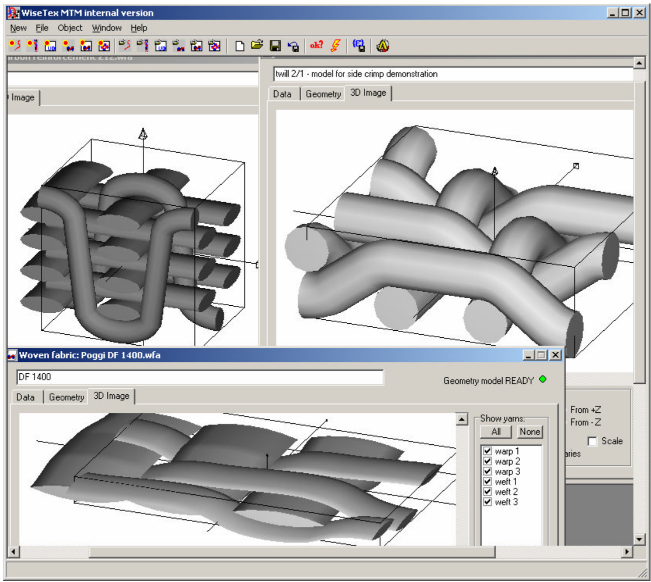

Figure 4.1.4: Modelling of textile preforms with WiseTex® software

Furthermore, the ***know-how on manufacturing*** (draping, tooling and impregnation) of integrated, complex-shaped preforms is ***only limited***. This results in ***large numbers of product development iteration loops*** and, furthermore, in an ***extensive testing effort*** necessary for qualification of dry fibre textiles, limited always to one single configuration.

The aim of ITOOL is to ***eliminate the gaps between the potential in application and the understanding and analysis of textile preformed composites***. To enable the design engineer to take advantage of these types of materials, ***practical guidelines*** like the HSB (Handbuch Strukturberechnung), widely used in Aerospace construction and analysis of metals and unidirectional reinforced prepregs, are further missing prerequisites to be worked out in the proposed project by ***collating available information in documents and educational tools***.

4.2 Achievements of the project

Whereas the technologies for the manufacturing of textile reinforced composite parts have been continuously improved in the past, flexible and qualitative methods for the analysis of these materials and their parts are difficult to find if yet not been developed. Within the ITOOL project a multi-level approach for the simulation of different aspects of textile reinforced composite material is developed.

Detailed geometrical models that represent 3d fibre architectures are developed and are used as a base to generate finite element models that enable the analysis of infiltration and draping processes as well as detailed analysis of the mechanical performance including failure, damage and high strain rate behaviours. Advanced homogenisation methods are adapted to predict average properties that can be used for part analysis.

The developments in work package 5 have lead to a first integration of different existing tools by the development of the data transfer protocols and the material data base (DataTool). These techniques enable a fluent communication between the previously existing tools.

Many of the features developed in the project have been validated against experimental investigations on industrial validation examples. For most of these features good compliance was obtained.

Basic structural elements as well as key manufacturing methods are identified and design guidelines and rules of thumb are set-up based on their evaluation. The know-how and obtained experience during the project was collected in a document that is intended for possible standardisation of textile reinforced composite features.

The cost benefit analysis described in task 6.4 has shown that the ITOOL approach is effective in terms of costs and effort and hence it is proven that further developments of the ITOOL features are definitely worth while.

5 Dissemination and use

5.1 Exploitable knowledge and its use

Table 6 shows a list of exploitable results that where obtained within the ITOOL project. A more detailed description and some comments are given in the description below the table.

Table 6: Table of exploitable results

Exploitable Knowledge (description)	**Exploitable product(s) or measure(s)**	**Sector(s)** of application	Timetable for commercial use	Patents or other IPR protection	**Owner** & Other Partner(s) involved
1. Effect of stitching on permeability	Permeability measurements	Aeronautics (composites processing)	2 years	N/A	**DAS**
2. Numerical prediction of permeability	ESI software	Aeronautics (composites processing)	2 years	IPR by ESI	**ESI**
3. New multi-scale analysis method for textile 2d-braid composites	Algorithm	Aeronautic Structures	1 year	Restricted to a group specified by the consortium (including the Commission Services)	**ALA**
4. Data Exchange Procedure	Software	Advanced Composites Industry	1 year	IPR by ESI	**ESI**
5. Composite Material Data Manager	Software	Advanced Composites Industry	1 year	IPR by ESI	**ESI**
6. Numerical prediction bird impact on textile composite plate	PAM-CRASH models	Aeronautics (composites processing)	3 years	N/A	**SISPRA**
7. Multi-level modelling approach for textile reinforcement of aeronautic structures	Software & methodology	Aeronautics	5 years	N/A	**EADS-G** **KUL**

Exploitable Knowledge (description)	**Exploitable product(s) or measure(s)**	**Sector(s)** of application	Timetable for commercial use	Patents or other IPR protection	**Owner** & Other Partner(s) involved
8. New modules for WiseTex	Software + database on experimental results	Composite industry and academics	>5 years	IPR by KUL	**KUL** ZARA EADS-G ESI
9. Draping model for textiles	Software+ database on experimental results	Composite industry and academics	> 5 years	IPR by LaMCoS?	**LaMCoS** EADS-F
10. New and enhanced damage models for textile composites	Software+ database on experimental results	Composite industry and academics	3 years	N/A	**KUL** **EADS-G**
11. Dynamic characterisati on of textile composites	Database of experimental results	Academic	3 years	N/A	**CRAN**
12. Out of plain mechanical properties	Database of experimental results	Academic	5 years	N/A	**DLR**
13. Design procedures	Documents	Academic	5 years	N/A	**IFB**

Exploitable result 1: Effect of stitching on permeability. Stitching is one of the methods employed to attach preforms together and ease their placement into a tool. However, during an infusion process, it is key to take into account the effect of these features, especially on the permeability.

Exploitable result 2: Numerical prediction of permeability. Permeability is a critical parameter in an infusion process and needs to be known previous to any manufacturing in order to ensure the success of the part. However, experimental measurements of the permeability are time and cost consuming. The availability of a numerical tool to predict this parameter is a huge benefit when using this technology.

Exploitable result 3: New multi-scale analysis method for textile 2d-braid composites. ALA jointly with University of Salerno – (DIMEC) Mechanical Engineering Department developed a multi-scale dedicated algorithm for the validation of a failure model for 2D tri-axial braided composites. Specific subroutines have been developed for calculation of the global behaviour of a tri-axial braided test specimen, modelled as a 2D structure, starting from the component characteristics of the composite. The software developed to predict mechanical properties of composite materials minimizing experimental testing support with considerable saving costs.

Exploitable result 4: Data Exchange Procedure. This exploitable result is software which ESI Group will commercialise in the near future. The software will be licensed on a yearly basis by ESI Group. The software was already shown at SETEC 07 and at the ITOOL special session organised at EUROPAM 2008. It was very well received and confirmed that ESI will commercialise it. Additional work will be necessary to augment the capabilities of the software. Additional research will be needed to offer good quality transfer of physical data from one location (nodes, Gauss points, elements, etc) to another.

Exploitable result 5: Composite Material Data Manager. The exploitable result is software which will be commercialised by ESI group in the near future. The software will be licensed on a yearly basis by ESI Group. The software was shown at SETEC 07 and at the ITOOL special session organised at EUROPAM 2008. It was very well received and confirmed the ESI will commercialise it. Additional work will be necessary to augment the capabilities of the software; for instance, storage of test results. Additional research will be needed to offer procedures to transform experimental results into material data for simulation.

Exploitable result 6: Numerical prediction bird impact. An extensive understanding of the damage modeling approach for stiffened panels was obtained during the simulation of the bird impact. An extensive database with simulation input properties is available and a good understanding of the innovative smooth particle hydrodynamics (SPH) method is obtained. For future simulation of bird-impacts the same technologies can be used.

Exploitable result 7: Multi-level modelling approach for textile reinforcement of aeronautic structures. Software routines for the geometrical and finite element modelling of textiles and textile reinforced composites have been developed and are available for use. The increasing interest of aeronautics industry for textiles as reinforcement material will definitely result in the use of these developments for future design of 0composite parts.

Exploitable result 8: New modules for WiseTex. New modules to generate models of through thickness structural stitching as well as three dimensional braiding have been developed by KUL and ZARA. These modules are currently still in development stage, but are intended to be implemented in the commercial version of the WiseTex software suite in the near future. A database with results is also obtained from the different experiments that have been performed to validate the software tool.

Exploitable result 9: ***Draping model for textiles***. An advanced mechanically based draping model has been developed by LaMCoS and EADS-F which enables prediction of fibre distortions of the textile due to the draping process. A database with results is also obtained from the different experiments that have been performed to validate the software tool.

Exploitable result 10: New and enhanced damage models for textile composites. Newly developed damage models as well as damage models specially modified for textile composites have been developed during the project. Most of them are still on a academic level and require further developments to be applied on an industrial scale. A database with results is also obtained from the different experiments that have been performed to validate the software tool.

Exploitable result 11: Dynamic characterisation of textile composites. A large amount of dynamic experiments was performed on different types of textile reinforced composite material. The results of these experiments are stored in a database and are available as input for future simulations or validation data.

Exploitable result 12:. Out of plain mechanical properties A new test rig was developed to test the mechanical properties of composite materials with out-of-plain load components. Experiments where performed on non- and through thickness reinforced material. The results of these experiments are stored in a database and are available for future use.

Exploitable result 13: Design procedures. The gained experience of different partners and information found in literature are combined in a set of design procedures. Especially the developed optimization approach using FEM codes in combination with effective optimization procedures offers a potential for usage in the academic sector. The documents are available for each partner and can be used in the future to improve the performance or reduce the design time of newly designed parts

5.2 Dissemination of knowledge

5.2.1 Publications

All partners presented their results on conferences or in international or national journals. In this way the results of all work packages is disseminated. University partners have the major part of the publications. Apart from publications in conferences and journals, Masters' and Ph.D. theses contain important findings and results of the project. A summary of the publications is shown in

table 7 whereas a detailed list of the publications can be found in the references (chapter 6).

Table 7: Overview of the different ITOOL publications

Type of publication	Type of audience	Amount
Conference paper	Higher education / industry	34
Journal paper	Higher education / industry	13
Workshops	Higher education / industry	3
Poster	Higher education	1
Project website	General public	1

5.2.2 Workshops

Two workshops are organised and have been held which present the results of the ITOOL project.

1. ***SAMPE Europe***. This workshop took place on April 2nd 2007 during the SAMPE European conference. A full session was dedicated to the project with five presentations on ITOOL results.
2. ***EUROPAM***. This workshop took place on may 30th 2008 during the EUROPAM conference. A full session was dedicated to the ITOOL activities.

6 References

6.1 Journal papers

1. Boisse, P., B. Zouari, and J.L. Daniel Importance of in-plane shear rigidity in finite element analyses of woven fabric composite preforming. Composites A, 37-12, (2006), 2201-2212
2. D.S.Ivanov et al 3-axial braided carbon-epoxy composite: Internal geometry, stiffness, damage and FE modelling, *Comp A*
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