

National Composites Network

Best Practice Guide

Design Tools for Fibre Reinforced Polymer Structures



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BEST PRACTICE GUIDE ON DESIGN TOOLS FOR FRP STRUCTURES

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GLOSSARY

CLT	Classical Laminate Theory
CSM	Chop Strand Mat
DMC	Dough Moulding Compound
FE	Finite Element
FEA	Finite Element Analysis
FoS	Factor of Safety
FPF	First Ply Failure (typically resin cracking between fibres not in the main loading direction)
FRP	Fibre Reinforced Plastic
ILS	InterLaminar Shear
MoS	Margin of Safety
PVC	PolyVinyl Chloride
RF	Reserve Factor
RTM	Resin Transfer Moulding
SE	Symmetric Even
SMC	Sheet Moulding Compound
UD	Uni-Directional
UPF	Ultimate Ply Failure
Hygrothermal properties	Thermal and hygric properties of the constituents.
Failure index	Ratio of applied stress over ultimate or allowable strength
Micromechanics	Structural analysis at the microscopic level (i.e. fibre/resin interaction)

NOMENCLATURE

[D]	Flexural stiffness matrix of a laminate
E	Young's Modulus
F	Applied force
G	Shear Modulus
P	Applied pressure
a	Plate length
b	Plate width
h	Laminate thickness
M_x, M_y, M_{xy}	Laminate resultant moments
N_x, N_y, N_{xy}	Laminate resultant in-plane forces
Q_x, Q_y	Transverse resultant shear forces
T	Temperature
u, v, w	Displacements in the x-, y-, and z-directions of the laminate coordinate system
x, y, z	Laminate coordinate system
ϵ	Direct strain
γ	Shear strain

κ	Curvature
ν	Poisson's ratio
1	Main fibre direction
2	Transverse fibre direction
3	Through thickness direction

1. INTRODUCTION

1.1 BACKGROUND

The analysis and design methods for composite structures are considerably more complex than those for their metallic counterparts. This is due to the large number of different materials available and to the anisotropic nature of typical composite materials. Several composite design tools have been developed with the aim of automating calculations for standard composite structures. Identifying the most appropriate tool for your requirements is essential but can be confusing and time consuming.

1.2 PURPOSE AND SCOPE

The objective of this best practice guide is to help composite design engineers to identify and select the best design tool set for their needs. This document is geared to small and to medium enterprises involved or interested in composite materials. It is divided into two main sections.

- a. In the first part, the contribution that composite design tools can make during the design process is described. This is done by briefly presenting the different families of software available today and describing their purpose and philosophy.
- b. The second part of the guide focuses on laminate and analytical design tools developed to carry out preliminary/concept design analysis and design of specific structural elements. Benchmark studies have been run using demonstration versions of several software products. The aim of the benchmark studies is to demonstrate the capability and support provided by analytical design tools. The examples presented are simple as they have been selected with the focus of presenting key issues of composite design.

This document provides general information on design tools and highlights key points to look at and be aware of when selecting or using composite design tools. It is not intended to promote any specific software as each product on the market is likely to suit different needs. Several software products are mentioned within this guide for information purposes. It is essential to understand that the list provided is not exhaustive.

1.3 DISCLAIMER

Information and advice in this document is provided in good faith and is based, where appropriate, on the best engineering knowledge available at the time. No warranty expressed or implied is given regarding the results or effects of applying information or advice obtained from this document, nor is any responsibility accepted for any direct or consequential loss or damage.

2. COMPOSITE DESIGN SOFTWARE: A TOOL FOR DESIGNERS

2.1 HOW CAN DESIGN TOOLS SUPPORT THE DESIGNER?

For the designer, FRP structures are a challenge due to the wide range of design variables. Design is typically an iterative process where applicable materials are identified, candidate laminates created, their performance studied and modified as needed. The use of design tools speeds up the design process and allows investigation of several possible concepts in order to define the optimal solution. Without design

software the process can become time consuming and a satisfactory but non-optimal solution is often selected.

2.2 IDENTIFYING THE DESIGNER'S NEED

Before selecting a design tool, it is essential that the designer identifies their need. This will be highly dependant on the nature of the work the organisation is engaged in. Several stages in the design can be identified:

- Conceptual design;
- Detailed structural design;
- Design for manufacture;
- Design for production (including tooling design).

Different design tools have been developed, which are aimed at different stages of the design process. Some tools have several modules which can be used independently or can be linked to each other to allow information to be transferred from one module to another in order to improve efficiency.

See Appendix 1 for further information on selecting design software for composites.

2.3 DESIGN TOOLS

As mentioned in section 2.2, different tools should be used at different stages of the design process. The following tool sets can be identified:

- Laminate design tools;
- Analytical design tools for structural elements;
- Finite Element (FE) software for more complex structures;
- Production design tools.

2.3.1 Laminate design tools

Laminate design tools enable the designers to carry out:

- Ply calculation;
- Laminate design;
- Laminate evaluation.

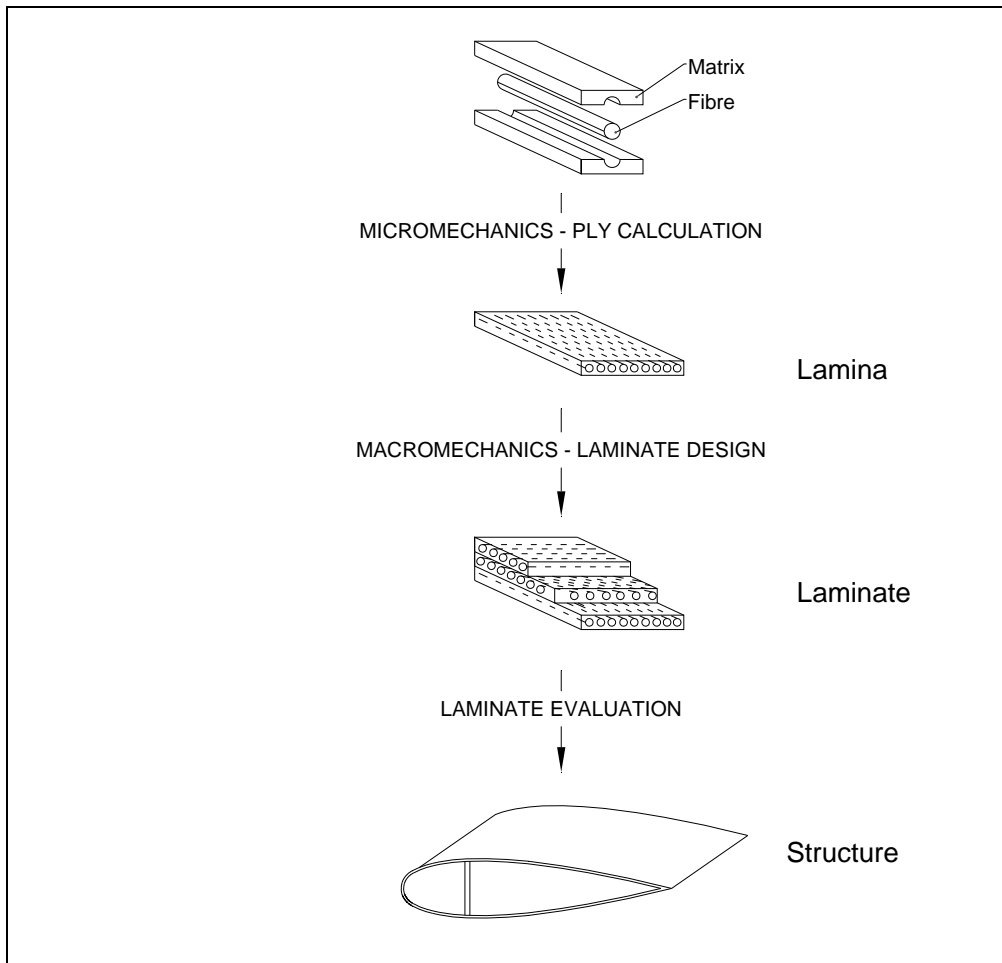


Figure 1: Levels of design and analysis for composite materials

a. Ply calculation

FRP material consists of reinforcing fibres (e.g. glass, carbon, aramid) held in a supporting resin matrix (e.g. epoxy, polyester, vinylester, polypropylene). Determining the engineering constants and thermal and hygrothermal expansion coefficients of each laminated ply is one of the first key steps of the design process. Engineering constants and laminate strengths can be determined using coupon tests. Some design tools come with a database containing mechanical data gathered for specific laminates. It is also possible to derive engineering constants using micromechanics theories from the knowledge of the fibre types and orientation, the matrix and the manufacturing process (i.e. achieved fibre volume or mass fraction). Such theories are implemented in ply calculation modules provided by some laminate design software tools allowing the designer to efficiently compute ply properties for possible configurations. Tools such as CoDA have experimentally validated their proposed theoretical approach.

b. Laminate design

Laminated composites are made up of a number of plies bonded together. Plies may have a different fibre material, thickness and/or orientation. Finding the optimum configuration for a given design can be time consuming.

The design module of laminate design tools allows the user to specify design constraints such as weight, cost and/or geometric constraints such as ply orientation, ply thickness and/or an acceptable range of mechanical or hygrothermal behaviour, strength or deformation. Possible laminates are identified based on the design constraints selected. These modules are key programs for the composite designer whose main task consists of finding feasible and efficient laminates for a given design. It should be noted that the

capabilities of the design module vary from one tool to another. However, most tools offer the feasibility to optimise the design for parameters such as mass and cost.

c. Laminate evaluation

A laminate evaluation module is provided by most laminate design tools. It enables the analysis of composite laminates subjected to in-plane loads, out of plane loads and thermal loading. This module is mainly used for tailoring a stacking sequence and inspecting the laminate behaviour layer by layer. This is often carried out using first ply failure (FPF) which consists of determining if failure is about to or has already occurred in a ply. This does not mean that ultimate failure or rupture of the laminate has occurred. Plies which have not failed may continue to carry load beyond FPF.

Most software provides the possibility to compute the additional load carrying capability of a given laminate by using a reduced stiffness approach initially developed by Tsai [1]. The reduced stiffness approach is used to reflect the presence of microcracks and fibre failure in some layers. Alternative theories such as Puck's non-linear ply degradation mode also exist for computing ultimate failure. A laminate evaluation module may also incorporate the ability to carry out hygrothermal stress analysis, moisture diffusion prediction, heat conductivity analysis, progressive formation of cracks and fatigue life prediction.

d. Summary

Several laminate design tools exist. Some software packages such as LPA, The Laminator and LAP have been developed specifically for this purpose. Other software such as Composite Pro, Composite Star, Kolibri, CoDA and ESAComp offer the laminate design tool as part of a more extensive tool. A non-exhaustive list of laminate design tools is provided in Table 1.

Software	Specification	Comments	Theories Used	Link
LPA	Online program	<ul style="list-style-type: none"> Free software. Ideal for-one off analysis. 		http://www.ccm.udel.edu/Techsite/Pages/Simulations-Index.html
The Laminator Version 3.6	Independent simple laminate design tool	<ul style="list-style-type: none"> Last released: April 2006. Download online. Good choice for quick laminate analysis. Material library available. Single licence valid for life. 	<ul style="list-style-type: none"> Micromechanics; CLT; Failure theories (Maximum stress, maximum strain, Tsai-Hill, Hoffman and Tsai-Wu) 	http://www.thelaminator.net/
ESDU Composites Series	Consists of: <ul style="list-style-type: none"> 40 'Data Items'; 26 Fortran programs. 	<ul style="list-style-type: none"> Collection of Fortran codes and programs. Volume 1 for laminated composites analysis and design Volume 5 for failure criteria 	Described in 'Data Item' associated with each program.	http://www.esdu.com
LAP Version 4.0	Independent laminate design tool	<ul style="list-style-type: none"> Three modules available: <ul style="list-style-type: none"> Basic module; Non-linear module; Additional failure criteria; Design module. Easy to use, efficient and robust solver. 	<ul style="list-style-type: none"> CLT; Failure theories (Maximum stress, maximum strain, Tsai-Hill, Hoffman and Tsai-Wu and custom); FPF and UPF. 	http://www.anaglyph.co.uk
CoDA Version 3.3	Analysis/Design software Can complement LAP	<ul style="list-style-type: none"> Experimentally validated; Extensive testing allowed integration of optional correlation factors which aim to provide more reliable predictions. Parametric option. Progressive formation of cracks (PREDICT module); Moisture diffusion module; Heat conductivity module; Fatigue life prediction module. 	<ul style="list-style-type: none"> Micromechanics/Material synthesiser; CLT Failure theory: Tsai-Wu (only available for in-plane loading) Full ply failure sequence (in-plane load only) 	http://www.npl.co.uk/coq/index.html http://www.anaglyph.co.uk
Kolibri Version 3	Analysis software	<ul style="list-style-type: none"> Laminate solver feature; Design features available: <ul style="list-style-type: none"> Ply analysis; Laminate analysis. 	<ul style="list-style-type: none"> CLT; Failure theories (Maximum stress, maximum strain, Tsai-Hill, Hoffman and Tsai-Wu). 	http://www.lightweight-structures.com/
ESAComp Version 3.5	Analysis/Design software	<ul style="list-style-type: none"> Laminate solver feature; Constant and variable load option; Database available. Design features available: <ul style="list-style-type: none"> Laminate evaluation; Laminate creation. Moisture diffusion module; Last released: February 2006; Next release schedule for February 2007. 	<ul style="list-style-type: none"> Micromechanics (rule-of-mixture and user defined capability); CLT; Failure theories (Maximum stress, maximum strain, Tsai-Hill, Hoffman, Tsai-Wu, Puck 2D, Puck 3D, Hashin 2D, Hashin 3D and user defined capability); FPF and UPF. 	http://www.compo-neering.com/esacomp/
Composite Star Version 2.0	Analysis/Design software	<ul style="list-style-type: none"> Laminate solver feature; Database available. Constant and variable load option. 	<ul style="list-style-type: none"> Micromechanics (rule-of-mixture and cylinder model); CLT and Netting analysis; Failure theories (Maximum stress, maximum strain, Tsai-Hill, Hoffman, Tsai-Wu, Simple Puck, Modified Puck, Hashin and Puck's action plane criterion); FPF and UPF. 	http://www.material.be/products/composite_star.html
Composite Pro Version 3.0	Analysis/Design software	<ul style="list-style-type: none"> Laminate solver feature; Last update: February 2006. New release available soon. Database available. Utility module (volume fraction converter, filament winding calculator, textile converter, radius of curvature and fabric builder). 	<ul style="list-style-type: none"> Micromechanics (rule-of-mixture, cylinder model and Chamis method); CLT; Failure theories (Maximum stress, maximum strain and Quadratic) FPF and UPF. 	http://www.compositepro.com/
Think Composites	Selections of software packages	<ul style="list-style-type: none"> Progressive failure of laminate; Hygrothermal stress analysis; Design module. 	<ul style="list-style-type: none"> Micromechanics; CLT; Failure theories (Maximum stress, maximum strain, Tsai-Hill, Hoffman, Tsai-Wu, Hashin and Dassault); 	http://www.thinkcomposites.com

Table 1: Non exhaustive list of laminate design tools

2.3.2 Analytical design tools for structural elements

Analytical design tools assist the conceptual and preliminary design of layered composite structures. They provide answers to structural problems where an exact elastic solution can be found. As for laminate design tools, several products exist. Each product aims to help the designer by providing analysis and/or design packages for specific composite structural arrangements. A non exhaustive list of products and their capability is provided in Table 2.

		Software						Think Composites
		ESDU Composites Series	CoDA Version 3.3	Kolibri Version 3	ESAComp Version 3.5	Composite Star Version 2.0	Composite Pro Version 3.0	
Capability	Homogeneous and laminated plates	✓	✓	✓	✓	✓	✓	
	Plate buckling			✓	✓	✓	✓	
	Natural frequency of plates	✓			✓	✓	✓	
	Sandwich plates (skin wrinkling)	✓	✓	✓	✓		✓	✓
	Sandwich plates (shear deformation)			✓	✓		✓	✓
	Sandwich plates (core shear)				✓		✓	
	Stiffened plates	✓	✓		✓			
	Curved plates	✓						
	Beams (bending)		✓	✓	✓	✓	✓	✓
	Beams (buckling)		✓	✓	✓	✓	✓	
	Beams (twisting)		✓	✓			✓	
	Natural frequencies of beams				✓	✓	✓	
	Flange or curved beams		✓					
	Tube (column stability)						✓	
	Cylindrical shell / pressure vessel				Under development		✓	
	Bonded joints		✓		✓			
	Bolted joints		✓		✓			
	Damping/response to acoustic loading	✓						
	FE export		✓		✓	✓		
	FE import				✓	✓		

Table 2: Non exhaustive list of analytical design tools

As mentioned in Table 2, analytical design tools offer the possibility to analyse several layered composite structural elements such as:

- Homogeneous and laminated plates;
- Sandwich plates;
- Stiffened panels;
- Beams;
- Curved plates;
- Cylindrical shells;
- Bonded joints;
- Bolted joints.

Analytical tools are often considered as a step further than laminate tools and most software that includes an analytical tool also has a laminate tool. Analytical tools require the input of the composite structure geometry and the loadings as well as the constitutive laminate properties, which in most cases are imported directly from the laminate tool. By combining the analytical and laminate tools, the input process and the output phase are automated. The loads calculated using the analytical tool that the constitutive laminate will need to withstand can be processed directly by the laminate tool to provide information on layer loading and failure modes. Composite design software that offers these two modules speeds up the task of the designer by providing an automated calculation tool.

2.3.3 Finite element software

By their very nature, composite materials present complex design and analysis challenges. Material selection, orientation and lay up all allow large degrees of customisation to enable the final material to have the desired properties. Additionally, failure criteria for composites are significantly different to other materials. This complexity means that the methods needed to analyse composites have to be flexible and sophisticated.

For many years traditional analysis has been used to verify the design. Now though there is a move to use Finite Element Analysis (FEA) techniques with optimisation codes to radically improve the design of complex parts (Figure 2). Software from Altair and GRM use these optimisation techniques. The designer sets up the problem as a series of loads, restrains and a space envelope for material, the code then does multiple FEA runs each time honing down the material used to give an optimum component. Some examples of this can be seen at <http://www.grm-consulting.co.uk/index.htm>.

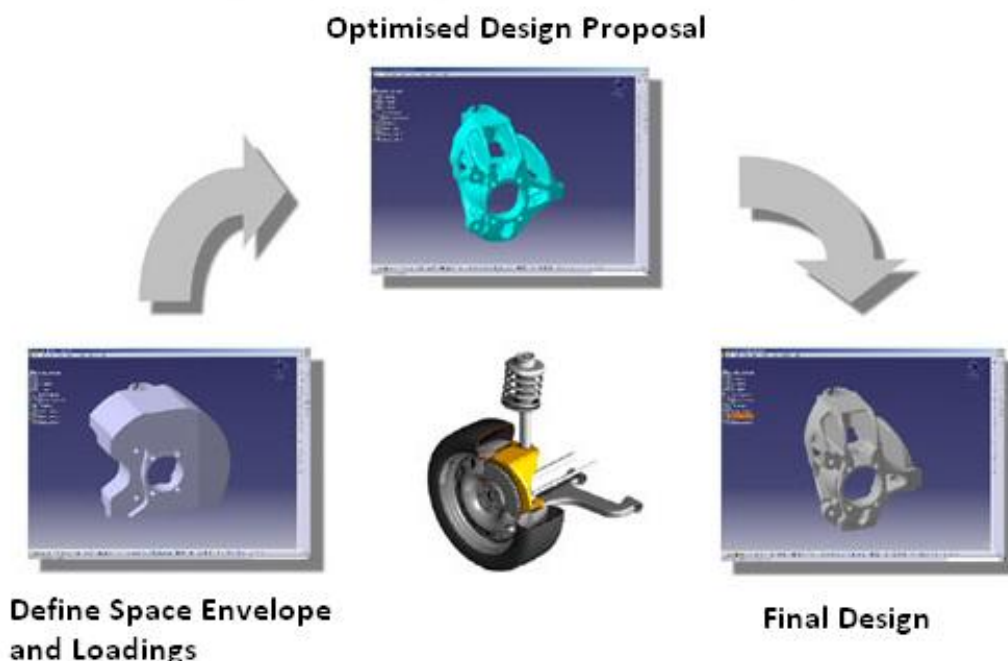


Figure 2: Component Optimisation http://www.altair.com/software/hs_catia.htm

Composite material failure modes are often made up of complex combinations of fibres, fillers and resins. Most FEA codes are used for the analysis of components where the composite is made of a material with homogeneous properties, e.g. chopped mat. For more complex composite materials, such as a multilayer fibre resin matrix, the FEA code must be able to handle orthotropic materials (materials with differing properties in the X, Y and Z planes). Once again depending on the uniformity of the laminate, and the complexity of the shape, it may be possible to simplify the analysis by amalgamating the different plies' material properties into one set which emulate the overall ply lay up. The analysis is then run using this set of material properties for the whole component. At all times these approximations should be checked with hand calculations and laboratory results.

A more accurate method is to consider the plies individually and their interactions together with the load conditions. Some FEA tools have specialised mesh types for this condition which enable the automatic generation of equations to tie dissimilar meshes together. This is an area where the skill and expertise of the engineer is vital to obtain good results.

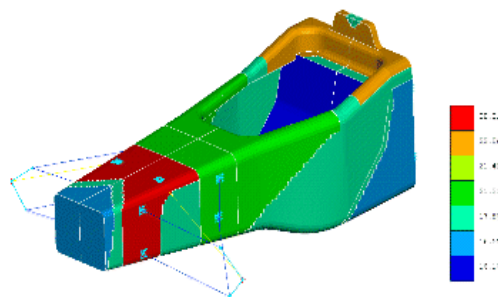


Figure 3: Optimised F1 Tub grm-consulting

<http://www.grm-consulting.co.uk/>

The FEA tool must be able to use the correct failure criteria for composite materials. These include:-

Tsai-Hill

Hoffman

Tsai-Wu (with Cowin extension)

Hashin (fibre and matrix)

Additionally, it may have to be able to handle specific failure modes such as delaminating and impact.

For more complex analyses, the FEA tool should allow for either the importation of lay-up definitions from laminate design tools or the rapid creation of ply lay-ups. Integrated products such as CATIA allow for simple translation of composite lay-ups to its own FEA codes. Other products rely on neutral data formats such as IGES and STEP. Products such as Laminate Modeller output Nastran or Ansys format input deck files that include all the laminate property information i.e. they translate lay-up information to finite element properties, ready for FEA analysis (PCOMP cards or SECTIONS or Real Constants).

Some of the FEA codes create the lay-up's plies within the code. An example of this is Lusas and Nastran (Figure 4). This enables the individual ply to be created with its material properties which is captured in a table like the ply books in the design codes.

The analysis of composite components produces large amounts of data to interpret. The post-processing of this data should allow for the presentation of the results in such a way that areas of concern are high lighted. Some of the specialist composite codes include tools that make interpretation of the results much easier (Figure 5).

Composite design is an iterative process. Any analysis tool should be able to feed results back to the design engineer to enable updates to be made that can be rapidly re-imported into the analysis tool with the minimum of re-applying loads and meshes. An integrated Computer Aided Design (CAD)/ Composite Design / analysis tools such as Catia or SolidWorks with Nastran would be most suitable in this context. Table 3 shows available FEA packages that have composite materials capabilities.

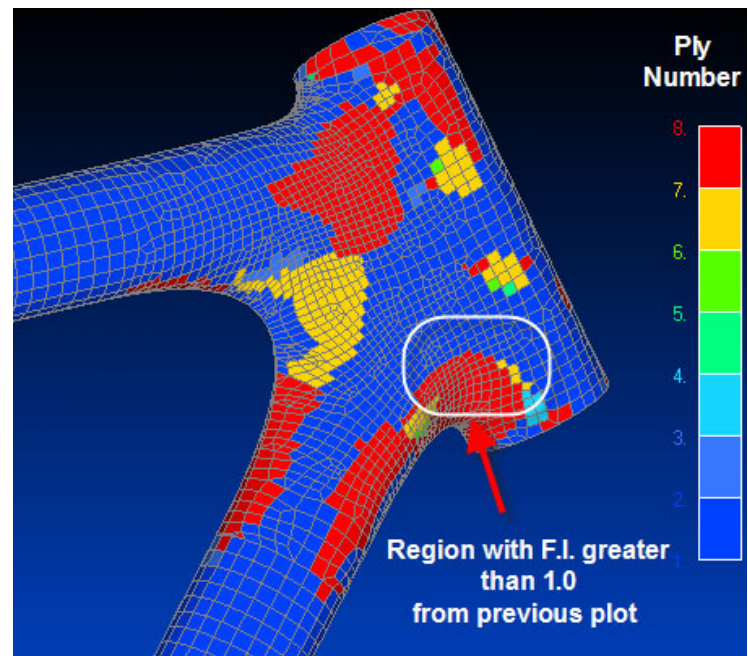
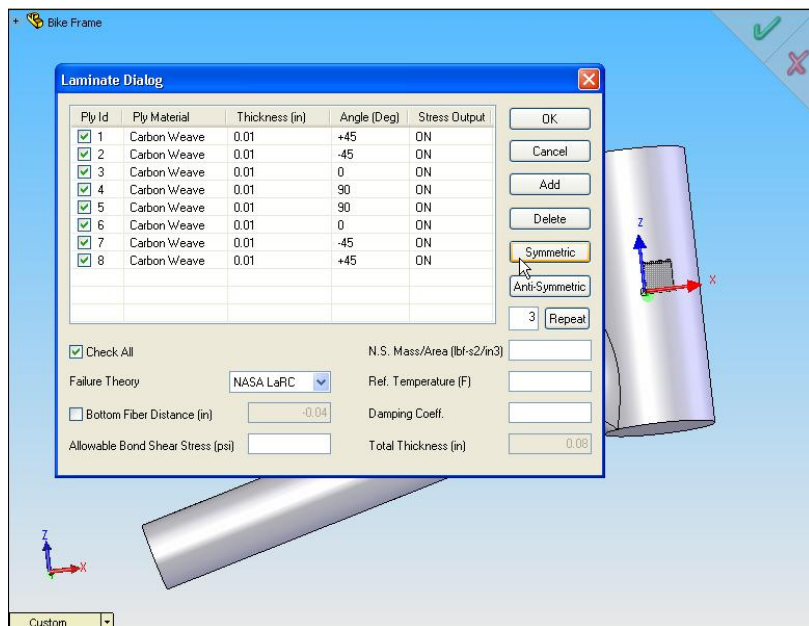


Figure 4: Ply settings in Nastran Composite

<http://www.nenastran.com/newnoran/composite#1>

Figure 5: Post processing bike frame showing high stress areas for each ply

<http://www.nenastran.com/newnoran/composite#1>

Product	Composite version	Website	Composite Features	Notes
Abaqus	VCCT	http://www.abaqus.com/vcct/	Delamination, debonding and non linear.	Also has extension for wound filament
ANSYS		http://www.ansys.com/solutions/solid-mechanics-composites.asp		
LUSAS	Composite	http://www.lusas.com/products/composite.html	Ply lay-up definition, delamination, non-linear and composite elements.	
Nastran	Composites	http://www.nastran.com/newnastran/composite	Ply lay-up definition, non-linear and composite elements.	Version integrated to Solidworks.
Cosmos	Advanced Professional	http://www.solidworks.com/pages/products/cosmos/cosmosworks/cosmosworks_adv.html?PID=41	Functionality to define composite mesh.	Solidworks integrated and Standalone.
Algor		http://www.algor.com/default.aspx		
genoa		http://www.alphastarcorp.com/right/genoa.html		
Mecano		http://www.samcef.com/en/pss.php?ID=24&W=products		
NISA	composite	http://www.nisasoftware.com/products/nisa-composite.html	Edge effects, delamination and temperature dependant material	
Pro/ENGINEER Advanced Mechanics	Advanced	http://www.ptc.com/appserver/mkt/products/home.jsp?k=1182		
SOLVIA		http://www.solvias.com/index.html		
STRAND7		http://www.strand7.com/		
ESI	Sysply	http://www.esi-group.com/SimulationSoftware/Design_composite/	Full suite of tools designed for composite analysis.	Can simulate filament winding and draping.
Mathmatica		http://www.wolfram.com/products/		
Extensive list of FEA codes		http://homepage.usask.ca/~ijm451/finite_fe_resources/fe_resources.html#CHILD_LINKS		

Table 3: FEA software with composite features

2.3.4 Production design tools

Commercial tools are available that take a component-based approach to the fabrication of the laminate, either allowing for the importation of the component from a CAD system or working within the CAD system itself. There are three well known products in the market for this, namely Dassault System's Catia Composite Design, Vistagy's Fibresim and Anaglyths's Laminate Modeller. A product such as Laminate Modeller takes CAD data and allows the laminate to be draped over it, simulating the manufacturing lay-up.

Catia's composite design tools (Figures 6 to 9) allow similar draping and ply build-ups but works directly onto the CAD model and has the advantage of not risking data translation errors. More importantly, the plies are in concert with the CAD model. This means that should the CAD model change, the composite design will too. Some of these draping tools allow for the creation of folds and darts (Figure 8) to allow for a better fit of the fabric. They also simulate the fabric orientation as it is draped over complex shapes (Figure 9). This is important to highlight area of rapid changes in curvature as these could cause ripples or folds.

It is important to have the fibre orientations for later analysis. These tools also enable the definition of ply staggering to prevent tearing and ply splicing and so ensure correct joining of fabric. Whilst all this is being done the systems hold a detailed list of the material, its orientation and order in a ply book. Normally the plybook can be exported to a spreadsheet for issue to production. (Figure 10)

Once the composite design has been completed, it is verified. All of these products allow for information about the plies, size, shape and orientation to be passed to an FEA code for verification.

Once the analysis is complete and any modifications arising have been made and again verified, the design systems can be used to output manufacturing data. Here, intergrated products have the advantage of not only being able to create ply books and template drawings but also produce full engineering drawings of the component. Moreover, Catia can convert the ply information back to a solid model that can be used for digital mockup and mold tool design.

The final task of the design tool is to output the laminate templates and optimise material usage. As this task involves material usage optimisation and template orientation, a specialised composites code should be

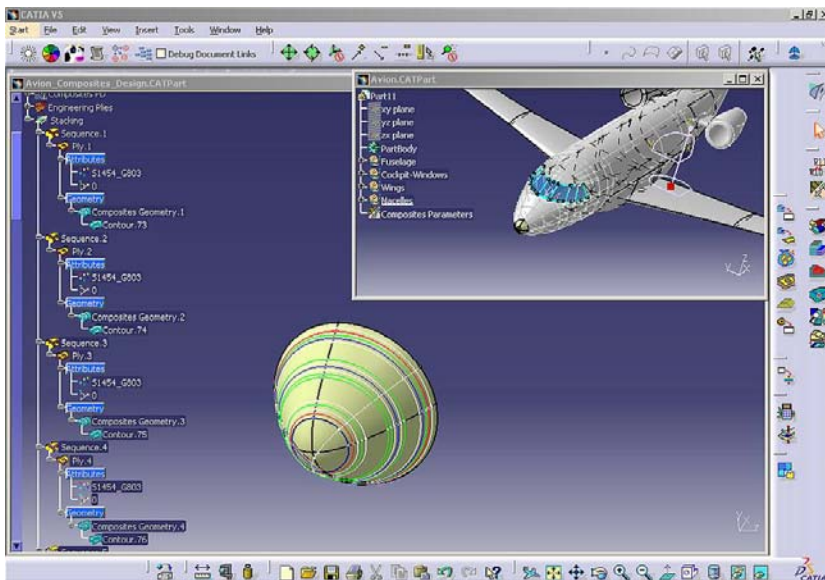


Figure 6: Draping Simulation CATIA CPD

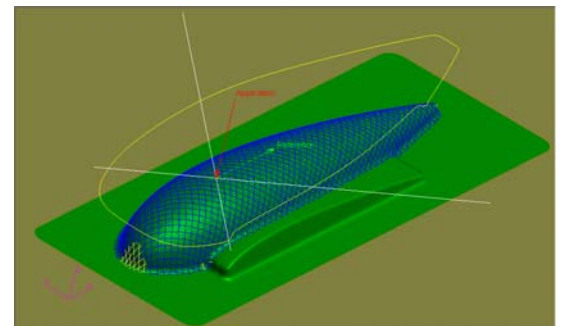


Figure 7: Draping simulation from Laminate Modeller <http://www.anaglyph.co.uk/>

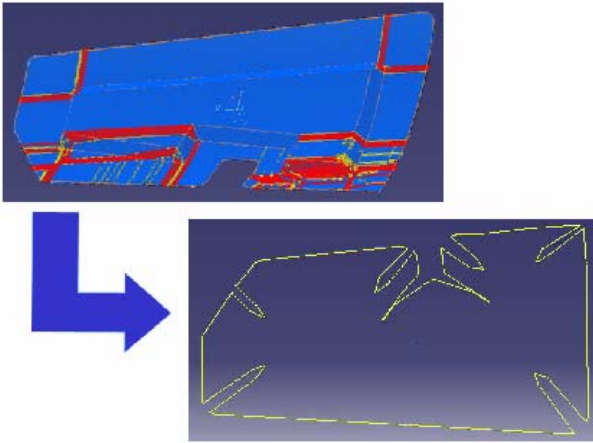


Figure 8: Catia Part flattening

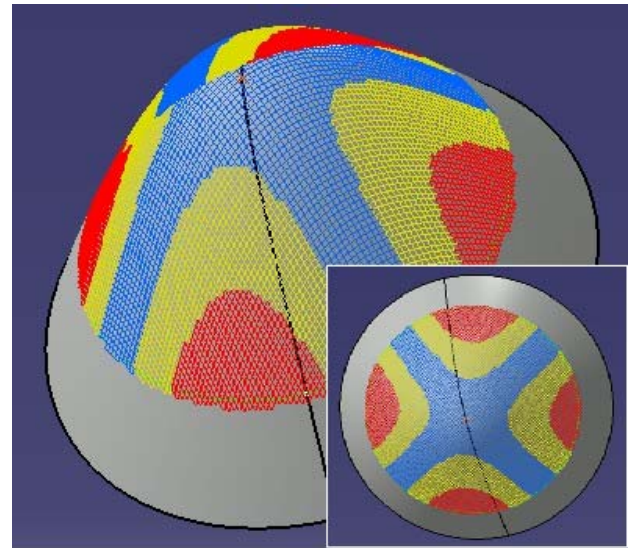


Figure 9: Catia Fibre orientation and manufacturability

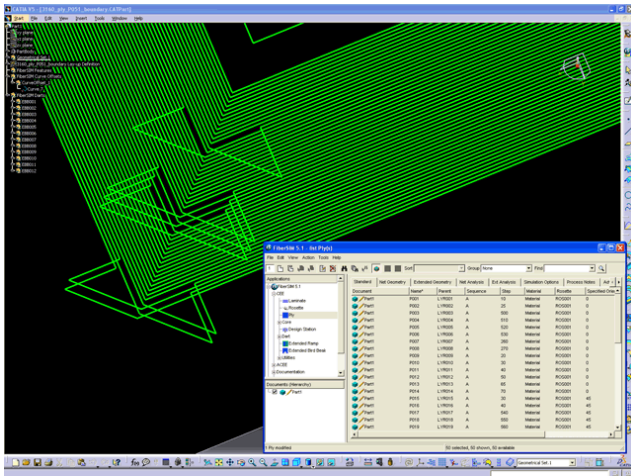


Figure 10: An image from FibreSim showing a Ply book

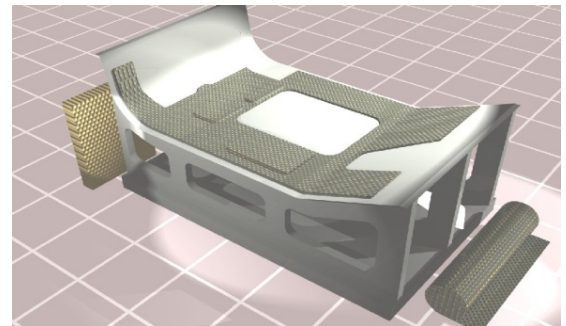


Figure 11: Tool Design

2.3.5 Production simulation

With the increased size and complexity of products being made through Resin Transfer Moulding (RTM) and Controlled Vacuum Infusion (CVI), the commercial risk of a failed process has made virtual testing a necessity. As with FEA analysis, the system purchased should enable the simple importation of the CAD model and the interface should allow for easy use and setup of the model. Due to the inconsistency of the process, the permeability of the composite varies depending on temperature, humidity and fabric tension. The system should therefore allow for quick changes in the material properties and fast runs to enable multiple runs with different values to optimise the process. Two companies produce products specifically for this market; ESI with its PAM-RTM product and Polyworx with RTM-worx.

For these tools to work effectively material properties and drape properties are critical, hence they should be able to import drape information from other products or produce their own. The permeability of a ply is important and should be found from laboratory tests.

The tools should allow for the simulation of injection ports, runners and venting. It should also accommodate the other process variables, e.g. tool temperature. The analysis solver should be fast to allow for multiple runs.

Once run, the post processors should highlight the possible failure modes of the process, such as air gaps, resin curing and easy flow paths. It should then be simple to change the injection points, vents etc. and re-run the simulation.

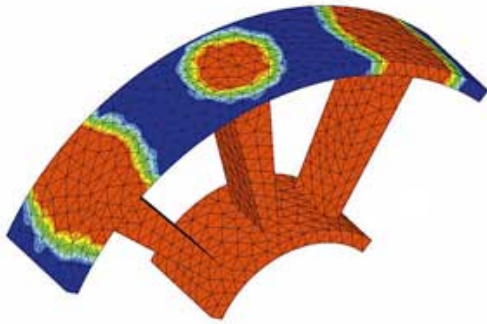


Figure 12: Filling based on the Kamal Sourour Model <http://www.esi-group.com>

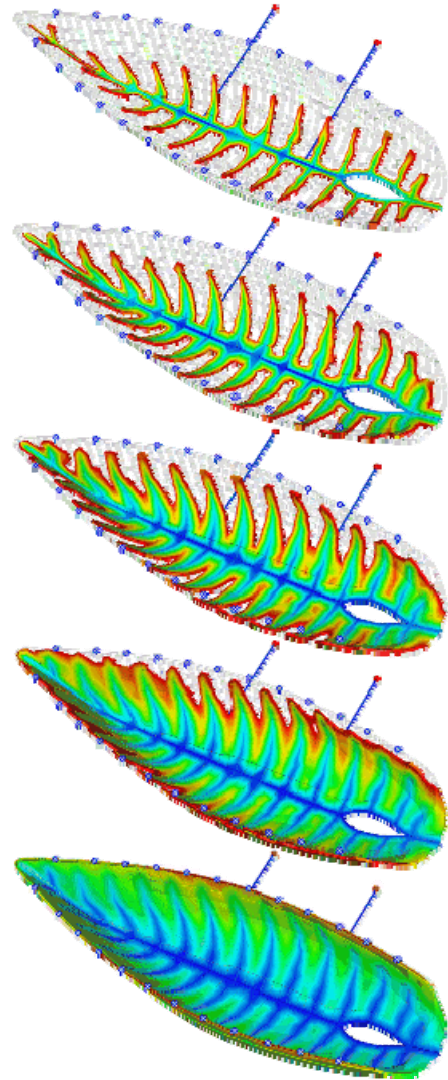


Figure 13: Vacuum Infusion <http://www.polyworx.com/>

2.3.6 Benchmarking CAD software

The primary consideration when evaluating CAD software is whether it is fit for purpose. This can be tested by means of a supplied benchmark test for the software vendor to complete and through research of the product. While software vendors will normally push their product as the correct solution, this is still a valid exercise as it enables the buyer to be confident that a product meets their requirements.

The benchmark test should be a realistic simulation of what the business does now and what it expects to do in the future. When benchmarking, buyers are often tempted to use their most difficult design problem and see whether new software can solve it. This often leads to the purchase of a product that solves that particular problem but is of little use for elsewhere. So while the benchmark test can evaluate the limits of the product, the more routine features of the software must not be overlooked. In addition to the benchmark test, it is useful to allow the software vendor to do their standard demonstration as this will encompass the full range of functionality and highlight areas the benchmark test may not.

When planning the test, it is worth considering that a 'blind' benchmark test (i.e. where the software vendor has been unable to prepare) can turn into a test of the vendor rather than the software. Where the software is complex and needs a lot of configuration, a 'blind' benchmark test is unrealistic. However, the buyer should ask to see at least some of the setup to see how simple or not it is.

Buyers should also consider how much training and support will be required. It is always worth building into the budget some contingency for follow up training and support after the initial training to build on the user's knowledge and assist through the initial projects.

Finally, the buyer should remember that the vendor is an important part of the solution and should be treated as such. Therefore, if a large purchase is being made, the buyer should ask for references from other buyers and possibly visit their sites to assure themselves of the vendor's abilities.

2.3.7 Choosing computer hardware for CAD and analysis

When choosing computer hardware for CAD and analysis applications, the following points should be borne in mind.

- Since the advent of Windows NT 3.51 there has been a decline in the use of the Unix RISC workstation for CAD applications. Although specialised products still run UNIX, companies such as SGI and Sun have seen their share of the CAD market diminish.
- Competition between Intel and AMD since the advent of the AMD Athlon and Intel's Pentium range has driven Central Processing Unit (CPU) or processor performance to very high levels. For CAD and design applications, the processor should support 64Bit operation. When combined with a 64Bit operating system, the PC will be able to use enormous amounts of memory and enable much more complex models and simulations to be run. This will also dramatically reduce the time taken to perform these operations.
- Multi-core processors (i.e. two CPU units available rather than one) are a relatively new occurrence. Most code on the market is not optimised for multi-core use although analysis and rendering are two CAD areas that do lend themselves to multi-core operation.
- Selecting the right graphics card can be problematical. Most 3D CAD and Analysis systems rely on a set of program calls called OpenGL for the manipulation of 3D graphics. OpenGL was originally made by SGI and was licensed by all the main workstation vendors and by Microsoft for Window NT. Most PC's graphics cards and their drivers do not fully comply with the standards for OpenGL and a "professional" card such as ATI's Fire range and

Nvidia's Quaddro range is required. Software vendors produce compatibility matrices of tested graphics cards and systems. Web links to two of them are included below.

<http://www.solidworks.com/pages/services/VideoCardTesting.html>

<http://www.3ds.com/implementation/technology/windows/certified-workstations-list/>

- As much Random Access Memory (RAM) should be purchased as possible. However, some RAM needs to be installed in pairs for maximum performance.
- Small Computer System Interface (SCSI) type disk drives have been widely used for reasons of performance. However, with the advent of cheaper, faster Serial Advanced Technology Attachment (SATA) disk systems it can be difficult to justify the cost of SCSI. Moreover, with the increases in RAM, the disk system only affects program and data loading, rather than the whole application.
- With regard to operating systems, Windows 2000 does not support 64Bit, so should not be considered. If the processor and application is compatible with 64Bit operation, a 64Bit operating system, such as Microsoft's Windows XP or Vista should be used.

2.3.8 Summary and comments

Different families of design software have been presented. Whereas finite element software, production design tools and specific design tools can provide great support to the designer they are outside the scope of this guide.

As illustrated in Table 1 and Table 2 , a variety of programs devoted to the analysis of composite laminates are available. They all provide slightly different features and theories. These assist the designer to accurately predict the material properties of a laminate, the response of a structure under specific loading conditions and the failure mode of a laminate, which are key issues in composite design.

Table 1 lists the micromechanics and failure theories available in the software listed. It should be noted that failure criteria for composite materials are significantly more complex than yield criteria for metals because composite materials can be highly anisotropic and fail in a number of different modes depending on their loading state and mechanical properties. Different failure criteria exist. This subject is well documented in the literature and it is the responsibility of the designer to understand and select appropriate design criteria. Table 2 provides information on the structural design capability of a range of analytical design tools.

What will differentiate one program from another are not only the features and theories available but also ease of use, flexibility, on-line help and quality of the presentation of the results. These features can only be determined by running trial versions of selected software. For example, it is obvious that a program such as LPA would be satisfactory for a one-off laminate analysis but not being able to save or print would quickly become an issue if used on a day to day basis.

2.4 ADVANTAGES AND RISKS ASSOCIATED WITH THE USE OF DESIGN TOOLS

Composite software, as mentioned in section 2.1, can help the designer during the calculation phase of his work. However it should always be kept in mind that they are computer programs and therefore their outputs will be directly dependent on input data (i.e., material properties, loads, geometry characteristics, etc.) and design criteria specified by the users. They should be considered as tools which will help the designer towards getting the desired solution but cannot replace the designer's knowledge.

It is necessary to spend time understanding the assumptions and theories used by the design programs. To be able to achieve this it is essential to check that the tool you intend to use comes with good documentation of the theories used and provides an easy to use up-to-date online help. Also, a sound knowledge of composite materials and the underlying principles of their mechanical response are essential. This is also necessary to interpret results and suggest any required modifications. This specific point will be illustrated via examples within the benchmark studies.

Finally, it is essential to ensure that the software selected does not limit the designer's analysis and design capabilities. This implies, as mentioned in section 2.2, that identifying the designer's needs is fundamental before selecting the most appropriate software.

2.5 COST

Design tool prices are often a major driver and should be considered when identifying the designer's needs. Most composite design tool suppliers will allow purchase modular licences and a self sufficient module can start at the cost of £200 to £300. Having the possibility at a later stage to increase one's design capability can be an important selection criterion. As a first indication, a single-user, indefinite floating licence with technical support for an independent complete laminate design tool would be around £1000, for a mid-range analytical tool around £2000 and for a high-end analytical tool around £4500. These prices are only indicative and it is advisable to contact the software supplier to get an accurate quote.

3. LAMINATE & ANALYTICAL TOOLS BENCHMARK STUDIES

3.1 INTRODUCTION

Several benchmark studies are presented. They are run using trial versions of four different composite design tools; LAP 4.0, CoDA 3.3, KOLIBRI and ESAComp 3.5 and the different features provided by each product are presented.

The overall aim of these benchmark studies is to:

- Give an overview of the support that can be provided by such tools;
- Understand the advantages of using these design tools;
- Understand the importance of being familiar with the implicit assumptions in the design software;
- Realise that these analytical tools provide a means of automating and accelerating design calculation but do not replace the need for sound design engineering.

Each benchmark study has been designed to present different key features of composite design.

3.1.1 Ply and laminate analysis

The first benchmark study presents the following aspects:

- Derivation of ply properties;
- Lay-up specification;
- Lay-up analysis.

3.1.2 Sandwich panel

The second benchmark study presents the following aspects:

- Sandwich laminate design;
- Sandwich panel analysis under in-plane and out-of-plane load;
- First ply failure analysis and available strength failure criteria;
- Skin wrinkling prediction.

3.1.3 Stiffened panel

The third benchmark study aims to investigate the following aspects:

- Laminate design tool;
- Panel buckling prediction;
- Design of stiffened panels.

3.2 FIRST CASE STUDY: PLY AND LAMINATE ANALYSIS

3.2.1 Ply definition

In the first part of this case study the properties of a ply made from pre-preg UD carbon fibres in epoxy resin are derived. For this analysis, it is assumed that high strength carbon fibres are used. The carbon fibres and epoxy resin properties are summarised in Table 4.

	Longitudinal modulus	Transverse modulus	Shear Modulus	In plane major Poisson ratio	Density	Coefficient of thermal expansion
High strength carbon fibres	235GPa	16GPa	87GPa	0.35	1800kg/m ³	-0.4e-6/°C
Epoxy resin	3.3GPa	3.3GPa	1.23GPa	0.34	1180kg/m ³	60e-6/°C

Table 4: Material properties

It is assumed for the purpose of this benchmark study that a fibre volume fraction of 0.55% is achieved.

Both CoDA and ESAComp can derive ply properties from the properties of the constitutive materials. Results obtained from both of these tools are presented in Table 5.

First of all, ply properties are derived with ESAComp using first of all the commonly used “rule of mixtures” model. Whilst this approach gives excellent agreement with experimental data for longitudinal properties, it is known to underestimate the transverse properties. This is due to the fact that the simple “rule of mixtures” model does not account for fibre shape, fibre spacing and fibre packing geometry.

Alternative semi-empirical methods have been developed and have lead to more accurate results. ESAComp allows the addition of user defined micromechanical models and provides the Halpin-Tsai approach as an example. CoDA uses the Halpin-Tsai approach to predict the transverse material properties of a ply made of unidirectional fibres. CoDA also allows one to derive properties of a ply made of discontinuous and/or random fibres. When using CoDA, it is possible to correct the derived theoretical values using correlation factors. These correlation factors are based on experimental evidence.

	CoDA (With correlation factor)	CoDA (No correlation factor)	ESAComp (Rule of mixtures)	ESAComp (Halpin-Tsai)
Density (kg/m ³)	1521	1521	1521	1521
Longitudinal modulus (GPa)	124.20	130.74	130.74	130.74
In plane transverse modulus (GPa)	6.57	7.73	5.86	7.73
In plane shear modulus (GPa)	3.86	4.06	2.69	5.35
In plane Poisson ratio	0.415	0.346	0.346	0.346
Longitudinal coefficient of thermal expansion (/°C)	0.286e-6	0.286e-6	0.286e-6	0.286e-6
Transverse coefficient of thermal expansion(/°C)	35.78e-6	35.78e-6	35.8e-6	35.8e-6

Table 5: Computed ply properties

3.2.2 Lay-up definition

Design tools allow one to create and derive the properties of a laminate made up from a stack of given FRP plies. In this section a single skin laminate made up prepreg carbon UD plies is considered. Each ply is assumed to be 0.3mm thick. The laminate is made of a total of 8 plies orientated from top to bottom at 0°, 90°, +45°, -45°, -45°, +45°, 90° and 0°.

All of the software tools considered within the benchmark study can calculate the laminate effective stiffness. Expected strength can be provided by LAP, CoDA and ESAComp. Examples of computed results provided by these three tools can be found in Figure 14, Figure 15 and Figure 16. The computed strength values are dependent on the failure criteria selected. This specific point will be discussed in more detail in section 3.3.

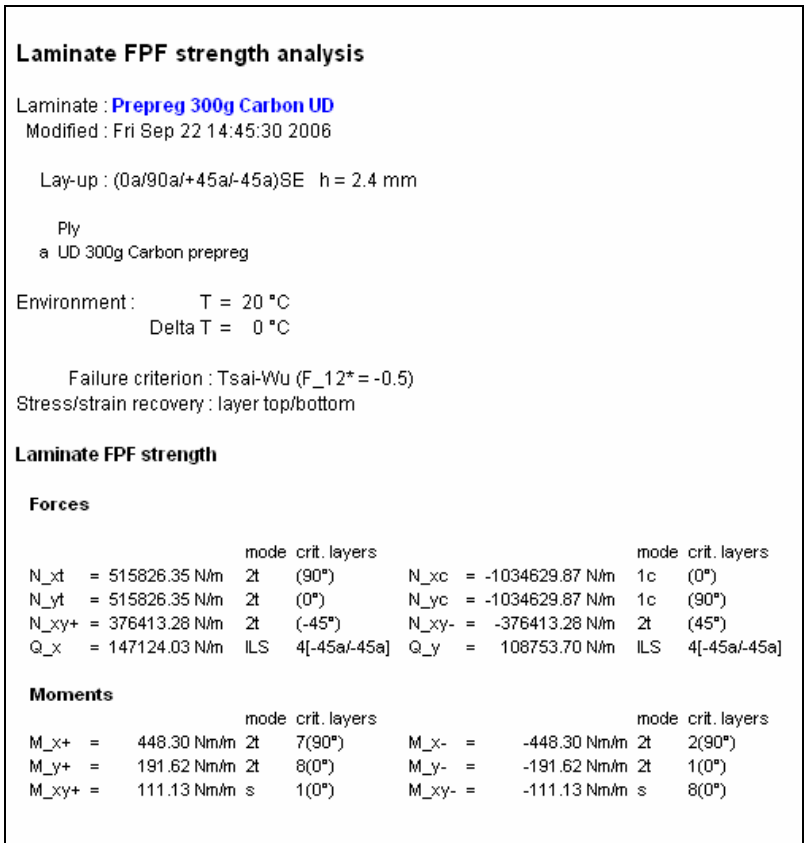


Figure 14: ESAComp laminate strength prediction (Tsai-Wu failure criteria selected)

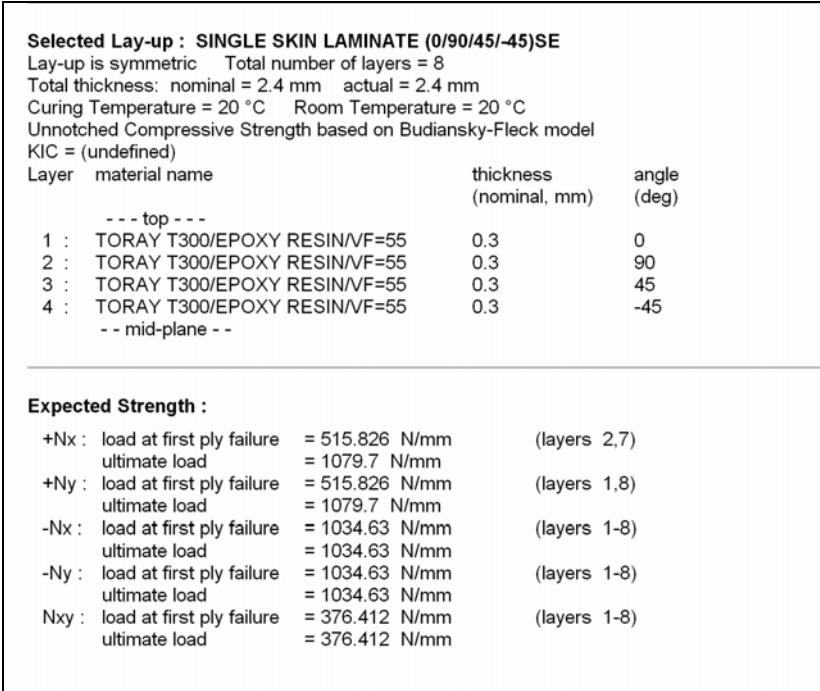


Figure 15: LAP laminate strength prediction (Tsai-Wu failure criteria selected)

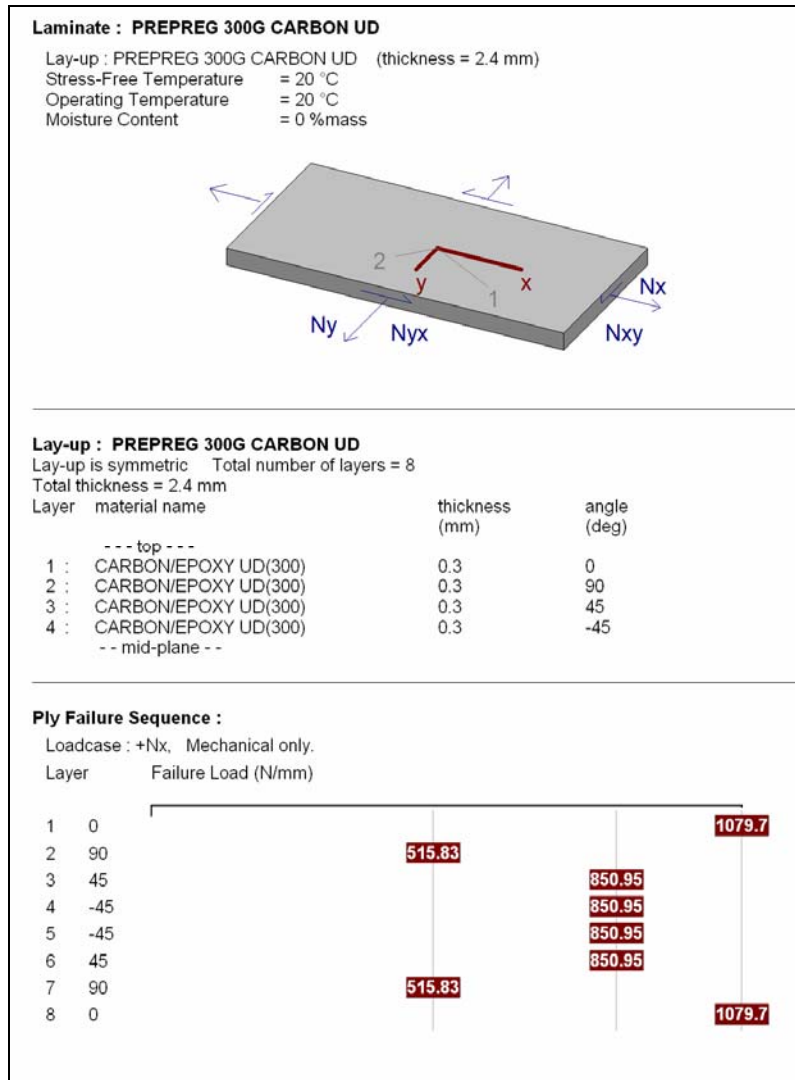


Figure 16: CoDA laminate strength prediction (Tsai-Wu failure criteria)

The LAP and CoDA laminates module can report the laminate layer direct and shear failure loads for each layer for mechanical, thermal and/or moisture expansion loading. CoDA can also provide the ply failure sequence as shown in Figure 1616.

ESAComp can report not only the laminate layer direct and shear failure stresses but also interlaminar failure stress as shown in Figure 14.

3.2.3 Laminate analysis

The laminate presented in section 3.2.2 is subjected to an in-plane load, N_x , of 600N/mm, see Figure 1717. According to the predicted strength value (see section 3.2.2) the 90° layer will fail due to micro-cracking under this load. This analysis has been carried out using ESAComp, LAP and KOLIBRI. The reserve factor, failure index and/or stress in each layer have been predicted. The results are presented in Figure 1818, Figure 1919 and Figure 20.

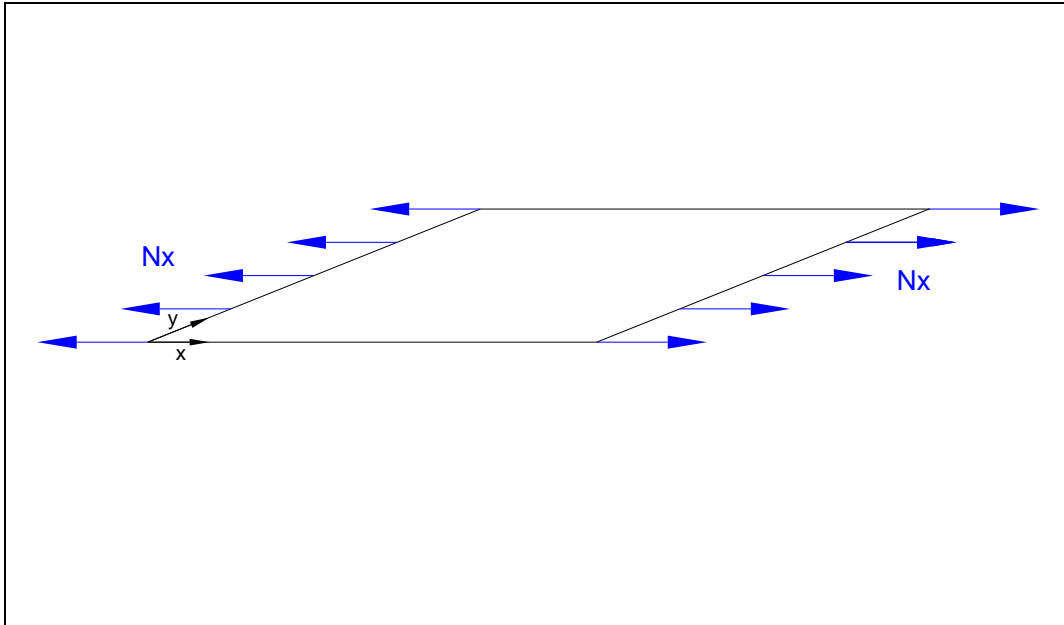


Figure 17: Laminate subjected to in-plane load

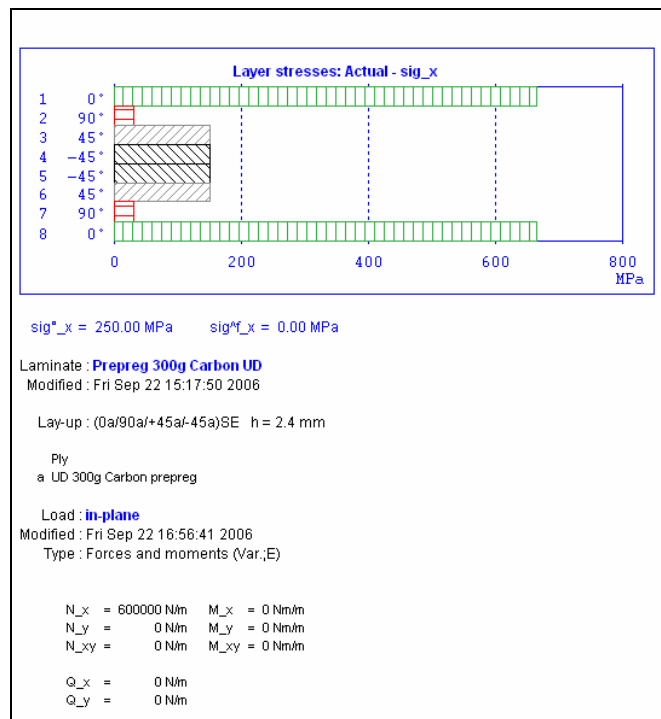
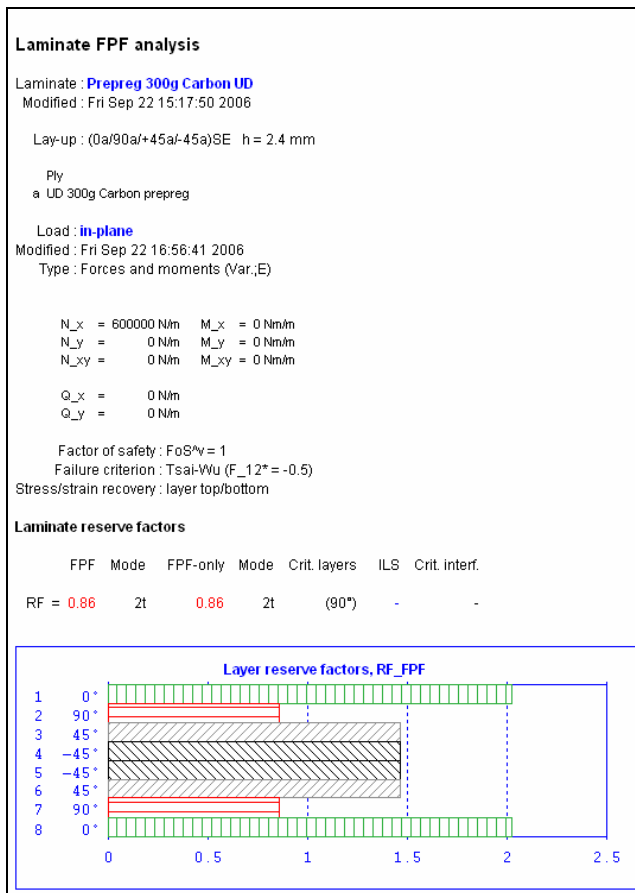


Figure 18: ESAComp results of laminate subjected to in-plane load of 600N/mm (Tsai-Wu failure criteria selected)

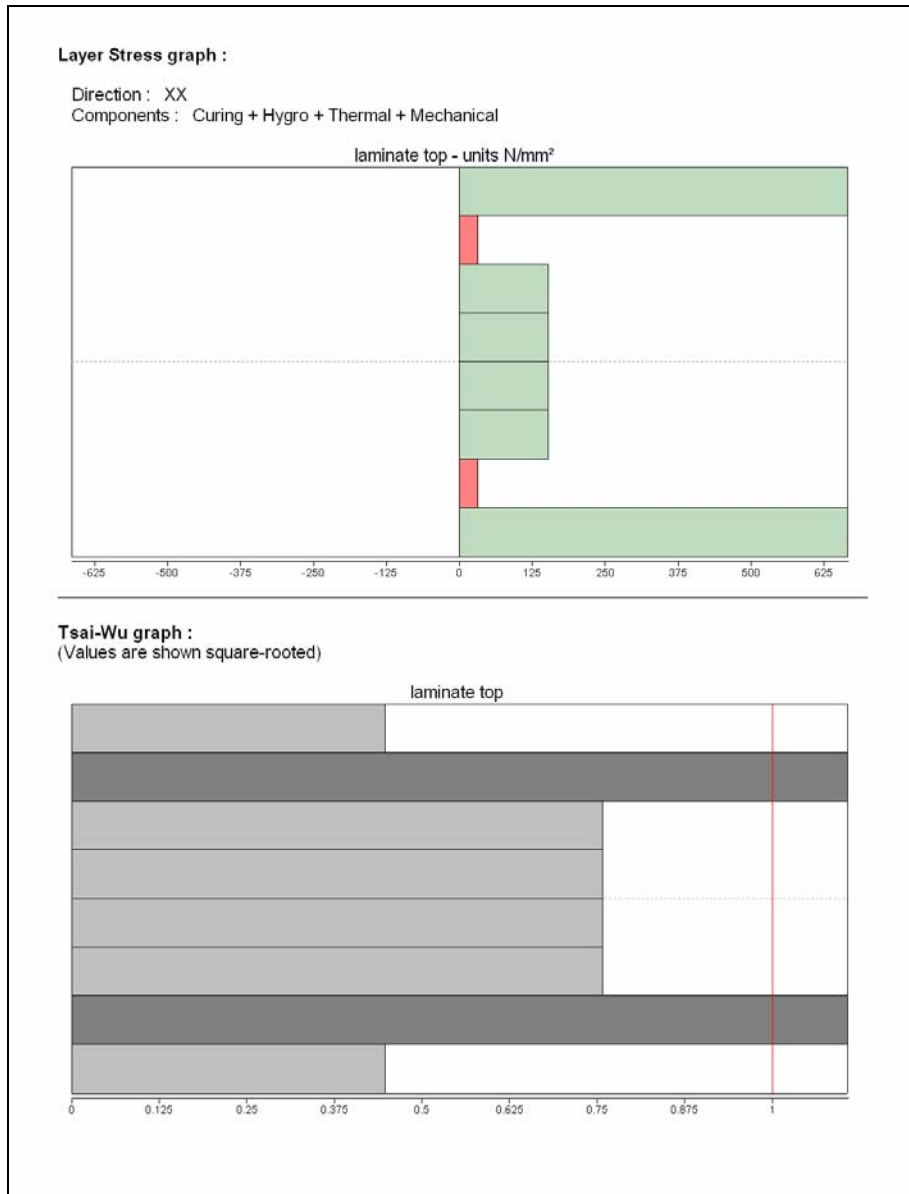


Figure 19: Example of results obtained from the LAP post processor. Top graph shows the applied stress in each layer and the bottom graph the failure indices in each layer.
 (Laminare subjected to in-plane load of 600N/mm)
 (Tsai-Wu failure criteria selected)

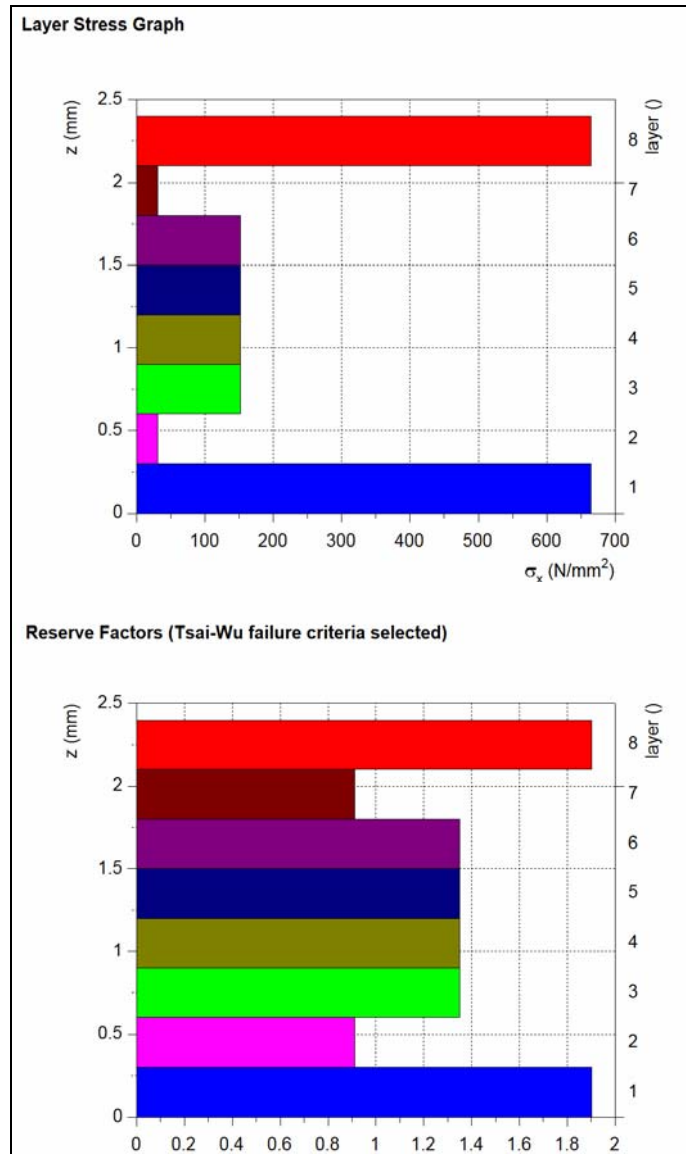


Figure 20: Example of results obtained from the KOLIBRI post processor. Top graph shows the applied stress in each layer and the bottom graph the reserve factors in each layer. (Laminate subjected to in-plane load of 600N/mm) (Tsai-Wu failure criteria selected)

ESAComp, LAP and KOLIBRI can compute the applied stress for each layer. As shown in Figure 1818, Figure 1919 and Figure 20 graphical results provided by these products allow one to quickly identify plies which fail under the applied load. A given ply has failed when its failure index is greater than one or its reserve factor is less than one. Both ESAComp and KOLIBRI provide reserve factors as output from which it is possible to calculate the failure load. This can be achieved by multiplying the applied load by the lowest reserve factor. LAP on the other hand calculates failure indices rather than reserve factors. The failure index is the value of the failure criterion function and the relation between failure load and failure index is dependent on the failure criterion selected. Computed failure indices should therefore be interpreted with care.

The information provided by the design tool should be interpreted and analysed by the designers in order to identify the exact type of failure and its impact on the overall integrity of the structure.

Design knowledge and experience are also required to improve and optimise the initial design based on the computed information.

3.3 SECOND CASE STUDY: SANDWICH STRUCTURE ANALYSIS

For the second benchmark study, a sandwich configuration made of 20mm PVC foam core and Chopped Strand Mat (CSM) skins is considered. The skins are assumed to be made from plies of 450g/m² CSM laminated using polyester resin with a mass fraction of 0.3%. The sandwich laminate is assumed to be subjected to in-plane and out-of-plane loads.

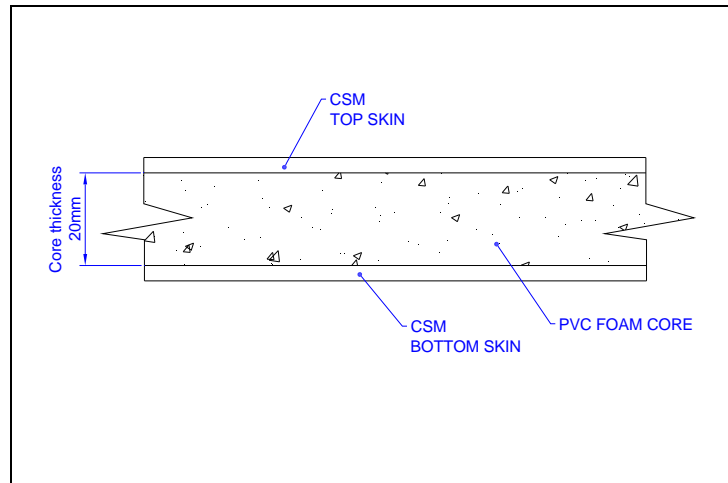


Figure 21: Sketch showing sandwich construction

3.3.1 In-plane load

The laminate is designed to withstand an in-plane load of $N_x=500\text{N/mm}$. It is assumed that the unloaded edges of the laminate are not able to move and are therefore subjected to an in-plane load of $N_x = \nu \times N_y$, where ν is the laminate Poisson ratio. For this analysis, it is considered that the skins could be made of 2, 3 or 4 layers of 450g/m² CSM plies. It should be noted that no material or load factors have been considered.

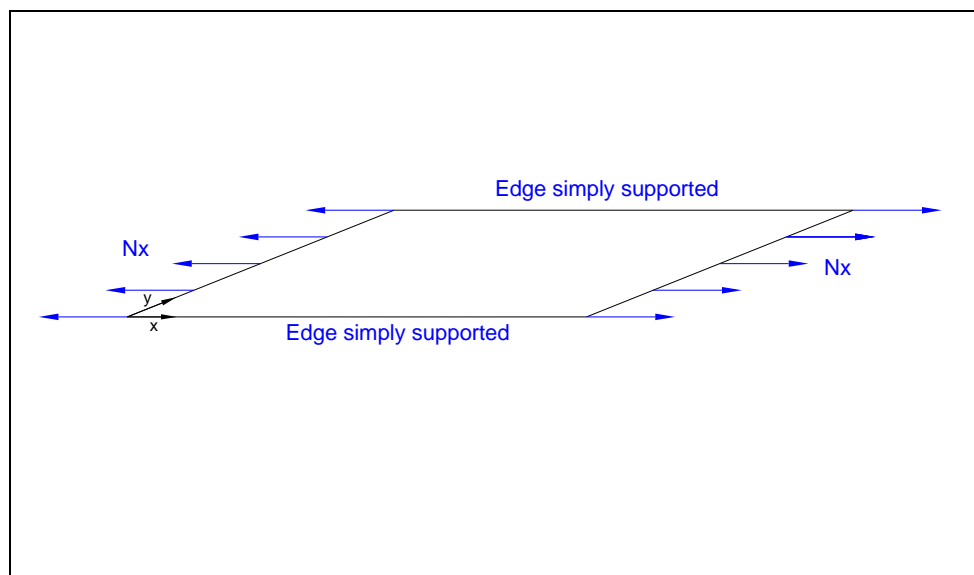


Figure 22: In-plane load case

a. LAP results

LAP allows one to run a preliminary analysis simultaneously for a range of laminates. The results, presented in the form shown in Table 6, provide a quick indication of which laminate can be considered as a possible candidate for further analysis.

LAP batch results
 LAP version: 4.0/356 Exported 29 Jun 2006 14:55

Lay-up	Loading	Stiffness	Tsai-Wu	Tsai-Hill	Hoffman	Max.Stress	Max.Strain
2*CSM-FOAM SANDWICH	IN-PLANE	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL
3*CSM-FOAM SANDWICH	IN-PLANE	PASS	PASS	PASS	PASS	PASS	PASS
4*CSM-FOAM SANDWICH	IN-PLANE	PASS	PASS	PASS	PASS	PASS	PASS

Table 6: Results from LAP

More information can then be obtained for a specific laminate. This is demonstrated below where the failure indices, obtained with LAP for a sandwich made of 3 layers of CSM in each skin, are presented. A failure index is given for the inner and outer surface of each layer. In Table 7, layers 1 and 4 represent the skin and layers 2 and 3 represent the core. It should be noted that by using LAP, one can run the analysis for several failure criteria.

Failure Indices (The energy-based criteria are shown square-rooted)

Layer	Tsai-Wu	Tsai-Hill	Hoffman	Max.Stress	Max.Strain
1	0.885588	0.781428	0.885588	0.885563	0.788905
	0.885588	0.781428	0.885588	0.885563	0.788905
2	0	0.3749	0	0.42209	0.383495
	0	0.3749	0	0.42209	0.383495
3	0	0.3749	0	0.42209	0.383495
	0	0.3749	0	0.42209	0.383495
4	0.885588	0.781428	0.885588	0.885563	0.788905
	0.885588	0.781428	0.885588	0.885563	0.788905

Table 7: Results from LAP showing failure indices for CSM sandwich structure subjected to in-plane load (3 layers of CSM in each skin)

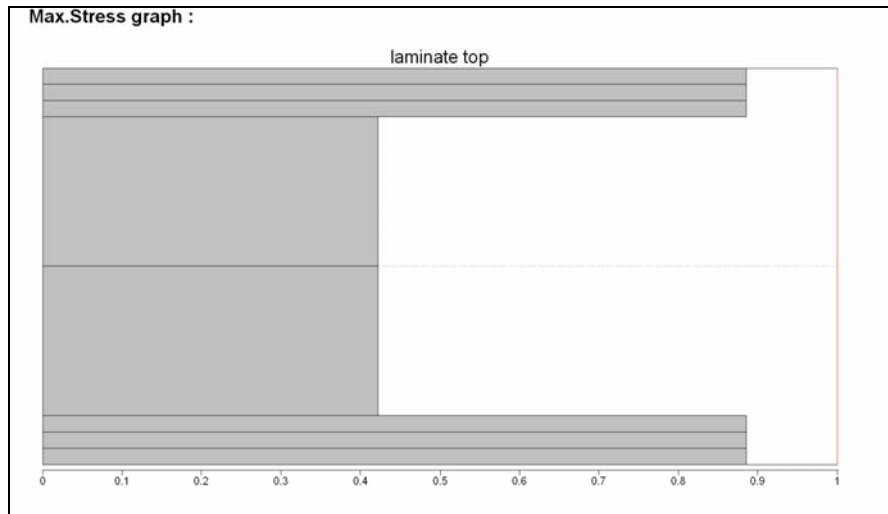


Figure 23: Results from LAP showing failure indices for CSM sandwich structure subjected to in-plane load (Failure criteria considered: Maximum stress)

If we consider the Tsai-Hill failure criteria, it is possible to derive the reserve factors as a function of the failure index. The reserve factor is the inverse of the square root of the failure index and so is equal to 1.28.

b. KOLIBRI results

With Kolibri the analysis can be carried out for one selected laminate and one selected failure criteria at a time. Results obtained for a sandwich laminate made with 3 layers of CSM in each skin are presented in Table 8. These results have been obtained using the Tsai-Hill failure criteria. Comparison of results obtained with a different failure criteria and a different laminate can still be made by running the same analysis several times.

Layer	Angle	Position in layer	RF	Criterion
Top skin	0	top	1.27970960377	Tsai-Hill
		bottom	1.27970960377	
Core	0	top	none	
		bottom		
Bottom skin	0	top	1.27970960377	Tsai-Hill
		bottom	1.27970960377	

Table 8: Results from Kolibri showing reserve factor (RF) for CSM sandwich structure subjected to an in-plane load with 3 layers of CSM in each skin. (Tsai-Hill failure criteria selected)

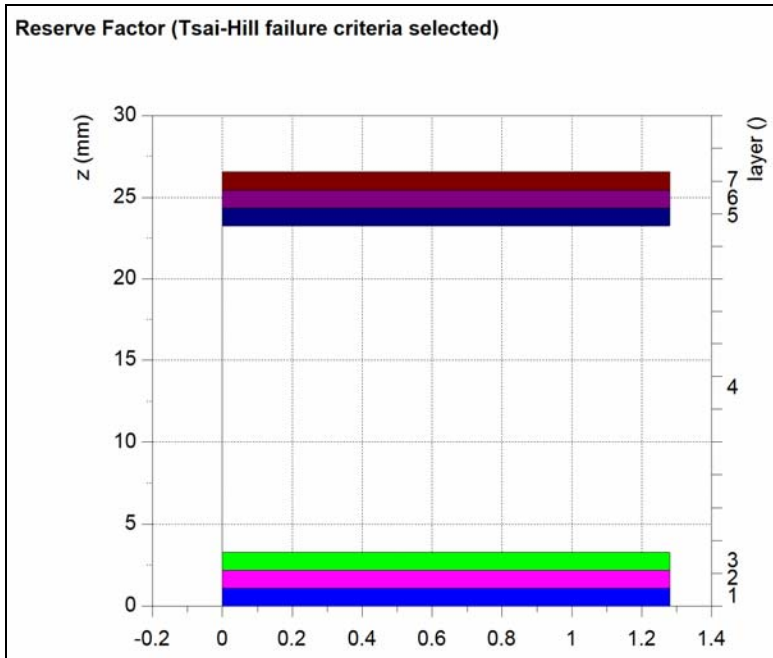


Figure 242: Results from KOLIBRI showing reserve factor for CSM sandwich structure subjected to in-plane load (Failure criteria considered: Tsai-Hill)

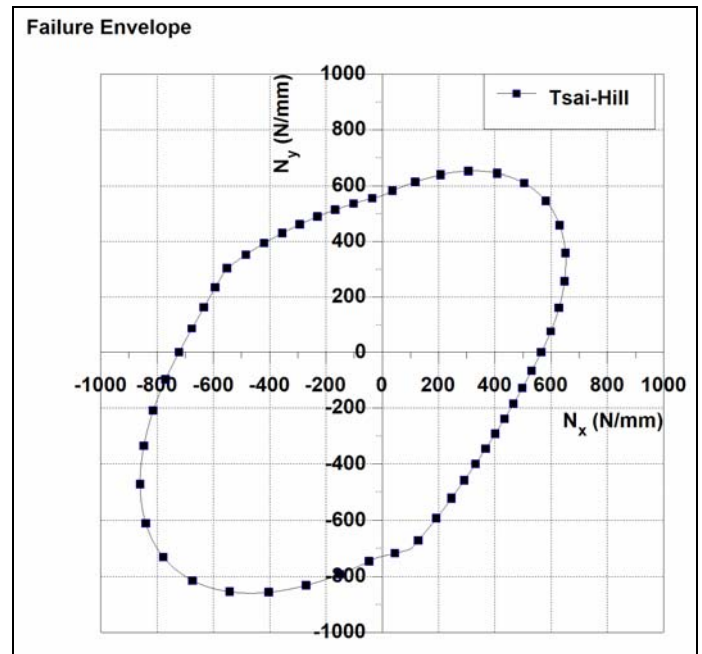


Figure 25: Results from KOLIBRI showing failure envelope for CSM sandwich structure (Failure criteria considered: Tsai-Hill)

c. ESAComp results

The results of the analysis carried out with ESAComp are presented below in Figure 26. These results have been obtained using the Tsai-Hill failure criteria.

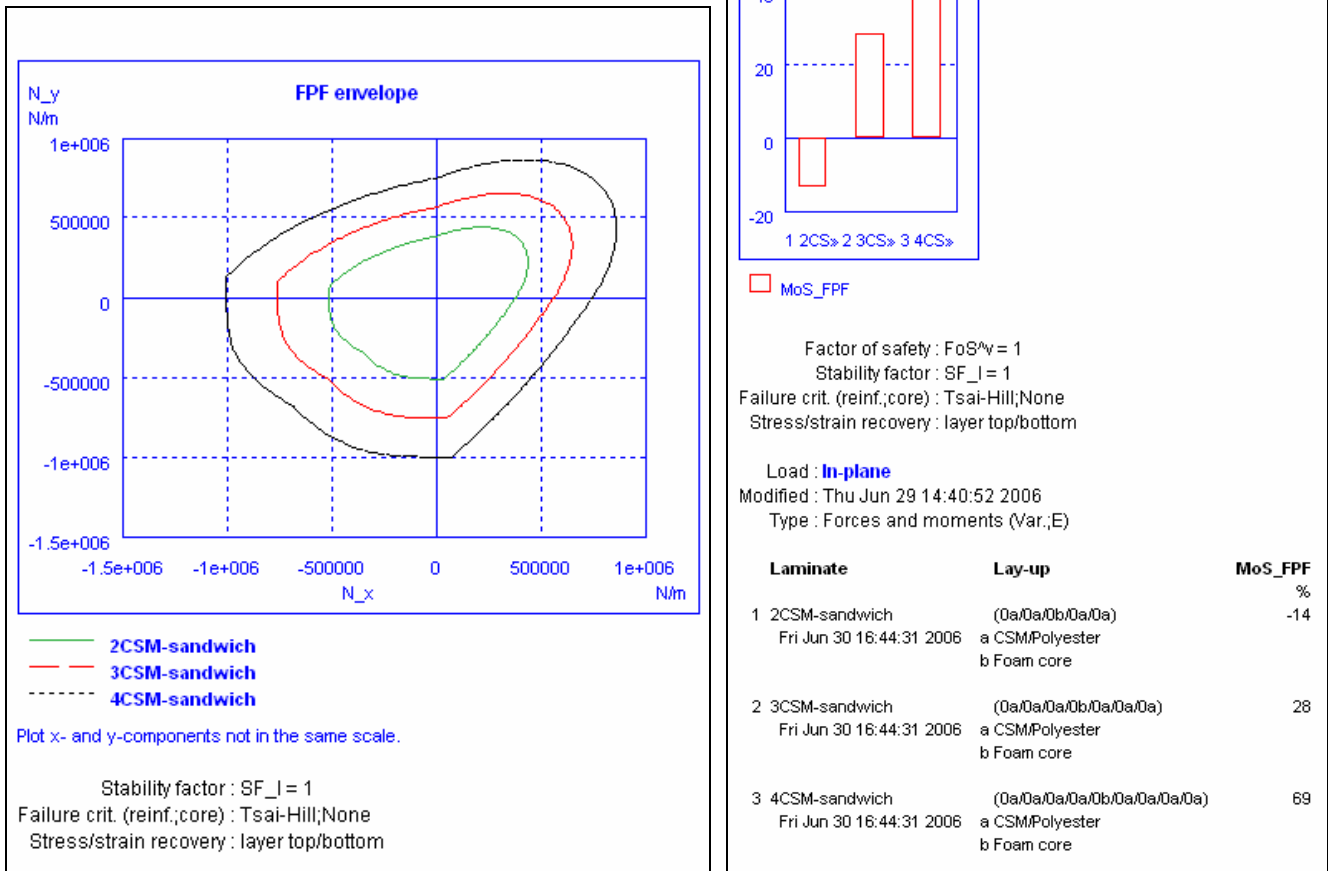


Figure 26: ESAComp results for CSM sandwich structure subjected to in-plane load.

d. Discussion

As expected all of the software provides the same final answer (RF=1.28). Results are presented using different notations which clearly highlights the importance of understanding the meaning of the outputs.

It is also important to understand the assumptions made in the software when running the analysis. The results presented have been obtained using the Tsai-Hill failure criteria. Several failure theories have been developed to model composite failure mechanisms. Often ply-stress failure theories such as maximum stress, maximum strain or quadratic failure (i.e., Tsai-Wu, Tsai-Hill and Hoffmann) are used. These criteria are formulated as a single equation and offer results that are

sufficiently accurate for many problems of practical interest. Other criteria such as Puck and Hashin distinguish between fibre and inter-fibre failure. Different mathematical formulations are then used for different phenomena. Understanding the advantages and limitation of each failure criteria is essential since all these criteria do not always agree and can lead to different failure envelopes as illustrated in Figure 27 and Figure 283.

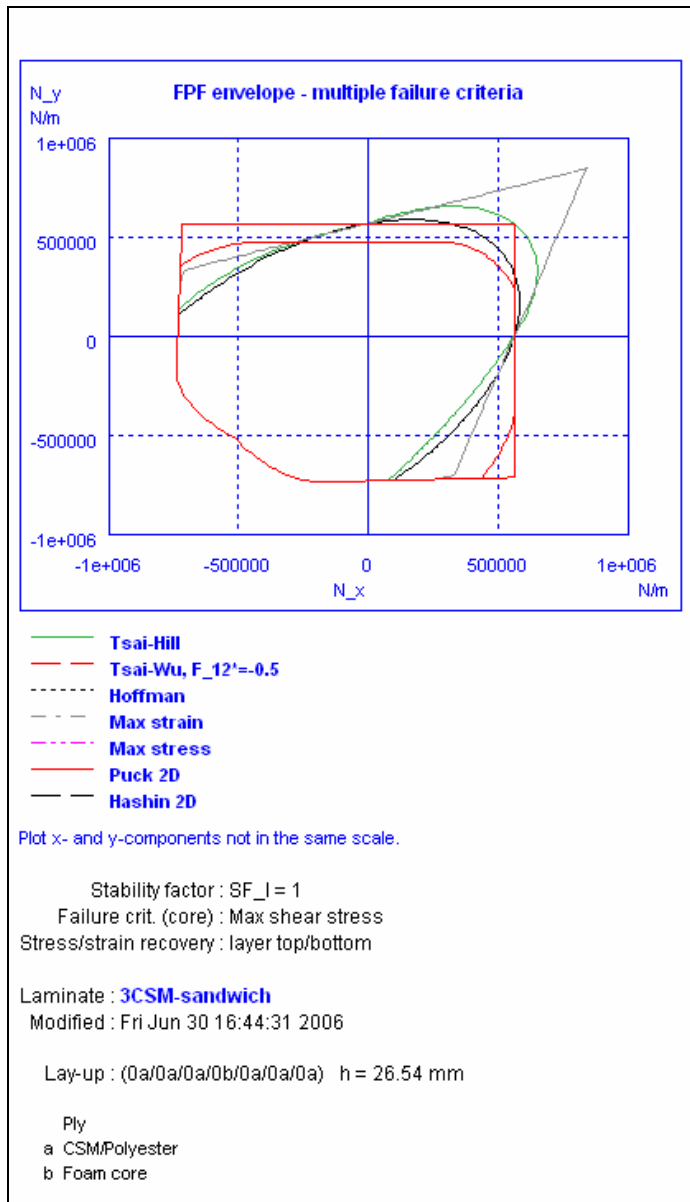
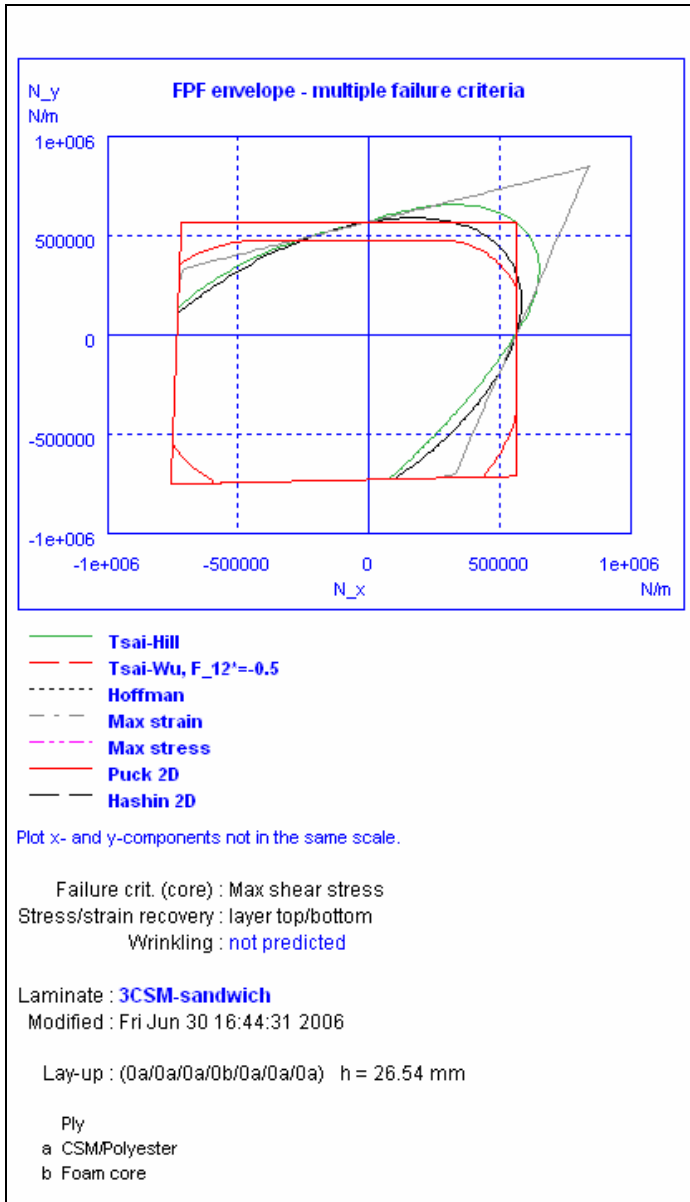


Figure 27: Failure envelopes derived using ESAComp software (ignores skin wrinkling)

Figure 283: Failure envelopes derived using ESAComp software (accounts for skin wrinkling)

Some failure criteria such as Tsai-Wu require the input of a parameter called the Tsai-Wu failure criterion. ESAComp allows one to manually input the Tsai-Wu failure criterion which can be determined via material testing. LAP and Kolibri allow the user to override the value that is calculated automatically for this term, as part of the material strength properties. Understanding the

assumptions made is essential to properly process the computed answers. This means that it is important to ensure that clear documentation on theories used is provided by the software supplier.

3.3.2 Out of plane load

It is assumed for this part of the analysis that a 1000mm by 500mm simply supported sandwich panel is subjected to a uniform design pressure. The skins are assumed to be made of CSM and the core is assumed to be made of PVC foam. It should be noted that the design is mainly stiffness critical. Nevertheless, for the purpose of the exercise strength results are presented and discussed.

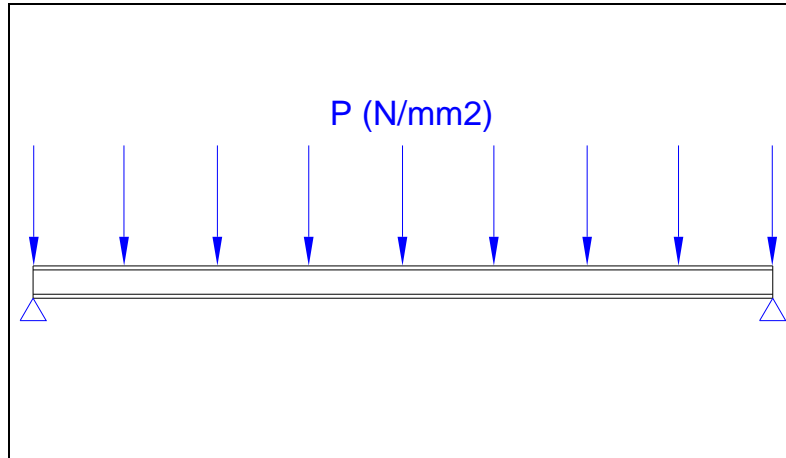


Figure 29: Applied out of plane pressure load case

a. CoDA results

The CoDA sandwich panel analysis allows one to investigate sandwich panels subjected to either design pressure loads, point loads or line loads. CoDA assumes that the core material is stiff enough for shear effects to be small. Shear deformation is therefore not accounted for when carrying out plate analysis with CoDA. The failure ratio provided by CoDA is the maximum panel stress divided by the maximum allowable material stress. CoDA also carries out a skin wrinkling check using two different mathematical models and skin dimpling when honeycomb core is considered.

In Figure30, the benchmark study results obtained using the CoDA tool are presented.

CoDA Panel Report

Data File : Z:\A031179 Design Tool Best Practice\Benchmark_analysis_MM\CoDA files\CSM-sandwich.cd

Sandwich : 3*CSM SANDWICH

Sandwich is fully symmetric.
 Total thickness = 26.54 mm
 Skin is composed of Material : CSM/POLYESTER
 Skin thickness = 3.27 mm (twice = 6.54)
 Core type is : Solid or Foam
 Core thickness = 20 mm
 Core is composed of Material : PVC FOAM CORE

Panel Stiffness :

	Membrane	Flexural	Membrane (skins only)	
Exx =	1.711	3.888	6.750	GPa
Eyy =	1.711	3.888	6.750	GPa
D1 =		6800.1		Nm
D2 =		6800.1		Nm
D3 =		6804.4		Nm

Panel Properties :

Area = 0.5 m²
 Weight = 5.2228 kg
 Weight/Area = 10.446 kg/m²
 Thin Skin approximation ratio = 0.007 (condition <<1 satisfied)
 Weak Core approximation ratio = 0.007 (condition <<1 satisfied)

Solution Parameters :

alpha = 0.01513
 c1 = 0.14803
 c2 = 0.30507

Solution Results :

max. Deflection = 7.419 mm
 at: x / a = 0.500
 at: y / b = 0.500
 max. Moment x = 986.89 N
 max. Moment y = 2033.8 N
 max. Stress x (skin) = 12.970 MPa
 max. Stress y (skin) = 26.728 MPa
 Buckling Coefficients (ult.) :
 skin wrinkling, method 1 - x - 0.873 - y - 0.873
 skin wrinkling, method 2 1.877 1.877
 Skin Failure Ratios :
 membrane tension, initial - x - 0.154 - y - 0.318
 membrane compression, initial 0.107 0.221
 membrane tension, ultimate 0.154 0.318
 membrane compression, ultimate 0.107 0.221
 skin wrinkling, method 1 0.123 0.253
 skin wrinkling, method 2 0.057 0.118
 Maximum Failure Ratio = 0.318
 critical mode : membrane tension y, initial

Figure 30: Results from sandwich plate analysis carried out with CoDA

CoDA computes the failure ratio for sandwich panels. If required, the predicted maximum bending moment can be imported into LAP in order to run a more detailed failure analysis and get failure indices based on selected failure criteria other than Tsai-Wu (see section 3.3.1 for discussion of failure criteria).

b. KOLIBRI results

The same analysis has been carried out with Kolibri. The results file from the panel analysis provides information on maximum deflection, maximum strains, curvatures, forces and moments. The analysis can be easily performed for several combined load cases such as point load with pressure.

Before carrying out a plate analysis with Kolibri, it is necessary to fix the computational settings such as mesh density and element type. When analysing sandwich structures, transverse shear flexibility cannot be neglected and so a thick element should be selected. When using thick elements the input of the material shear modulus in all directions is required. In the results presented below the deflection predicted with first thin and then thick element types are displayed. In this particular case, it has been found that with thin elements, where shear deformation is not accounted for, the overall panel deflection is under-predicted by 36%.

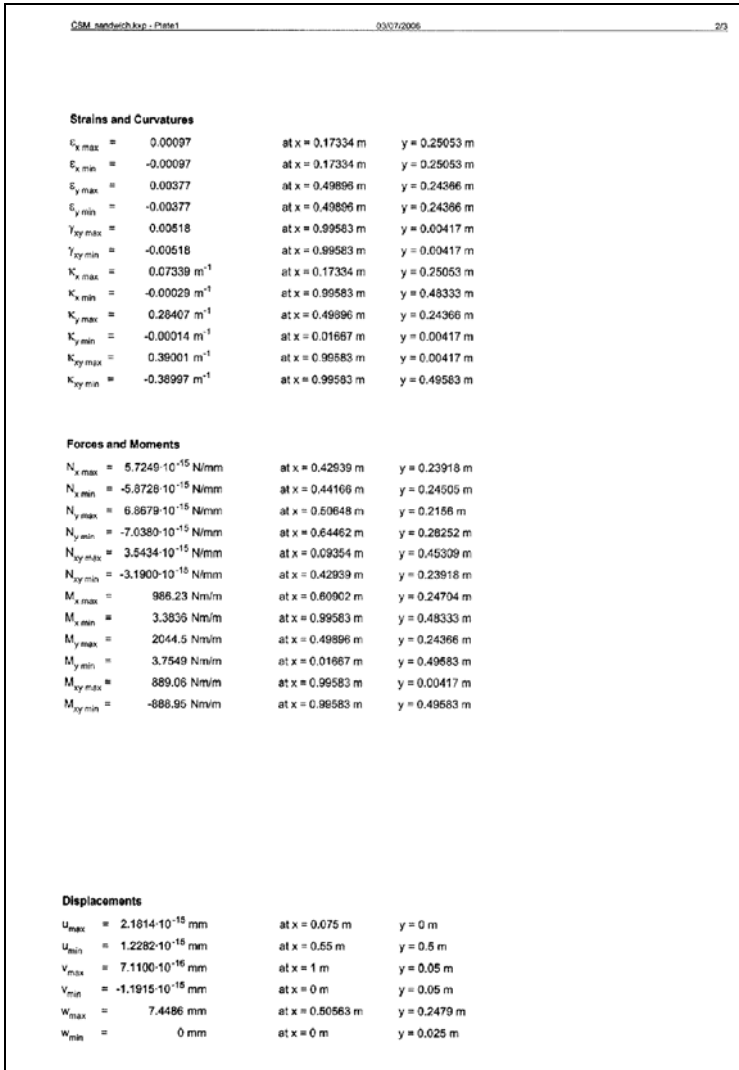


Figure 31: Report showing results obtained using thin elements

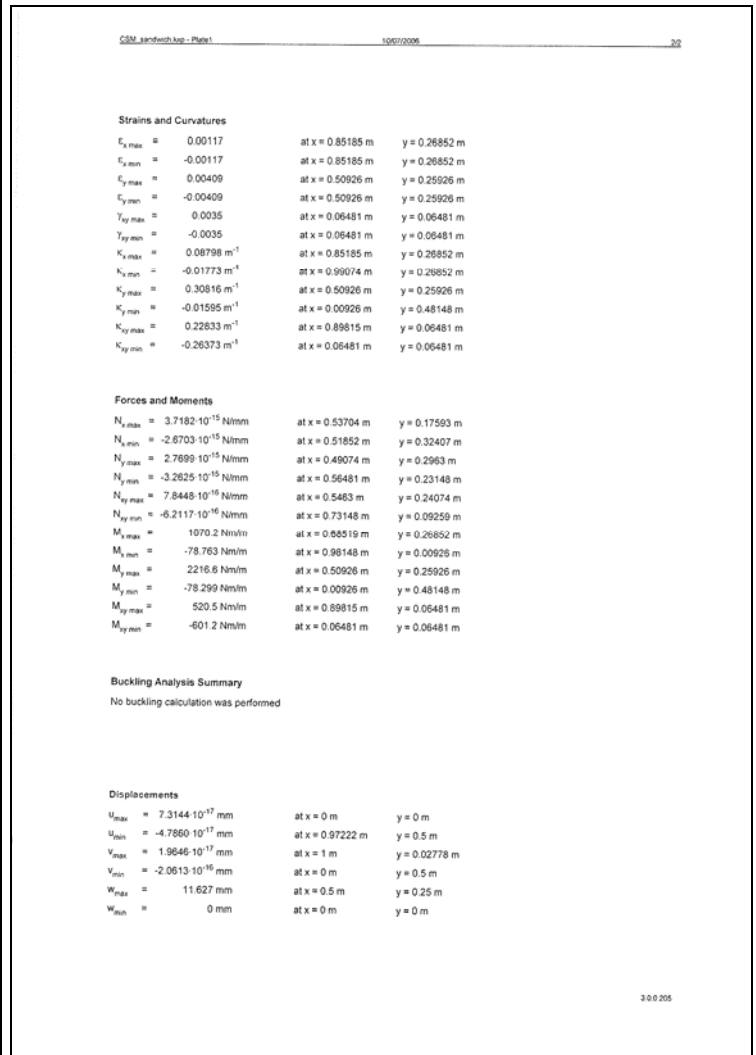


Figure 32: Report showing results obtained using thick elements

Failure indices are not computed when running a panel analysis in Kolibri. However it is possible to enter the results, such as maximum moments, into a laminate analysis and obtain failure indices for each layer.

c. ESAComp results

Results computed using ESAComp are presented in the figure below. ESAComp can compute the predicted deflection, reactions, maximum moments and failure information. In the results presented below, the plate has been found to fail due to core shear. A table of failure mode versus location on the plate is also given.

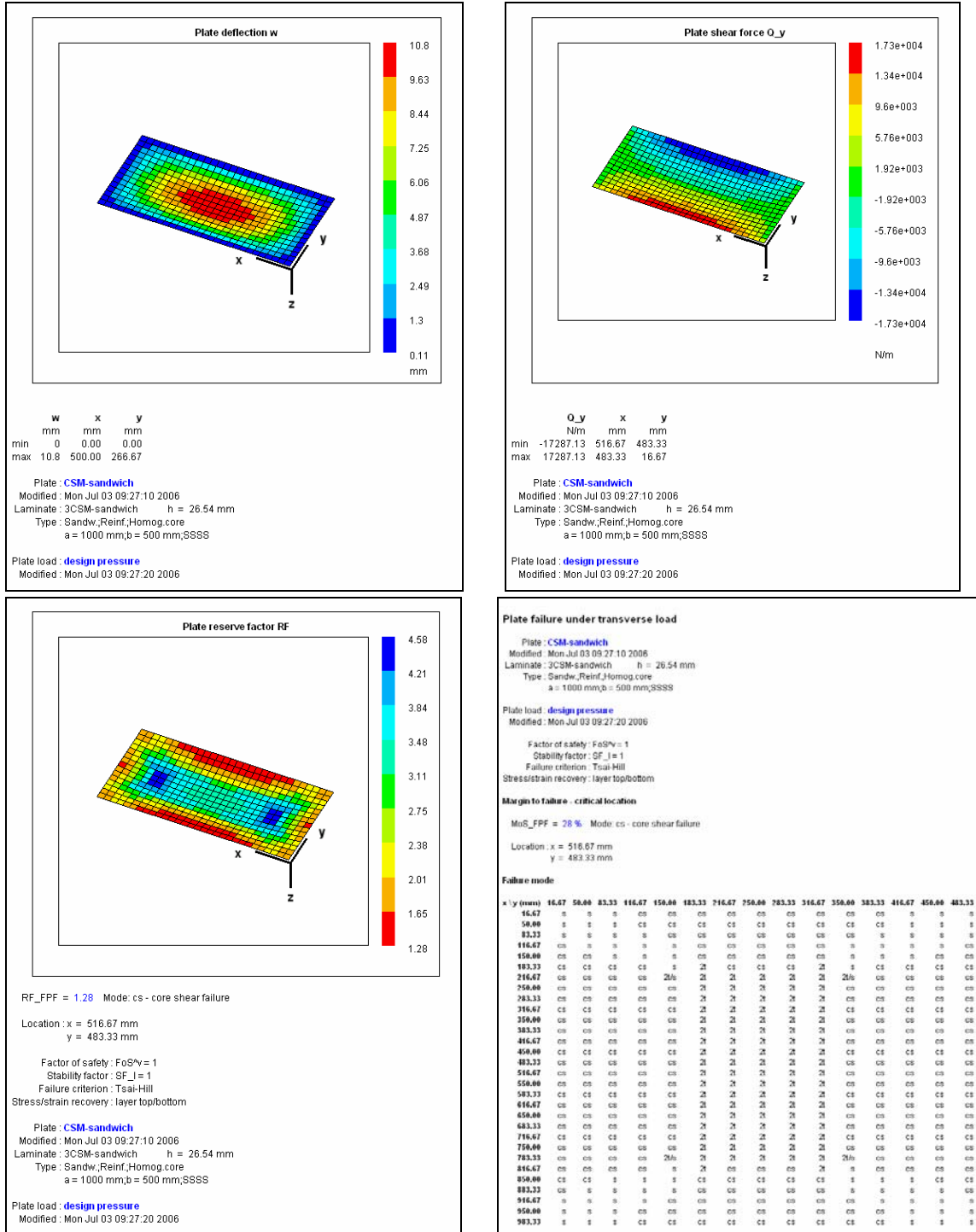


Figure 33: Results from out of plane sandwich plate analysis carried out with ESAComp

With ESAComp, panel loads such as design pressure loads, point loads and line loads can be applied individually or simultaneously. ESAComp requires the input of the through thickness material properties to be able to perform the panel analysis. The First Order Shear deformation theory is used instead of Classical Laminate theory. By using a different mathematical model to predict the response of the composite plate, ESAComp can account for shear deflection and core shear failure.

d. Discussion

As shown in the example presented, most design tools can predict panel deflection. However accurate prediction of sandwich panel deflection required shear deformation to be accounted for in most cases. It is important to be aware that not all the design tool offers this option.

When carrying out design of sandwich structure, the following failure modes should be investigated:

- Skin failure;
- Core shear failure;
- Face wrinkling;
- General buckling;
- Shear crimping;
- Face dimpling;
- Local indentation.

Sandwich failure modes other than skin failure are not always accounted for. General plate buckling can be computed by Kolibri and ESAComp. Skin wrinkling analysis can be carried out using CoDA or ESAComp. Several skin wrinkling theories have been published and it is essential to ensure that the theory provided by the software satisfies your design. CoDA for example computes two skin wrinkling coefficients based on different approaches and ESAComp computes the wrinkling load by considering the face sheet as a plate on an elastic foundation, using empirical values to account for the effect of imperfections. Skin dimpling can occur when honeycomb core is being used. CoDA allows one to compute skin dimpling. Core shear failure, as shown in the example presented, is a common cause of failure for sandwich structures. It can be computed using ESAComp. Shear crimping and local indentation are factors that are not covered by the tools considered.

It can be concluded that depending on the software selected different sandwich failure modes can be investigated. Further software development might resolve this issue. In the mean time, it is essential for the designers to understand the limitation of each tool and to ensure that parameters not accounted for are checked independently.

3.3.3 Summary Tables

Table 9 below summarises the options available within the software presented. It must be noted that this list is based on the information available at the time of the analysis and will need to be reviewed with future software releases.

		LAP	CoDA	Kolibri	ESAComp
Failure criteria for orthotropic plies	Tsai-Wu	✓	✓	✓	✓
	Tsai-Hill	✓		✓	✓
	Max stress	✓		✓	✓
	Max strain	✓		✓	✓
	Hoffman	✓		✓	✓
	Puck 2D				✓
	Puck 3D				✓
	Hashin 2D				✓
	Hashin 3D				✓
	Custom	✓			✓
Failure criteria for homogeneous plies	Von Mises			✓	✓
	Max Stress	✓		✓	✓
	Max Strain	✓		✓	✓
	Max Shear Stress				✓
Stability criteria	Skin Dimpling		✓		
	Skin Wrinkling		✓		✓
	Plate buckling			✓	✓
Shear Effect in plate analysis	Shear deformation			✓	✓
	Through thickness shear failure				✓

Table 9: Summary table for sandwich laminate and panel analysis

3.4 THIRD CASE STUDY: CROSS-PLY LAMINATE ANALYSIS

For the third benchmark study, a cross-ply laminate configuration made of UniDirectional (UD) glass fibre reinforced polymer layers orientated at 0° and 90° is considered. It is assumed that a fibre volume fraction of 0.31% is achieved and that 500g/m^2 fabric weight is used.

3.4.1 Laminate design – In plane compressive load.

In this section, the following laminate sequences are considered:

- Laminate 1 : $(0^\circ/90^\circ/90^\circ/0^\circ)$ denoted $(0^\circ/90^\circ)_{SE}$;
- Laminate 2 : $(0^\circ/90^\circ/0^\circ/90^\circ)_{SE}$;
- Laminate 3 : $(0^\circ/90^\circ/0^\circ/90^\circ/0^\circ/90^\circ)_{SE}$.

The capability of these three laminates to withstand a given in-plane compressive load of 1000N/mm is investigated using the software evaluation design tools.

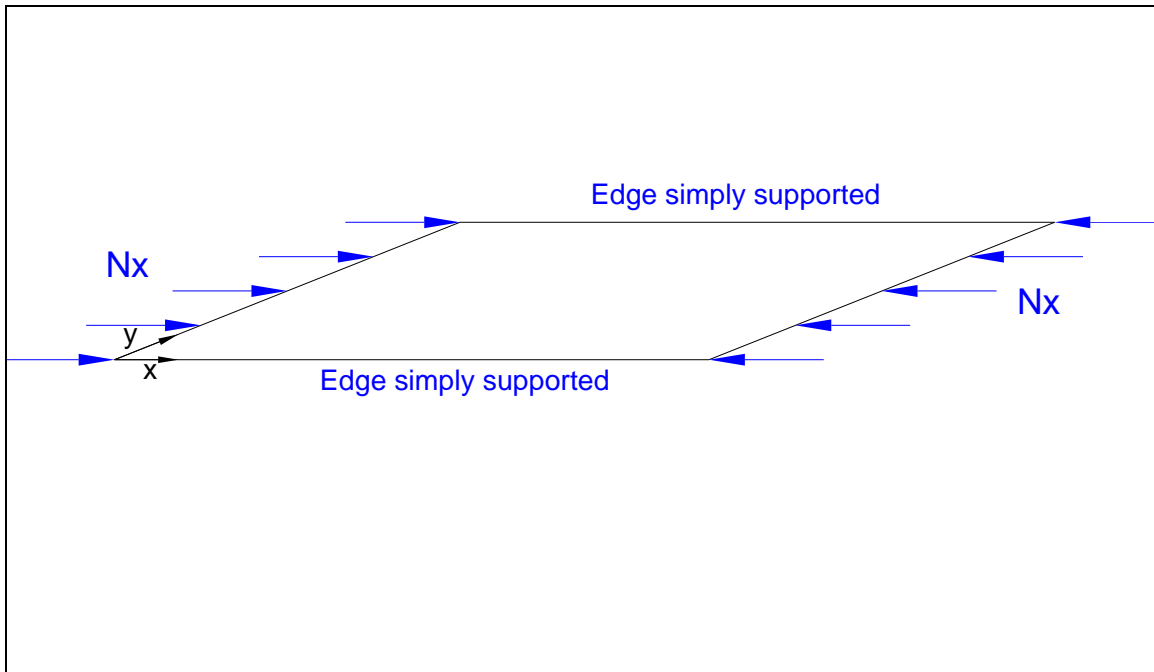


Figure 34: Sketch showing a laminate subjected to an in-plane compressive load

Evaluation design tools provide the engineer with a fast and efficient way to get a first assessment of a selection of laminates subjected to defined load cases.

Results of the evaluation analysis carried out with both ESAComp and CoDA are summarised below. Both products indicate that only laminates 2 and 3 can withstand the load if no factor of safety (FoS) is applied. The factor of safety can be dealt with directly by the designer when post processing the results or by applying factored loads. ESAComp simplifies the post processing task of the designer further by allowing him/her to include a factor of safety as a design input. Different factors of safety can be applied to constant load and variable loads. Stability factors can also be applied when computing wrinkling and buckling loads. Figure shows that if a factor of safety of 1.8 is applied, only laminate 3 should be considered for the design.

Laminate evaluation - Attribute feasibility

Target structure : Laminate

Laminate	Lay-up
1 (0/90)SE Fri Aug 18 15:58:40 2006	(0a/90a)SE a UD (Eglass/Polyester)
2 (0/90/0/90)SE Thu Aug 24 09:29:54 2006	(0a/90a/0a/90a)SE a UD (Eglass/Polyester)
3 (0/90/0/90/0/90)SE Fri Aug 18 15:58:40 2006	(0a/90a/0a/90a/0a/90a)SE a UD (Eglass/Polyester)

Factor of safety : FoS^v = 1
Failure criterion : Tsai-Hill
Stress/strain recovery : layer top/bottom

Laminate Status	(0/90)SE	(0/90/0/90)SE	(0/90/0/90/0/90)SE
	infeasible	feasible	feasible

Lay-up

Ply types	reinforced;	Solid;Reinf.	Solid;Reinf.	Solid;Reinf.
Stacking	symmetric; balanced;	Symm.;Cross-ply	Symm.;Cross-ply	Symm.;Cross-ply
Layer angles	0; 90	feasible	feasible	feasible

Load carrying capability

	infeasible	feasible	feasible
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Load carrying capability

Ibxx=-1000N/mm, Iyy=-40.6N/mm	MoS_FPF (%)	Lam. 1	Lam. 2	Lam. 3
		-40	21	81

Figure 35: Results from ESAComp laminate evaluation design tool (FoS=1)

Laminate evaluation - Attribute feasibility

Target structure : Laminate

Laminate	Lay-up
1 (0/90)SE Fri Aug 18 15:58:40 2006	(0a/90a)SE a UD (Eglass/Polyester)
2 (0/90/0/90)SE Thu Aug 24 09:29:54 2006	(0a/90a/0a/90a)SE a UD (Eglass/Polyester)
3 (0/90/0/90/0/90)SE Fri Aug 18 15:58:40 2006	(0a/90a/0a/90a/0a/90a)SE a UD (Eglass/Polyester)

Factor of safety : FoS^v = 1.8
Failure criterion : Tsai-Hill
Stress/strain recovery : layer top/bottom

Laminate Status	(0/90)SE	(0/90/0/90)SE	(0/90/0/90/0/90)SE
	infeasible	infeasible	feasible

Lay-up

Ply types	reinforced;	Solid;Reinf.	Solid;Reinf.	Solid;Reinf.
Stacking	symmetric; balanced;	Symm.;Cross-ply	Symm.;Cross-ply	Symm.;Cross-ply
Layer angles	0; 90	feasible	feasible	feasible

Load carrying capability

	infeasible	infeasible	feasible
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Load carrying capability

Ibxx=-1000N/mm, Iyy=-40.6N/mm	MoS_FPF (%)	Lam. 1	Lam. 2	Lam. 3
		-67	-33	0

Figure 36: Results from ESAComp laminate evaluation design tool (FoS=1.8)

LAP batch results
LAP version: 4.0/356 Exported 16 Aug 2006 15:46

Lay-up	Loading	Stiffness	Tsai-Wu	Tsai-Hill	Hoffman	Max.Stress
Max.Strain						
(0/90)SE	COMPRESSION	FAIL	FAIL	FAIL	FAIL	FAIL
(0/90/0/90)SE	COMPRESSION	PASS	PASS	PASS	PASS	PASS
(0/90/0/90/0/90)SE	COMPRESSION	PASS	PASS	PASS	PASS	PASS

Table 10: Results from LAP laminate evaluation design tool

In addition to getting a direct answer on the feasibility of selected laminates to withstand a given load, the ESAComp design tool allows one to plot design envelopes. Design envelopes provide more general information on the maximum loads that can be applied to given laminates. In Figure, two examples of failure envelopes are provided. In the first example design envelopes for in-plane loads are shown and in the second example design envelopes for applied moments are provided. These plots help the designer to get a good understanding of the load capacity of the selected laminates.

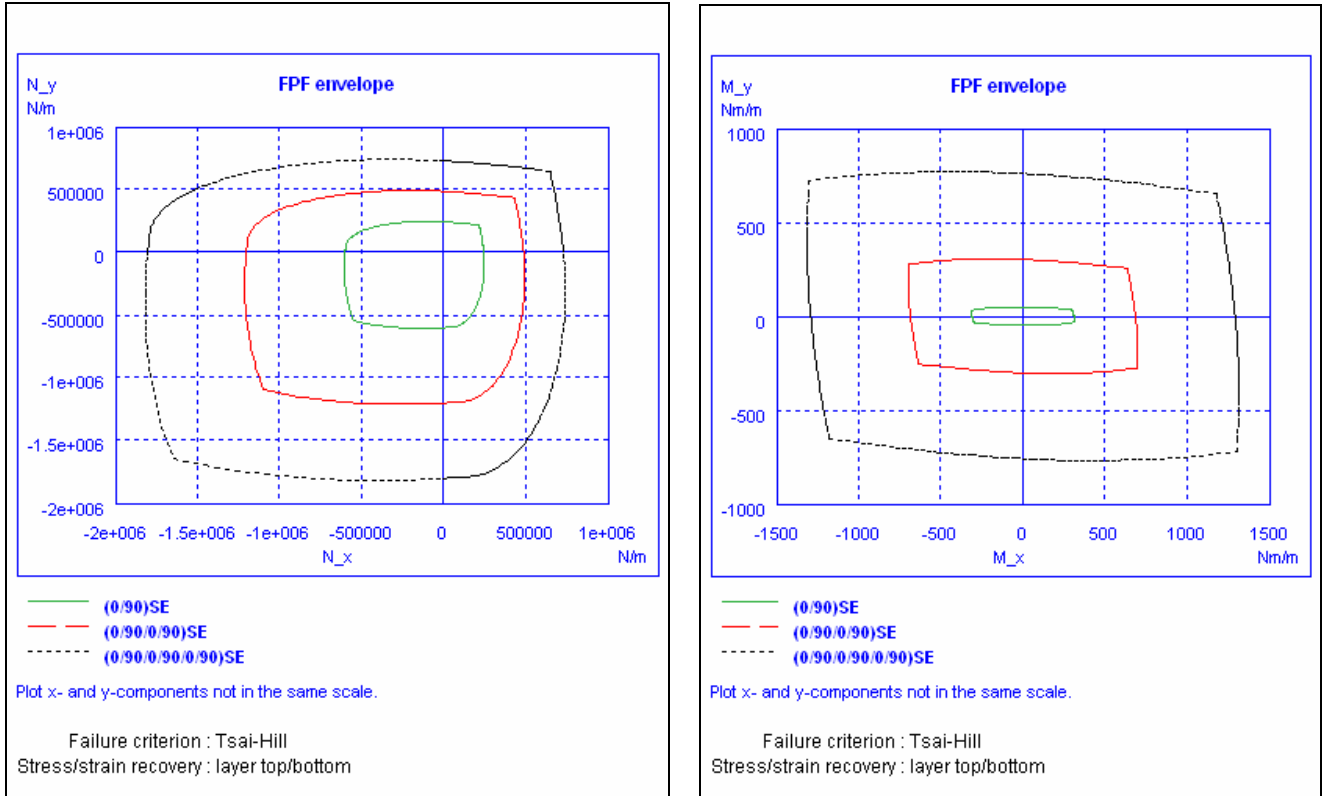


Figure37: Design envelopes from ESAComp

3.4.2 Panel analysis – Stability check

Designing FRP panels requires not only checking the strength of its constitutive laminate but also deriving the panel buckling load and ensuring its stability. This can be achieved using close form solutions and/or design panel tools as shown in the following.

A 1000mm by 125mm simply supported plate subjected to an in-plane compressive load of 1000N/mm is considered. The plate is assumed to be made of laminate 3 defined in section 3.4.1. According to the preliminary design analysis carried out, this laminate is strong enough. This, however, does not mean that the plate is stable under this load. This must also be checked.

a. Closed form solution

The buckling load of a rectangular orthotropic composite plate with a symmetric lay-up can be derived using a closed form solution based on the classical laminate theory. The predicted buckling load for such a simply supported panel can be derived using the following equation [Ref.3].

$$N_{x,cr} = \frac{\pi^2}{b^2} \left(D_{11} \frac{b^2}{l_x^2} + D_{22} \frac{l_x^2}{b^2} + 2(D_{12} + 2D_{66}) \right)$$

Where, $l_x = \frac{a}{i}$ and i represents the number of half waves in the x direction.

Using the above relation it has been found that the lowest critical buckling load for the 1000mm by 125mm plate is obtained for 7 half waves in the x direction and is equal to 950N/mm.

b. Kolibri results

As already mentioned in section 3.3, Kolibri can run the analysis using thin or thick element types. The results presented below shows the difference in the predicted buckling load depending on the type of element used to carry out the analysis.

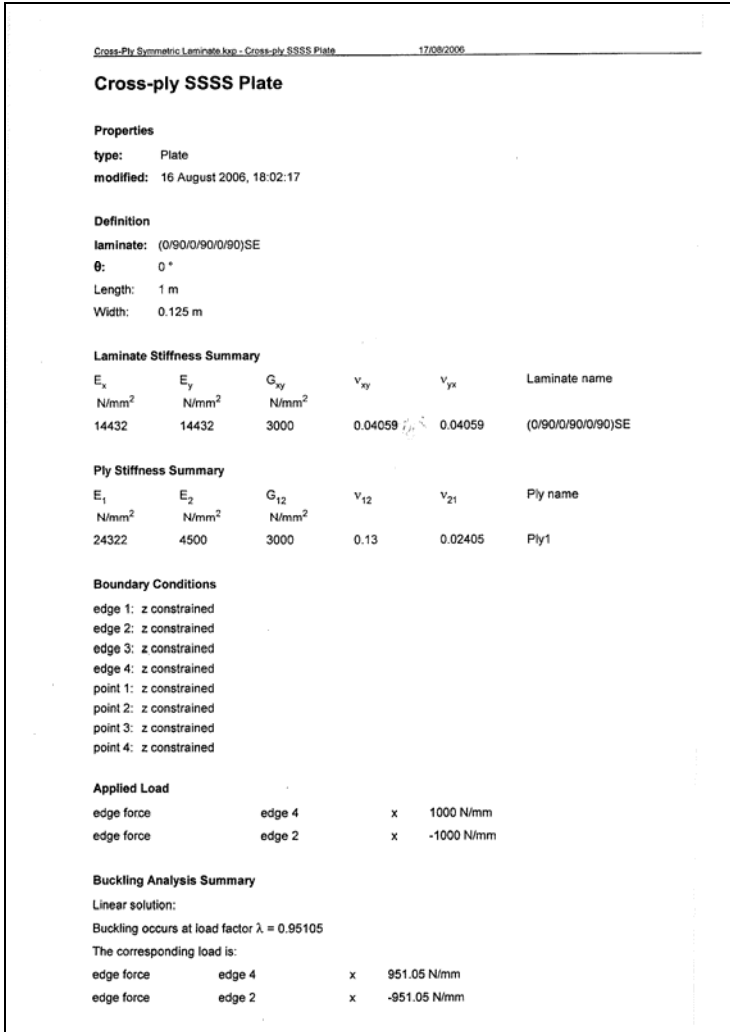


Figure 38: Report showing results obtained using thin elements

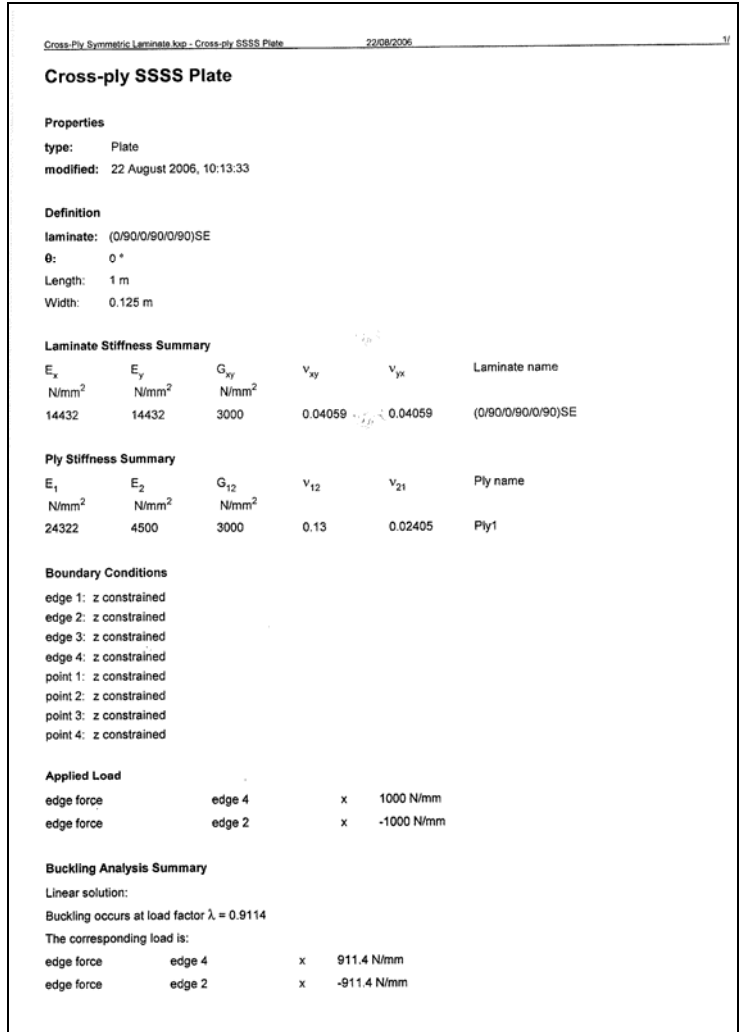


Figure 39: Report showing results obtained using thick elements ($G_{23}=00\text{MPa}$)

The results obtained using the closed form solution and using the Kolibri panel analysis tool are summarised in Table 3. These results, which do not include any factor of safety, indicate that the plate fails due to buckling.

	Closed form solution	Kolibri with second order thin elements	Kolibri with second order thick elements ($G_{23}=1800\text{MPa}$)
Buckling Load (Ncr)	950N/mm	951N/mm	911N/mm

Table 3: Calculated buckling load

As expected when using thin elements, the predicted buckling load is identical to the buckling load predicted using the closed form solution. By using thicker elements, the transverse shear deformation is accounted for. Accounting for shear deformation becomes important when the thickness of the laminate increases as demonstrated by Reddy's work [Ref.4]. However to be able to account for this effect, the out-of-plane properties of each layer is required. However, such properties are not widely available and using a tool based on classical laminate theory is often the only option.

c. ESAComp results

ESAComp can also be used to carry out buckling analysis. For the same plate, ESAComp gives a buckling load of 1012N/mm. This value is 6.5% higher than the buckling load predicted using the closed form solution. This higher value is directly linked to the mesh size used to compute the results. ESAComp confirmed that a finer mesh option will be available in their next release 4.0.

d. Discussion

The above analysis indicates that it is important to carry out stability analysis as well as strength analysis on structural elements under compressive load. Buckling analysis of panels can be carried out using some panel design tools. The study presented demonstrates that it is essential to understand the theories used, the assumptions made by the solver and the implications these can have on the design.

ESAComp allows one to define a stability factor and will provide the factored buckling load.

3.4.3 Non-stiffened panel subjected to out of plane load

In this section, the analysis of a 600mm by 300mm simply supported laminated panel subjected to point or patch load of 2500N is carried out as shown in Figure 40 and Figure 41. The same laminate is considered as in section 3.4.2.

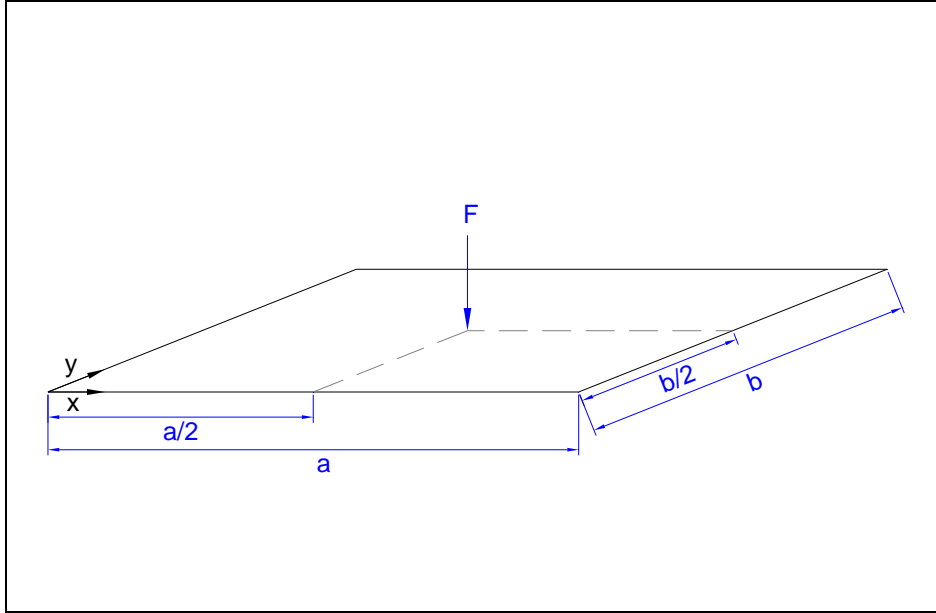


Figure 404: Rectangular plate subjected to point load

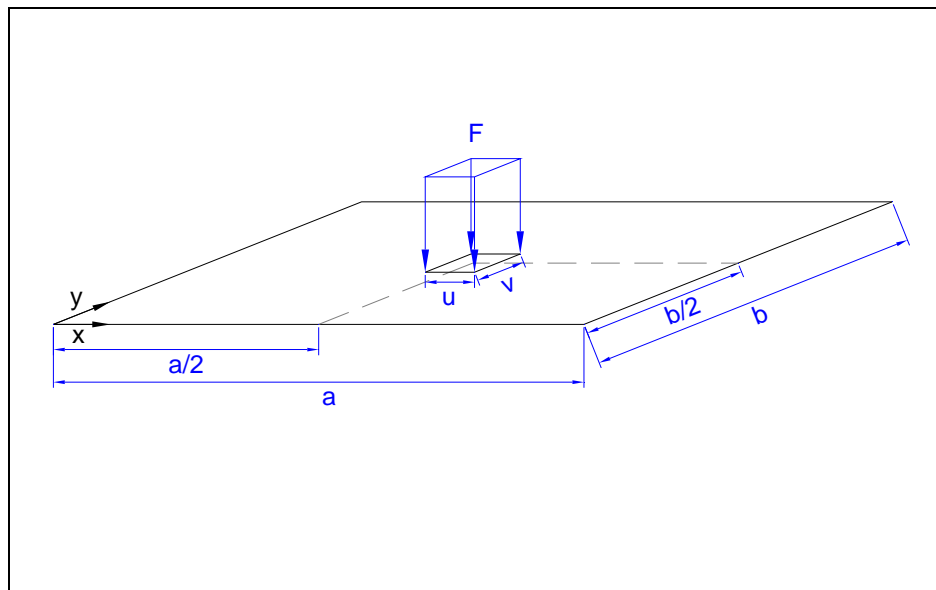


Figure 41: Rectangular plate subjected to patch load

a. Closed form solution

Using anisotropic plate theory from Timoshenko [Ref. 5], a closed form solution of a plate subjected to out of plane loads can be derived. Deflection and maximum moments can be calculated for the plate subjected to a point load and a 35mm wide square patch load both applied at its centre. The results derived using an in-house spreadsheet are summarised below. It should be noted that the predicted results do not account for shear deformation.

	Closed form solution based on Timoshenko theory (point load applied)	Closed form solution based on Timoshenko theory (patch load applied)
Maximum deflection	9.57mm	9.42mm
Maximum moment, M _x	993 Nm/m	658 Nm/m
Maximum moment, M _y	1080 Nm/m	724 Nm/m

Table 42: Plate results based on Timoshenko's plate theory

b. Kolibri results

The same analysis has been carried out with Kolibri using the following computational settings:

- Small mesh density and thin elements;
- Small mesh density and thick elements.

As expected, the results obtained using thin elements are similar to the results obtained using the in-house program.

	Point load - Second order thin elements - Fine mesh	Point load - Second order thick elements - Fine mesh	Patch load - Second order thick elements - Fine mesh
Maximum deflection	9.58mm	9.72mm	9.50mm
Maximum moment, M _x	994Nm/m	978Nm/m	639 Nm/m
Maximum moment, M _y	1052.5Nm/m	1075.4Nm/m	703 Nm/m
Maximum moment, M _{xy}	82Nm/m	82Nm/m	81 Nm/m

Table 53: Kolibri's plate results

c. CoDA results

Two analyses have been carried out using CoDA. In the first case all the plies have been modelled whereas in the second case a laminate made of 1 layer with equivalent properties to the 12 layer laminate has been considered. This has been done to demonstrate that by using an equivalent uni-layer laminate it is possible to compute not only plate deflection and applied moment but also failure and reserve factors with the CoDA plate design tool as shown in Figure 42. Figure 42 also indicates that CoDA provides results corrected for geometric non-linearity.

	CoDA	CoDA (plate modelled using equivalent uni-layer laminate)
Maximum deflection	9.72mm	9.75mm
Maximum moment, M _x	720N	723N
Maximum moment, M _y	880N	883N
Failure information	N.A	Reserved factor provided

Table 64: CoDA's Plate results for a point load

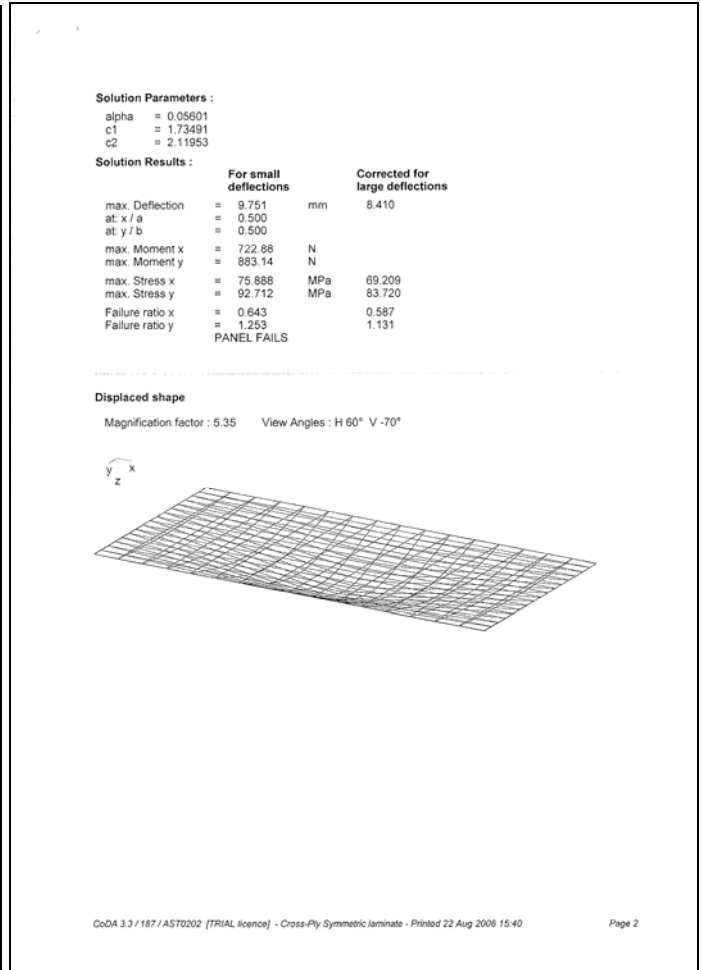
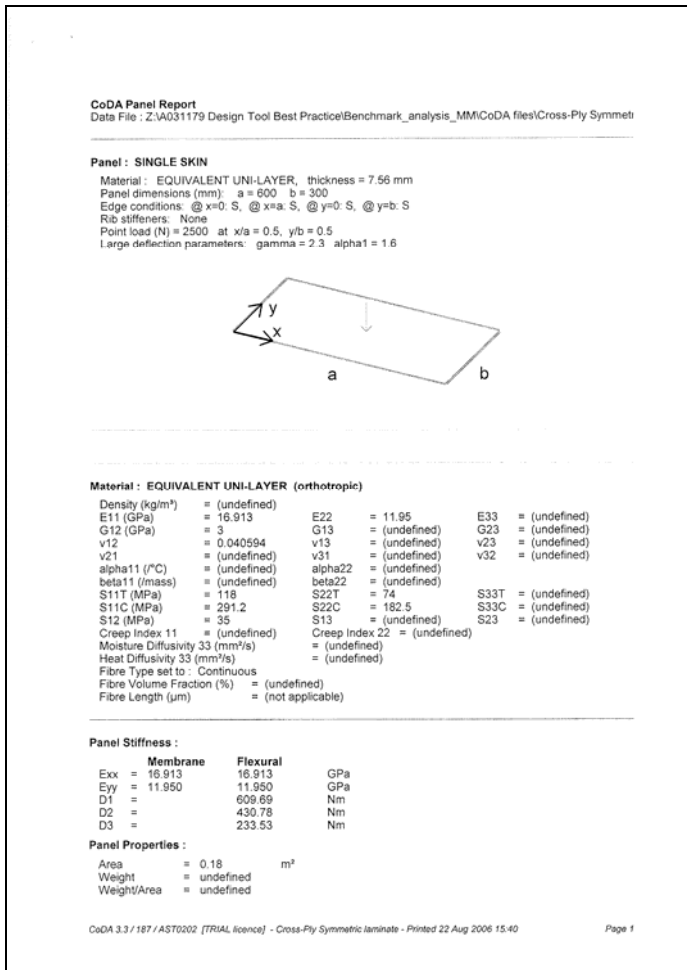


Figure 42: CoDA results for uni-layer plate subjected to point load

d. ESAComp results

The same analysis has been carried out with ESAComp for a point load applied at the centre of the plate, see Table 75.

Maximum deflection	9.69mm
Maximum moment, M _x	638.6Nm/m
Maximum moment, M _y	718Nm/m
Maximum moment, M _{xy}	± 80Nm/m
Failure information	Provide warning on large Computed reserve factors

Table 75: ESAComp's plate results

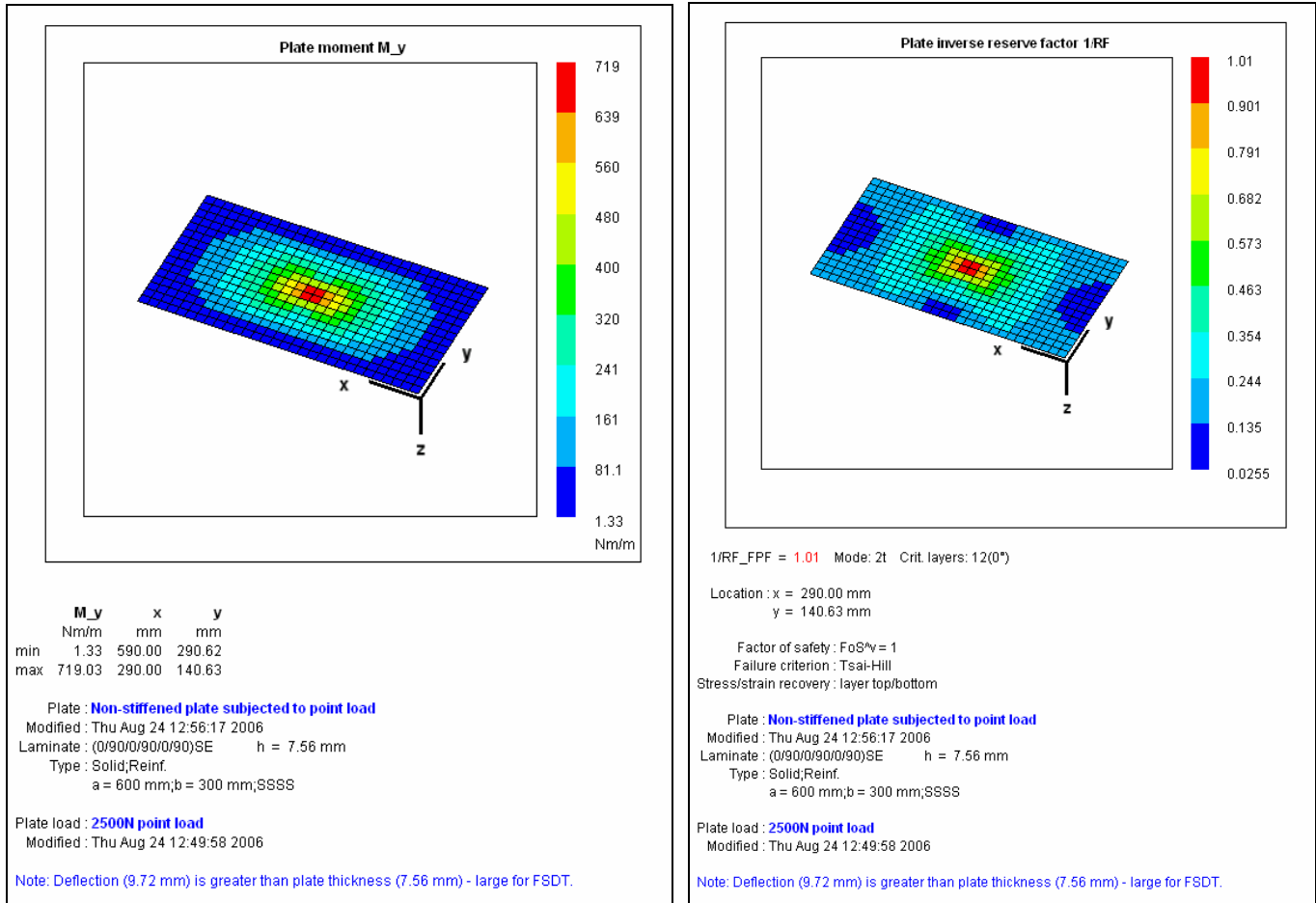


Figure 43: ESAComp results for plate subjected to point load

Due to the default mesh density used by ESAComp, the results are valid for a load applied over a small area. This explains why ESAComp results for a plate subjected to a patch load are similar to those from a closed form solution and Kolibri. It should be noted that in most design cases, any out of plane load acting on a panel is likely to be spread over a small area. Using a point load approach is, in most cases, a conservative design approach.

e. Summary and discussion

The deflection values predicted with the different design products are within 1.5% of each others. All the design tools which account for shear deformation give the same answer (scatter in the results being less than 1%). ESAComp and CoDA can provide information on possible failure. This could also be obtained with Kolibri by importing the maximum bending moment into the laminate analysis. ESAComp also provides a warning on panel flexibility. This highlights an important issue. Linear analysis does not accurately predict the response of a structure subjected to large deflection. Indeed, if the plate is supported along its edges the resulting in-plane or membrane stress carries part of the load and the plate is effectively stiffer than expected from a bending analysis.

When large deflection occurs nonlinear analysis should be carried out. This is often carried out using a finite element model. Kolibri allows one to carry out non linear analysis. This type of analysis should be carried out using a computer equipped with a fast processor as it has been found to be time consuming. CoDA on the other hand allows one to estimate the plate response subjected by large deflection using a revised load-deflection relation. This requires the input of large

deflection correction parameters. These parameters are dependent on the plate shape and edge conditions. The default values provided by CoDA are for guidance only. It is the responsibility of the designer to ensure that these values are satisfactory for a given design. The plate analysis presented in this section has been run using default CoDA large deflection parameters for a rectangular simply supported plate. A reduction of 11.7% in deflection is predicted.

By assuming that the load is acting over an area of 35mm by 35mm a decrease of 34% in the applied bending moment is obtained. This will have an effect on the stress in the laminate plies and on the predicted failure. It is essential to ensure that the computed results are realistic and valid for the design case considered. This highlights the fact that interpretation of the results requires a good understanding of the assumptions made in the analysis.

Large deflection and failure of the plate have been predicted indicating that the design concept needs to be revised. One possible way to improve the design is to add stiffeners. This is investigated into in the next section.

3.4.4 Stiffened panel subjected to out of plane load

CoDA and ESAComp allow one to analyse stiffened plates. The design of the plate presented in the previous section is reviewed below using both of these products.

a. Design of stiffened plate using CoDA

CoDA allows one to analyse rectangular panels stiffened by means of integrated stiffeners. The program determines the increased stiffness of the panel by modelling it as an equivalent orthotropic plate with enhanced flexural rigidity in the direction of the ribs. The ribs have to be made of the same material. This module is mainly suitable for SMC, DMC and thermoplastic moulding compounds and it is possible to account for up to ten ribs. The rib height and width must be specified.

For the purpose of this benchmark study, the plate analysed in section 3.3.3 is stiffened with one 50mm deep and 4mm wide transverse rib half way along the plate. The stiffener and computed results are presented in Figure.

Adding the rib reduces the deflection to an acceptable level of 0.6mm. It should be noted that CoDA does not account for any factor of safety. This should be accounted for by the designer.

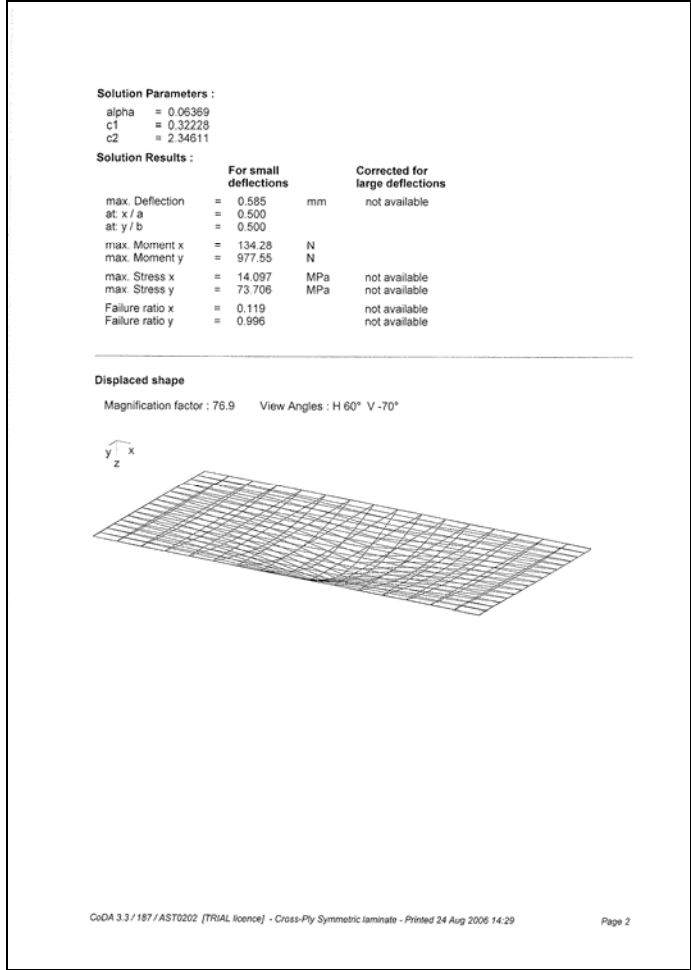
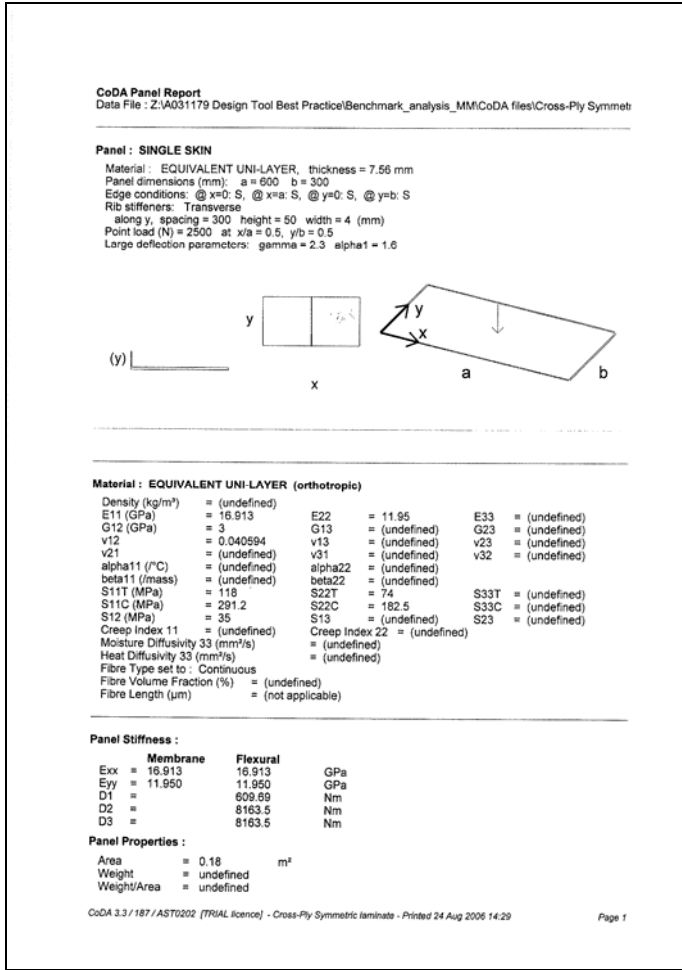


Figure 44: CoDA results for stiffened plate subjected to point load

b. Design of plate stiffeners using ESAComp

ESAComp allows one to carry out analysis of a plate stiffened using I, C, T or Z ribs. Different laminates can be specified for the flange and the webs. For the purpose of this exercise, the stiffened plate configuration analysed with CoDA's tool is used. The results are presented below.

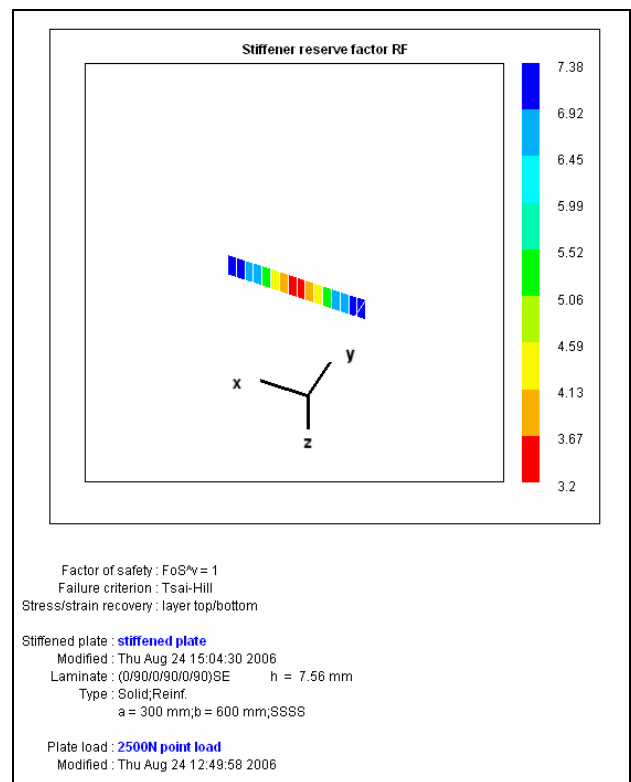
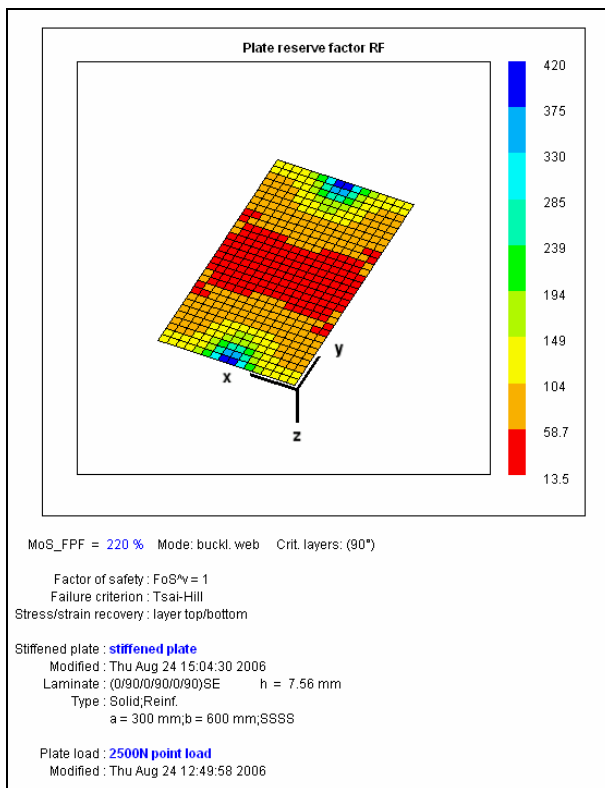
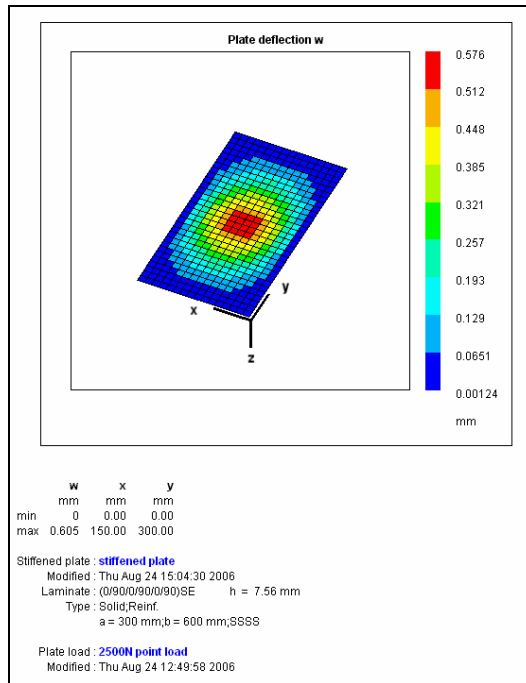


Figure 45: ESAComp results for stiffened plate subjected to point load

As expected a similar deflection of 0.6mm is predicted. Because ESAComp looks at a small patch load the applied moment values predicted are lower and so the computed reserve factor is higher. It should be noted that ESAComp accounts for possible buckling of the rib as well as the plate and

gives independent reserve factors for the rib web, rib flanges and the plate, helping the designer to identify which structural elements need to be reviewed and/or optimised.

3.4.5 Summary Table

The table below summarises the options available within the software products reviewed. Please note that this list is based on information available at the time of the analysis and will need to be reviewed with future software releases.

		CoDA	Kolibri	ESAComp
Load cases	Point load	✓	✓	✓
	Patch load		✓	
	Constant Line load	✓		✓
	Linearly varying line load			✓
	Uniformly distributed load	✓	✓	✓
	Distributed load varying linearly along edges		✓	✓
Boundary conditions	Edge simply supported	✓	✓	✓
	Edge free	✓	✓	✓
	Edge clamped	✓	✓	✓
Outputs	Maximum Deflection	✓	✓	✓
	Maximum moments, Mx and My	✓	✓	✓
	Maximum moment, Mxy		✓	✓
	Maximum shear force, Qx and Qy			✓
Plate buckling		✓	✓	
Failure indices	Direct output			✓
	Direct output for direct stress in homogeneous plate	✓		
	Can be computed but require to run laminate analysis		✓	
Stiffened plate		✓	✓	

Table 16: Summary table for panel analysis

3.5 CONCLUSION ON LAMINATE & ANALYTICAL TOOLS BENCHMARK STUDIES

Several benchmark studies have been carried out to demonstrate the potential of composite design tools and to highlight the importance of understanding the theories used by each product and their limitations. It is important to appreciate that only some of the capabilities of the tools have been presented within the benchmark studies. Tables 1 and 2 in section 2.3 give an overview of the capability of the design tools reviewed.

4. REFERENCES

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2. Henrik Karlsson, *Evaluation of FE-Software for Mechanical Analysis of Composite Materials*, Master's Thesis, Luleå University of Technology, 2005.
3. László P. Kollár and George S. Springer, *Mechanics of Composite Structures*, Cambridge University Press, 2003.
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5. S. P. Timoshenko and S. Woinowsky-Krieger, *Theory of Plates and Shell*, McGraw-Hill International Editions, 1959.
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Appendix 1

A Second Opinion on Factors for Selecting Design Software for Composites

Functionality

- What does it do? Predict properties, stress analysis, failure, and fatigue in composites.
- Does it handle different composite structural types, laminates fabrics, sandwich/cored structures, short fiber composites?
- What level of detail does it predict: micromechanics, macromechanics, structural only, or all levels?
- Does it handle manufacturing and predict properties based on processing which include predicting flow, fiber alignment, and degree of cure, residual stresses and final morphology?
- Is it an effective manufacturing design tool that truly captures the process for draping, fiber placement, and pattern generation? Is optimization possible for any of the above?

Accuracy in prediction

Unlike isotropic structures, predicting composite properties is not trivial and requires complex models to accurately capture the behavior of these complex structures. Accurate models are required as the results from these models define your design and, beyond testing, there is no way to know whether the part meets structural requirements. There are also many other factors to deal with composites, such as internal thermal stresses, property variations, defects that can lead to catastrophic failure unless these factors are taken into account. Accurate predictive software is a must especially when much of the design will hinge on the numbers it predicts.

Ease of use

As you know there is a lot more to deal with when designing with composites, more properties, more modes of failure and inherently more flexibility and complexity in design as a result.

- Can the software be easily utilized to facilitate such design considering the nature of these materials?
- How dynamic are the design loop features of the software?
- Can an engineer quickly optimize a composite knowing all the design parameters or can the software help the user when parameters are somewhat flexible or unknown?

Adaptability with other commercial packages

Any design software on the market must be able to transfer data to most of the major FEA packages. Designers can then make decisions with one package to the best of that code's ability and then transfer properties, laminate data etc. to their standard in-house codes for detailed analysis. Engineers should be able to use what they know in FEA or custom analytical tools and combine it with the output of from the composite software. Software tools that aid in processing must also seamlessly communicate to the equipment used in manufacture: filament winders, tape placement, laser projection systems etc.

Cost

Now you might consider cost to be higher up on the scale, and for smaller businesses it usually is. But ultimately you have to weigh the cost of time for engineers designing poorly without the adequate tools, against the investment cost in design software that allows engineers to effectively optimize composite structures. Poor design can lead to cost headaches downstream

when expensive composite parts are made, tested and fail prematurely. It's always better to know up front than pay for it later. This applies to any engineering discipline but especially so with composites due to cost and complexity.

There are a number of other minor areas, that include training, support etc. that should be considered but these are the big five. If the software has all these then you're a long way towards having the right tool for the job.

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