Composite design procedure for racing cars

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Abstract

In this document few tested procedures to design composite parts for racing cars:

	DESIGN for STIFFNESS	**DESIGN for STRENGTH**
METAL PARTS	Checking the deformations	Checking the Von Mises Stresses < Yield stress
Possible modifications:	➢ Thickness ➢ Shape ➢ Material (Al, Fe, Mg,…) ➢ Adding or removing ribs	
COMPOSITE PARTS	✓Checking the Strain Energy ✓The strains ✓The deformations	Checking the Principal stresses and using failure criteria like Tsai-Wu or maximum strain
	For both approaches a global or a ply-by-ply analysis is possible	
Possible modifications:	➢thickness and angle of the single ply ➢materials, type of fiber, Tape or Fabric ➢shape ➢Use of different cores ➢special reinforcements into the lay-up	

Introduction

Main differences with metals:

- ✓ Composite materials are orthotropic and not isotropic
- ✓ Tensile and compressive strength are different
- ✓ The strengths along the fibers are different from those transverse to them
- ✓ Shear strength is also independent making a total of five strengths instead of one
- ✓ The elastic modulus changes drammatically according to the material used, the angle, the kind of fiber and the type of prepreg (tape or fabric)
- ✓ Delamination problems
- ✓ They don't have yield point so they completely work in the linear field
- ✓ Low properties for load out of plane and mainly depending from the matrix system

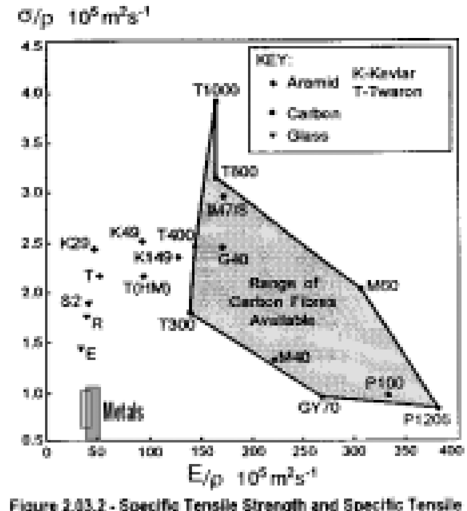


Figure 2.03.2 - Specific Tensile Strength and Specific Tensile Modulus (for Fibres in Figure 2.03.1)

Composite common use at Dallara

Monolithic structures

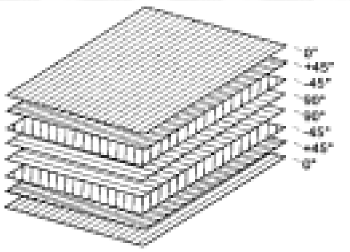
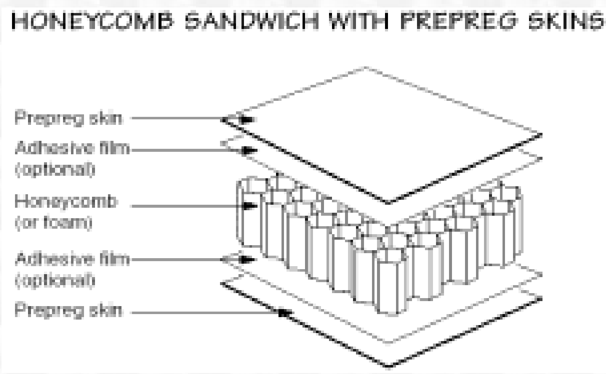
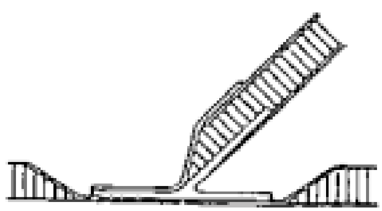
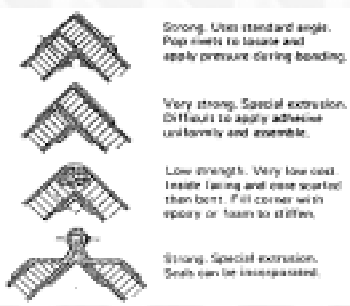
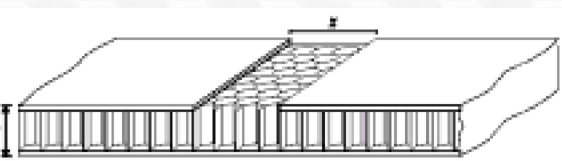


Figure 17.05.5 - Symmetrical Lay-Up: Avoids Warpage & Minimizes Loading the Resin Matrix









Basic Composite Theory

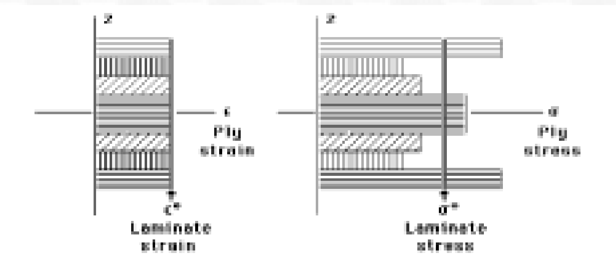


FIGURE 4.2 STRESS AND STRAIN DISTRIBUTIONS IN A SYMMETRIC LAMINATE

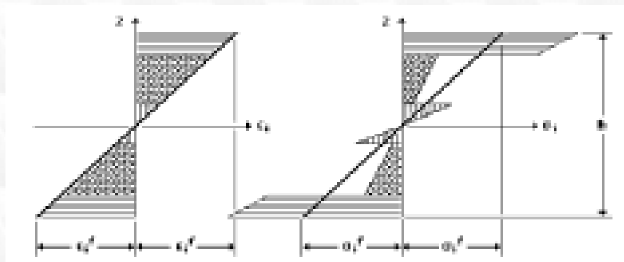


FIGURE 5.1 ASSUMED LINEAR FLEXURAL STRAIN AND STRESS DISTRIBUTIONS

Tension load $\sigma = \varepsilon E$

Flexural load

In a typical laminate ε remains constant but E changes
it means we have different stresses through the thickness.
This effect determines the necessity
to check the laminate ply by ply

Basic Composite Theory

Angle influence on Elasticity Modulus of Composites
vs.
aluminum

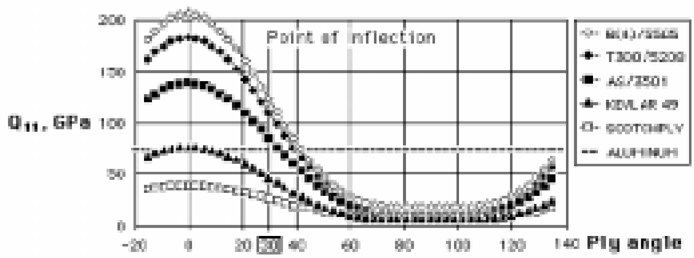


FIGURE 3.23 THE "11" STIFFNESS COMPONENT FOR VARIOUS COMPOSITES AND ALUMINUM. MAX AND MIN ARE REACHED AT 90 DEGREE INTERVALS. SHOWN ALSO IS THE POINT OF INFLECTION NEAR 30 DEGREE.

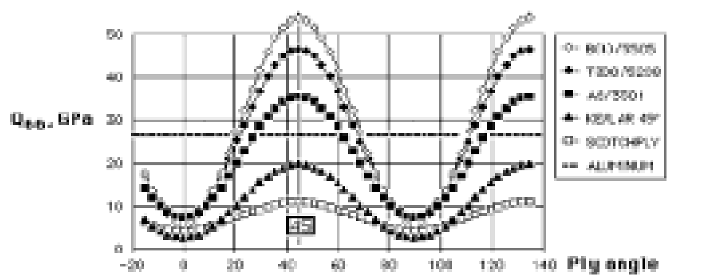


FIGURE 3.24 THE "66" STIFFNESS COMPONENT FOR VARIOUS COMPOSITES AND ALUMINUM. MAX AND MIN ARE REACHED AT INTERVALS OF 45 DEGREES.

DESIGN for STIFFNESS

Strain Energy concept

- Recall from mechanics of solids that for a linearly elastic material the *unit strain energy* (strain energy per unit volume) is given by:

$$\Omega_0 = \frac{1}{2}\boldsymbol{\sigma}^T\boldsymbol{\varepsilon}$$

$$= \frac{1}{2}\begin{bmatrix}\sigma_x & \sigma_y & \sigma_z & \tau_{xy} & \tau_{xz} & \tau_{yz}\end{bmatrix}\begin{Bmatrix}\varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \\ \gamma_{xy} \\ \gamma_{xz} \\ \gamma_{yz}\end{Bmatrix}$$

Low level study for quick response

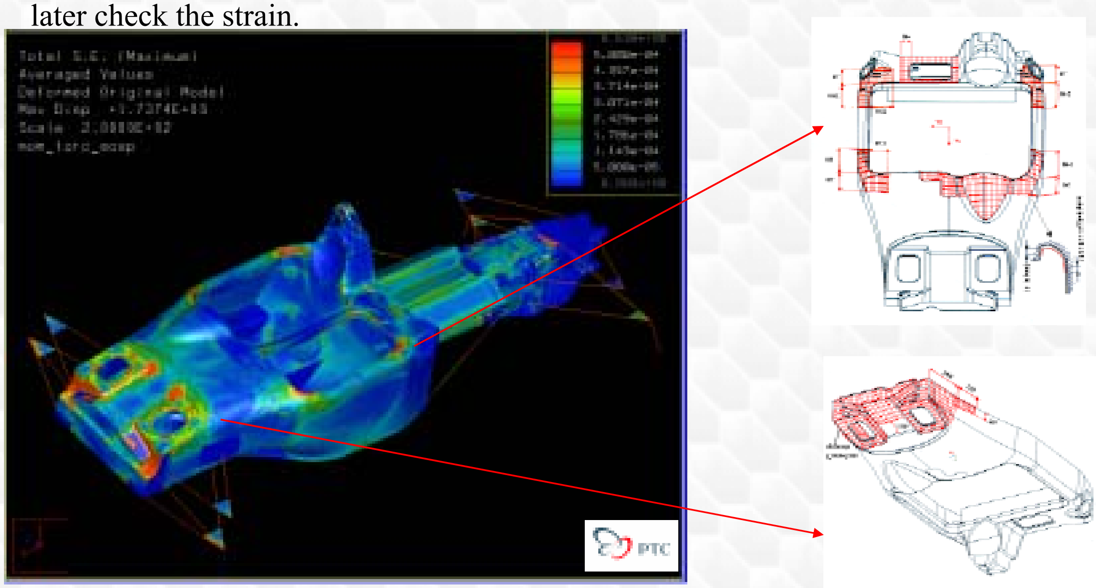
3D Strain definition

$$\boldsymbol{\varepsilon} = \partial\mathbf{u}(\mathbf{x})$$

$$\begin{Bmatrix}\varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \\ \gamma_{xy} \\ \gamma_{xz} \\ \gamma_{yz}\end{Bmatrix} = \begin{bmatrix}\frac{\partial}{\partial x} & 0 & 0 \\ 0 & \frac{\partial}{\partial y} & 0 \\ 0 & 0 & \frac{\partial}{\partial z} \\ \frac{\partial}{\partial y} & \frac{\partial}{\partial x} & 0 \\ \frac{\partial}{\partial z} & 0 & \frac{\partial}{\partial x} \\ 0 & \frac{\partial}{\partial z} & \frac{\partial}{\partial y}\end{bmatrix}\begin{Bmatrix}u(x,y,z) \\ v(x,y,z) \\ w(x,y,z)\end{Bmatrix}$$

Strain Energy in FEM practical use

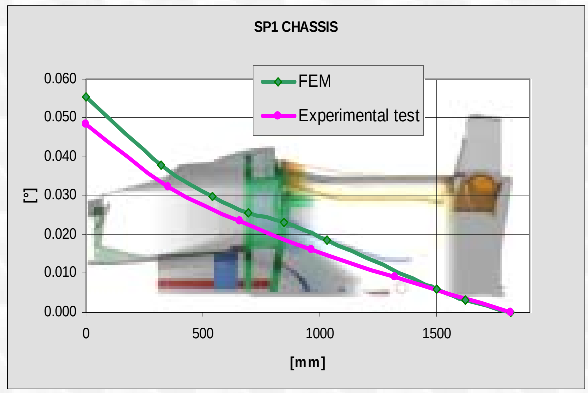
Instead of a long ply by ply check we use the strain energy result as a quick “quality” value to reinforce composite structures in the first design step. For more accurate analysis we later check the strain.



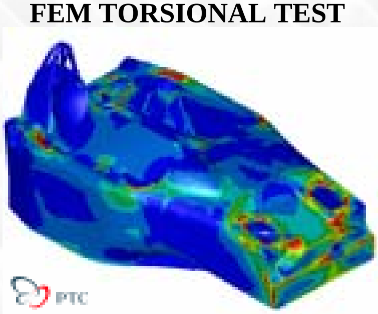
Dallara LMP900 for 24h of Le Mans TORSIONAL TEST

FEA validation

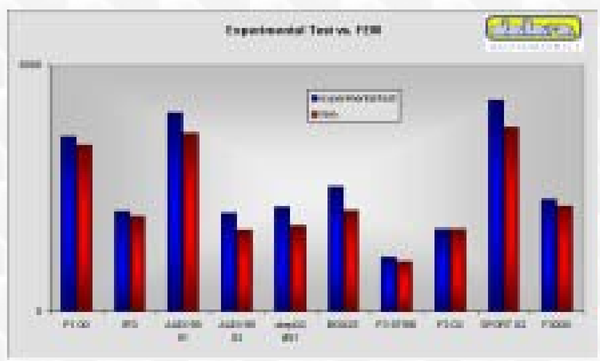
Experimental TORSIONAL TEST



FEM TORSIONAL TEST



Gap between reality and FEA always < 10%



DESIGN for STRENGTH

Failure Criteria

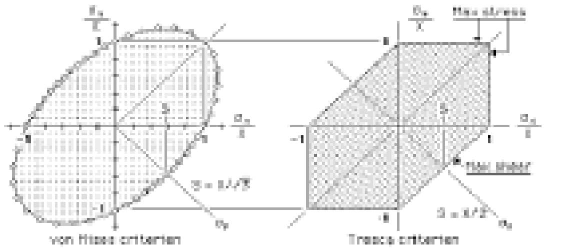


FIGURE 8.1 FAILURE ENVELOPES FOR ISOTROPIC MATERIALS
If tensile and compressive strengths are different, the von Mises failure criterion above can be modified as shown Figure 8.2, where, in this case, the tensile is less than the

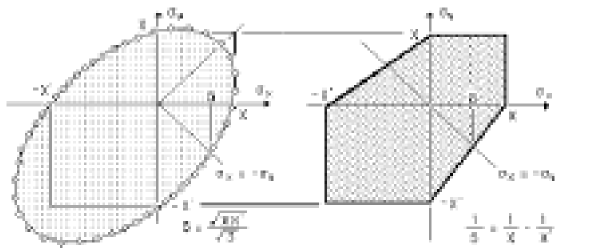


FIGURE 8.2 FAILURE CRITERIA FOR AN ANISOTROPIC MATERIAL HAVING DIFFERENT TENSILE AND COMPRESSIVE STRENGTHS

But composite materials have different properties at 0° and 90°:

Safety Factor Formulation

Input data:

- ✓X: Ultimate tensile strength 0°
- ✓X':Ultimate compressive strength 0°
- ✓Y: Ultimate tensile strength 90°
- ✓Y':Ultimate compressive strength 90°
- ✓S: In plane shear strength

ZTL Hypothesis

$$a := \frac{\sigma_x^2}{R_{m1t} \cdot R_{m1c}} + \frac{\sigma_y^2}{R_{m2t} \cdot R_{m2c}} + \frac{\sigma_{xy}^2}{R_{m12} \cdot R_{m12}} + 2 \cdot F_{12\_Star} \cdot \frac{1}{\sqrt{(R_{m1t} \cdot R_{m1c} \cdot R_{m2t} \cdot R_{m2c})}} \cdot \sigma_x \cdot \sigma_y$$

$$b := \sigma_x \cdot \left(\frac{1}{R_{m1t}} - \frac{1}{R_{m1c}} \right) + \sigma_y \cdot \left(\frac{1}{R_{m2t}} - \frac{1}{R_{m2c}} \right)$$

$a = 0.013$

$b = 0.182$

$c := -1$

$$RF_{zfb} := \frac{-b + \sqrt{b^2 - 4 \cdot a \cdot c}}{2 \cdot a} \qquad RF_{zfb} = 4.245$$

Tsai-Wu Failure Criteria

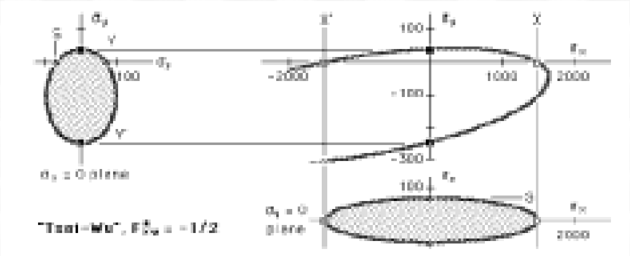


FIGURE 8.7 FAILURE ENVELOPE OF TSAI-WU CRITERION HAVING AN INTERACTION TERM OF -1/2 FOR T300/5208

Failure envelope of TSAI-WU Criterion

The formulation has an interaction term to keep in account if you are using a UD or a Fabric

TSAI-WU Criterion for different composite materials

FIGURE 8.22 TSAI-WU ENVELOPES IN STRAIN SPACE FOR GFRP AND KFRP

In the figure below, similar envelopes for AS/PEEK and IM6/epoxy are shown.

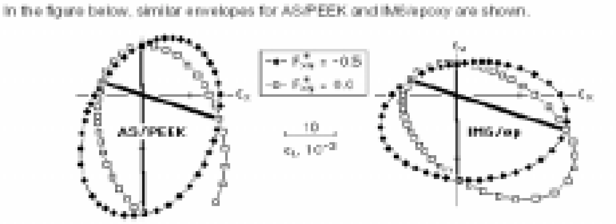


FIGURE 8.23 TSAI-WU ENVELOPES IN STRAIN SPACE FOR AS/PEEK AND IM6/EPOXY COMPOSITES

Failure Criteria Procedure

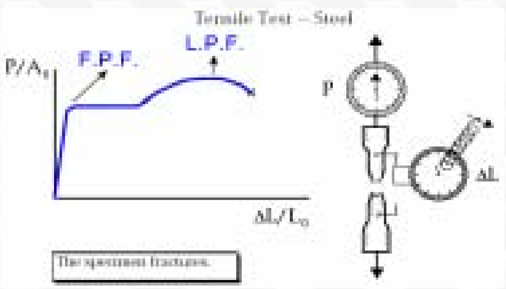
Sorting ply by ply through the thickness
of the laminate we check:

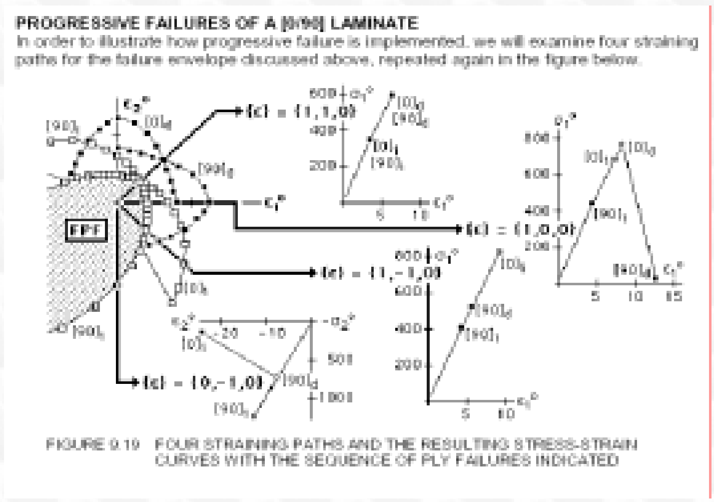
FIRST PLY FAILURE (F.P.F)

Iteractive Procedure

LAST PLY FAILURE (L.P.F)

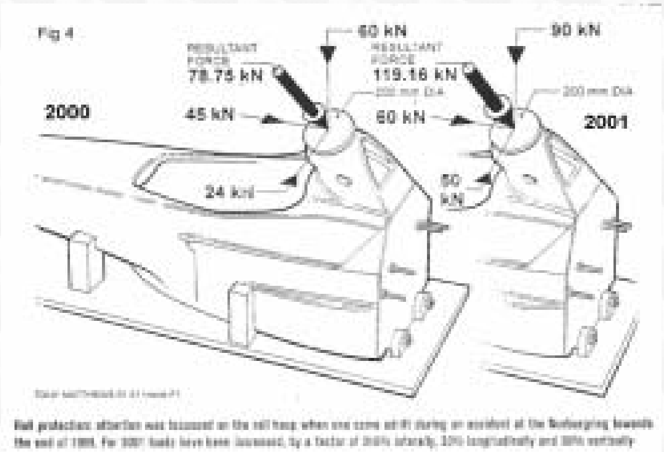
Similitude with metal stress-strain curve

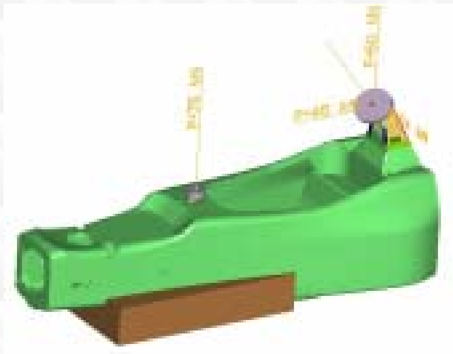


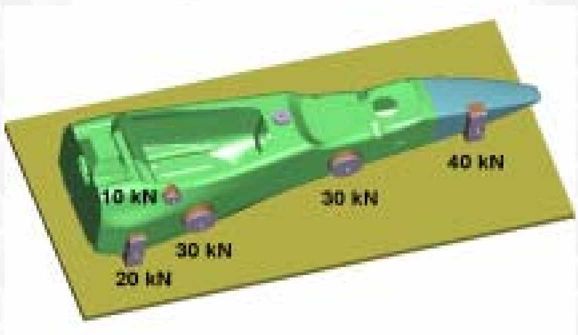


We work to stay far away from the first ply failure like from the yield stress for metals

Carbon Monocoque homologation tests



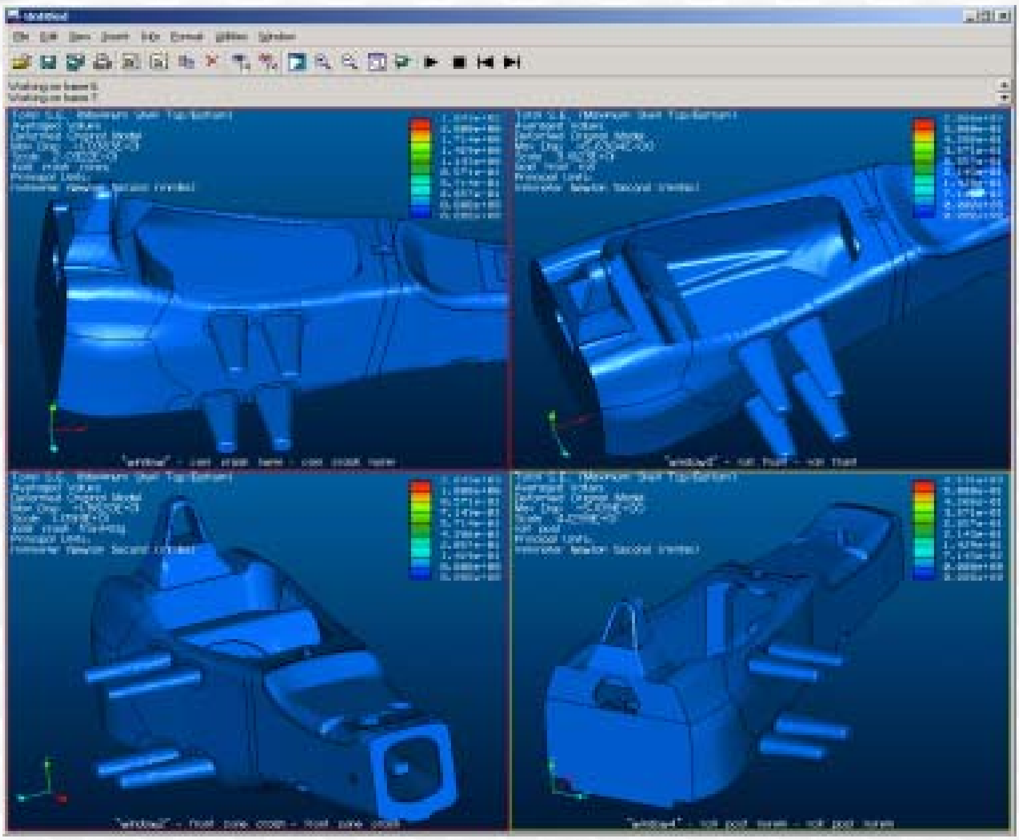




Article 17 of FIA Roll structure testing

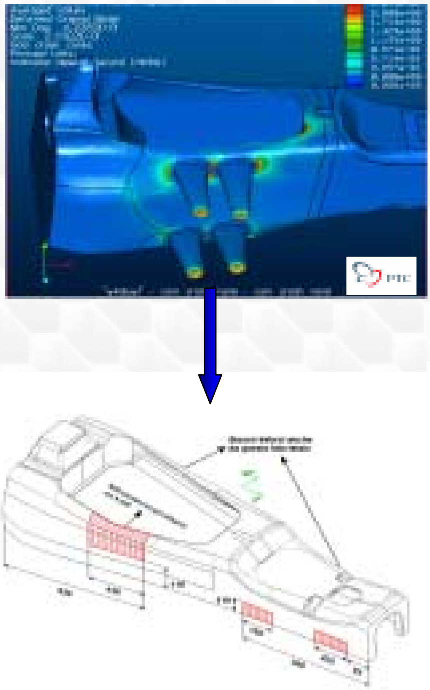
No failure on the chassis
Max displacement: 50 mm
FIA delegate must attend all the tests

FEA STRUCTURAL ANALYSIS

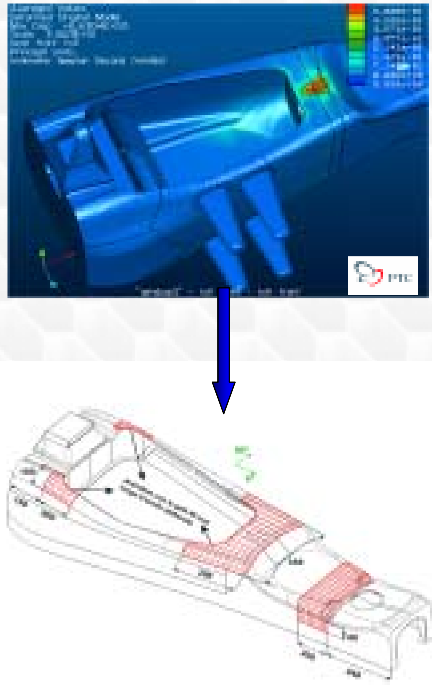


PLY BOOK

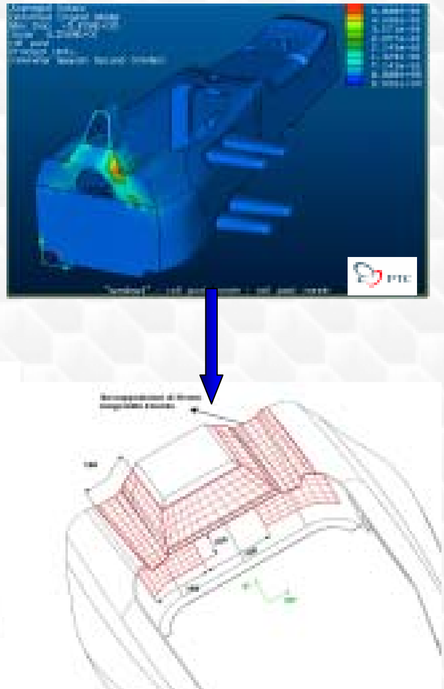
SIDE TEST



FRONT ROOL HOOP

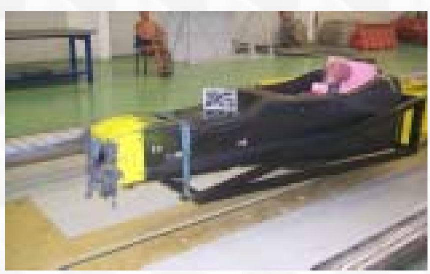


MAIN ROOL HOOP



HOMOLOGATION

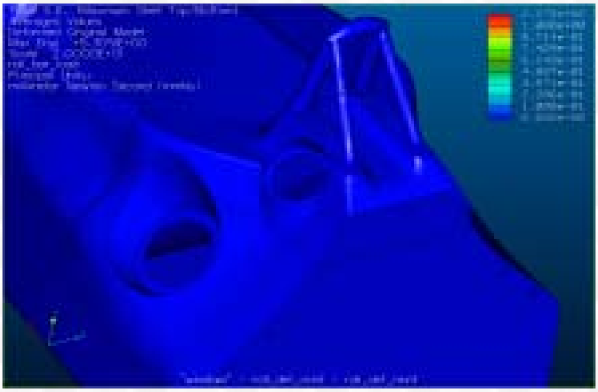
After all the calculations a real test has to be performed and passed successfully in order to homologate the car.

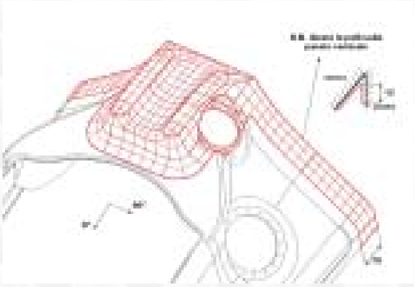


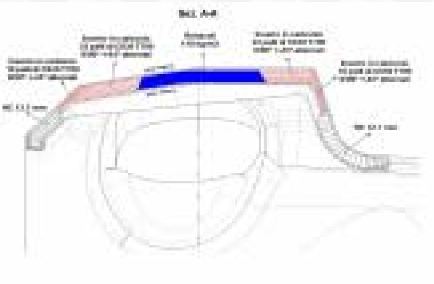
IRL ROLL HOOP TEST

Real pre-test

Simulation model





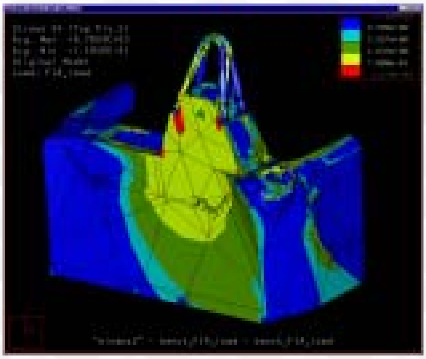


Direct influence on the Ply Book

FEA benchmark

In order to verify the quality of our calculation procedure we made a benchmark with the reference software: NASTRAN

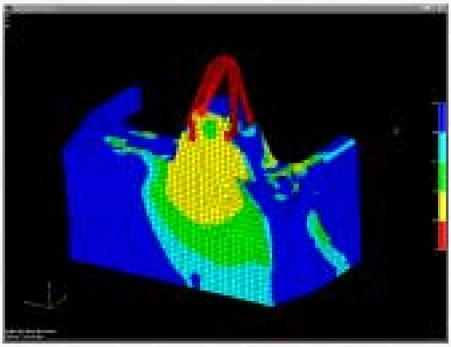
PRO/MECHANICA (release 22)



P-element mesh

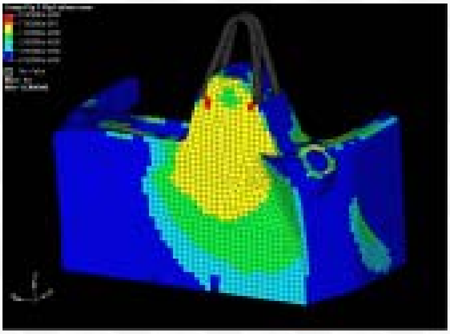
In use at Dallara

NASTRAN (Femap release 7.0)



H-element mesh

HYPERMESH & OPTISTRUCT 5.1



H-element mesh

In use at Dallara

Real test to homologate the car passed successfully

Global discrepancy of the safety factor value among the 3 different softwares < 3%

CONCLUSION

- ✓ Composite materials work in the linear field as the major FEA codes so the results of the calculation could be quite realistic.
- ✓ On the other hand the parameters to play around are a lot and complex
- ✓ Design for stiffness or for strength are two completely different approaches and the second needs much more input data than the first one
- ✓ The manufacturing problems (ignored in this discussion) had to be seriously kept in account because a ‘human’ is going to laminate most of the parts end FEM model could be quite different from the real one, in other words we should think ’composite’ and not any more ‘metal’ during the analysis.

REFERENCES

- Structural Materials Handbook (ESA)
- Engineered materials handbook COMPOSITES (ASM)
- Theory of composites design (Stephen W. Tsai, Stanford University)
- BOEING Procedures
- Advanced Composites Group procedures