Addressing Automotive Engineering Challenges in Composite Development by Simulation

Michael Hack,
Lazslo Farkas, Christophe Liefooghe, Michaël Bruyneel & Alexander Sztatecsny
Siemens PLM Software

During the past decades, the ecological footprint caused by various human activities has largely increased with a clear tendency to further grow. This global socio-economic problem triggers environmental action plans in order to attenuate the ecological impact of the human activities. As a result, manufacturers in the transportation sector are under increasingly large pressure to reduce the ecological footprint of their products and to comply with the ever more stringent emission requirements of the European Union. The deployment of advanced lightweight materials (especially in the aerospace and automotive sector) is a response of the transportation industry to deal with this challenge. It is widely acknowledged that there is large weight-saving potential in the new composite materials that lead to increased energy efficiency and less emissions. Further strong socio-economic relevancies (next to cleaner vehicles) can be linked to the application of new composite materials such as improved products in terms of safety and reliability.

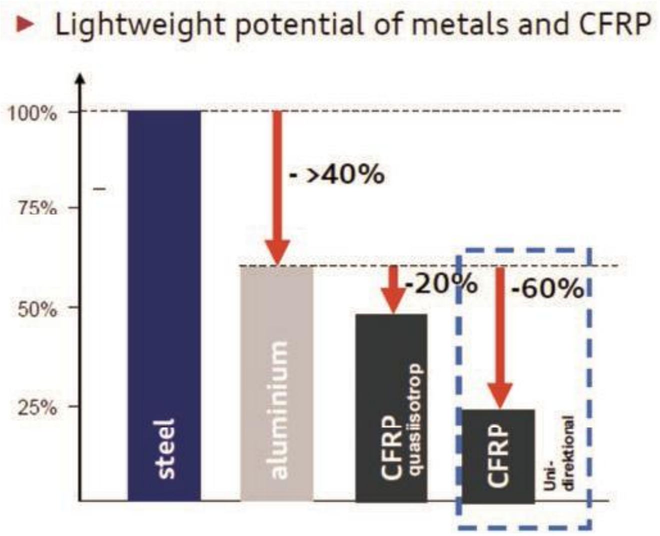

Figure 1: ©Audi, IQPC Conference Automotive Composites, Munich, Germany, 7-8 December, 2011

Motivation

According to the automotive sector, a weight saving of approximately 60% can be achieved on the body-in-white with the application of composite materials (see Figure 1). This important advantage w.r.t. metal car bodies is attributed to the higher specific stiffness and specific strength (or specific energy absorption capacity) of composites (see Figure 2).

At present, the massive deployment of lightweight composite materials is limited by three major bottlenecks in the automotive sector:

1. In the industrial manufacturing process such materials cannot be produced with the production rates common for the metal-based structures and furthermore the industrial manufacturing processes are very expensive as compared to the metal-dominated manufacturing technologies; this means that manufacturing processes for composite materials, and joining techniques for composite materials (with composite and other components) still have to be fine-tuned and matured to the level of industrial applicability.
2. The industrial engineering design and development process is limited by the lack of predictive modelling tools that are able to accurately mimic the real-life behaviour of lightweight material structures. This aspect is more apparent for design attributes such as crashworthiness and fatigue, which require the material predictions beyond the elastic limits (strength and damage under dynamic loading conditions); this means that the industry has to largely rely on expensive tests for which the results become available only very late in the product development process. Furthermore the full lightweight potential cannot be exploited as the uncertainties in the performance predictions are typically compensated by safety factors, leading to overdesigned components.
3. The integration of predictive tools with manufacturing simulation and the manufacturing process that allows an efficient implantation of new materials in the production process.

In order to address the CAE challenge, experience from other industries is being leveraged in the traditional automotive domains like NVH (Noise, Vibration & Harshness) & Durability to develop advanced solutions in damage, fatigue, NVH & Crash. At the same time full computer aided integration of the manufacturing process from definition of the laminate through like in Figure 3 is being implemented.

State of the art

For simulation of the various automotive performance attributes, the basic physical phenomena driving the composite material's behaviour need to be understood. Accurate predictions of stiffness and also failure and damage are necessary to be able to achieve a virtual CAE-based development process of composite-intensive vehicles. While stiffness prediction models are well developed, reliable and available in commercial FEM packages, the strength and damage predictions are still rather inaccurate nowadays, based on approximate descriptions of the relevant phenomena.

Currently large research efforts are dedicated to the study and analysis of composites mechanical behaviour at different scales:

- the micro-scale is focusing on the physical phenomena at the fibre level and fibre-matrix interface level,
- the meso-scale is concerned with the details at the level of a representative volume element (RVE) or unit cell, while
- macro-scale is focusing on the homogenized continuum.

In the typical mechanical product manufacturing industries, state of the art is the macro-scale modelling approach as it is today the only feasible way to model the behaviour of complex structures such as a car body that is discretized in multi-million finite elements. As homogenized finite element modelling (FEM) has its limitations in terms of the detailed representation of the mechanical behaviour, the authors believe that a breakthrough in predictive CAE of composite structures can be achieved by multi-scale modelling.

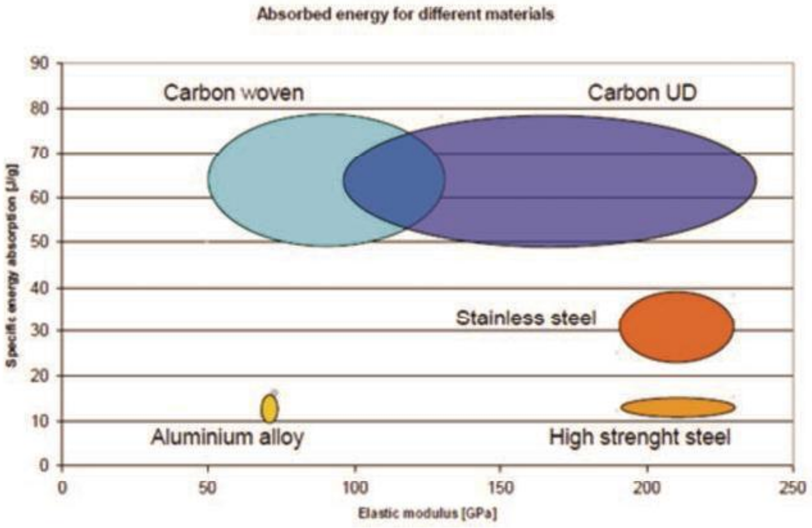

Figure 2: ©Dallara, Altair Americas HTC – Detroit, USA, May 16th 2012

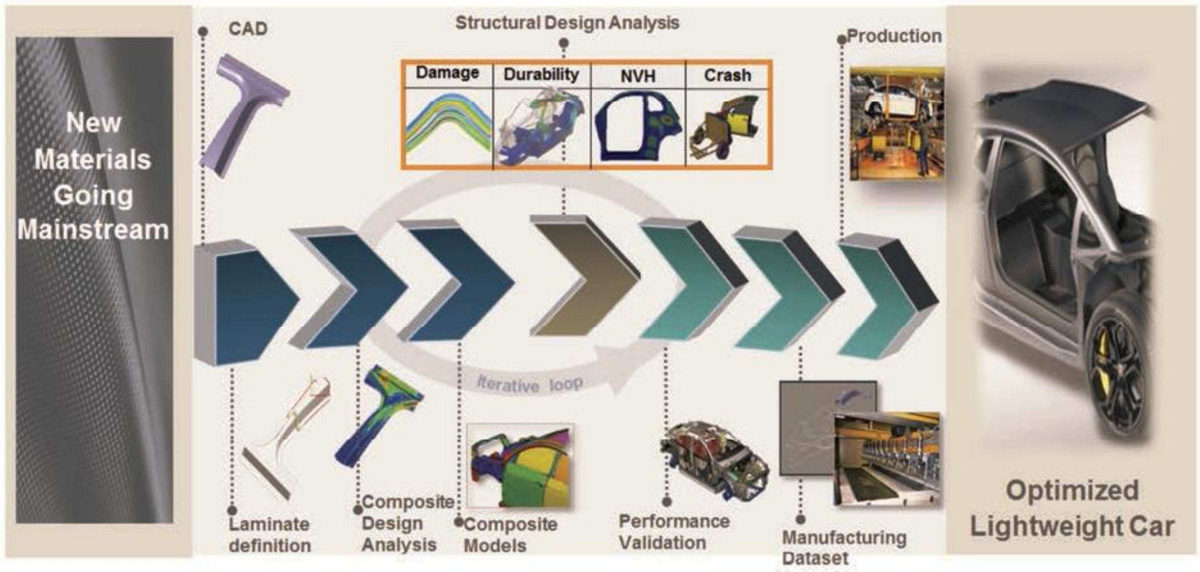

Figure 3: Integrated design process for laminated carbon fibre reinforced composites

Damage modelling

Continuum damage modelling (CDM) is the current state of the art for the progressive failure predictions of composite materials (See e.g. [2]-[5]). Based on CDM theories, the complex phenomena of damage initiation and propagation under static or dynamic loads can be efficiently modelled at the level of a homogenized composite cell. This macro-level modelling approach for composite laminates captures both the intra-ply and inter-ply damage evolutions by stiffness degradation laws. Figure 4 shows the typical damage modes accounted in CDM models for ply damage (intra-ply). Inter-ply (delamination) damage captures the stiffness degradation at the interface between plies (see Figure 5).

Damage models capability are implemented in finite element solver technology and need to include intra- and inter-laminar damage progression in complex composite lay-up [1]. Latest developments in advanced FE codes include the ability to study the progressive damage inside the ply [2]-[3], accounting for fibres breaking, matrix cracking and fibre-matrix de-cohesion. On the other hand, delamination can also be studied with the cohesive elements approach [4]. Cohesive elements models are based on continuum damage mechanics. A new non-local model has been developed recently, coupling the two kinds of damages, meaning that the transverse micro-cracking appearing inside the plies will influence the initiation of delamination at the interface of the plies [5]. With this new model, delamination occurs earlier in terms of load level, which is closer to what is observed in physical tests. The available solution for the non-linear damage modelling of composites has been validated on different industrial structures [6]-[8].

An important point to mention is that all CDM need material parameters that today need to be estimated from experiments. The correct setup and conduction of the experiments are key for successful parameter identification and therefore also highly important for good simulation results. (The NAFEMS Composite Group sees this as a point of high importance [9]) Only the combination of well defined experiments, material parameter identification, and finite element modellingallows predictive simulation [10]-[12].

The material behaviour and therefore the material parameters are highly influenced by the manufacturing process. For the future a virtual testing procedures should replace a large part of the physical tests.

Fatigue modelling

Following the state-of-the-art analysis presented in references[13] - [16] one can state that fatigue models for composites are still in their "infancy". The main approaches are based on SN-curves, a methodology adopted from the fatigue of metals. They are typically based on fatigue experiments in the main load direction. Modelling of fatigue in cross-ply laminates and especially for textile composites is difficult, as all models are based on experimental data for the full laminate, which requires that each change in the laminate structure leads to expensive experimental programs.

Damage modelling for fatigue of composites is an emerging research field. Relevant publications refer to damage models that are based on CDM approach [17]-[19]. Damage state variables are evolving in function of the fatigue stresses and are typically linked to the degradation of the elastic orthotropic properties on ply level. This approach has a number of advantages as compared to the classical SN approaches:

- Representation of the correct global behaviour by stiffness degradation
- The simulation can follow the full life of the components, so profiting from the typically good fatigue behaviour of composite structures
- Cross influences between damages can be considered (multi-axiality)
- Stress redistribution can be accounted for during the cycling
- No re-testing is needed for a change in layup (while keeping the same ply properties)

The main challenge today in this approach is to make it feasible for industrial applications in terms of computational efficiency. All state of the art implementations (like so called N-Jump based methods, that extrapolate (jump) the damage accumulation and stiffness reduction of a given load cycle for N cycles) are limited to simplified block loads. E.g. Siemens has implemented methodologies for composite-specific fatigue and stiffness degradation, both for short fibre as well as for long fibre applications based on combining progressive damage models with hysteresis operators allowing accurate and efficient fatigue life predictions of composites structures with complex, multi-axial, long-duration loading cycles as typically encountered in automotive full vehicle and body applications [20].

The damage models for fatigue rely basically on the same CDM mechanisms as the static damage. Hence a similar process for material testing and parameter identification is used. Elastic properties on ply level can be re-used when identified for static damage behaviour.

NVH modelling

In the NVH (Noise, Vibration and Harshness) domain, the main research focus currently is on assessing the effect of the complex material geometry (e.g. fibre orientations in short fibre composite structures, micro-level material topology in poroelastic materials) on the stiffness properties and vibro-acoustic performances of lightweight material systems, on dynamic correlation and updating of lightweight numerical models using experimental data and on simulating the vibro-acoustic properties of complex lightweight material systems, including noise and vibration control treatments. (See [21]- 24]) Through manufacturing simulations, highly accurate models for the stiffness properties of composite components can be incorporated to augment the vibro-acoustic prediction accuracy of numerical models. In order to further increase the fidelity of dynamic model of often complex assemblies of composite components, numerical-experimental correlation and model updating techniques can be applied. In this way the impact of hard to model features such as complex joints and manufacturing defects can be introduced in the numerical models. In a next step, these models can be incorporated in e.g. system-level vibro-acoustic models.

The lightweight nature of composite structures presents additional challenges for the design of effective noise control treatments. Due to their decreased weight, the acoustic transmission properties of such structures are significantly degraded. Moreover, due to the lower weight of the structural components, adding one kilogram of sound package has a much higher impact on their dynamic behaviour than in metal constructions.
In a recent paper [25] the applicability of these formulations is experimentally validated based on two test rigs dedicated to NVH analysis of automotive trim components.

In the past decades modal representation techniques have been applied extensively to reduce model sizes in computational dynamic analysis at component and system level. This has become the default approach for dynamic analysis of industrial sized models.
Nevertheless, many advanced materials (like some epoxy based composites for instance) exhibit a highly frequency dependent behaviour which prohibits the use of such approaches. Additionally, the modal superposition technique also fails to provide an accurate dynamic representation of structural components when noise or vibration control treatments such as visco-elastic patches are locally applied. It also cannot work if many composite components are assembled through bonding techniques whose properties are both frequency and position dependent. To address these limitations, efficient direct solution strategies are developed and significant research effort is invested in the development of advanced non-modal model reduction strategies [24].

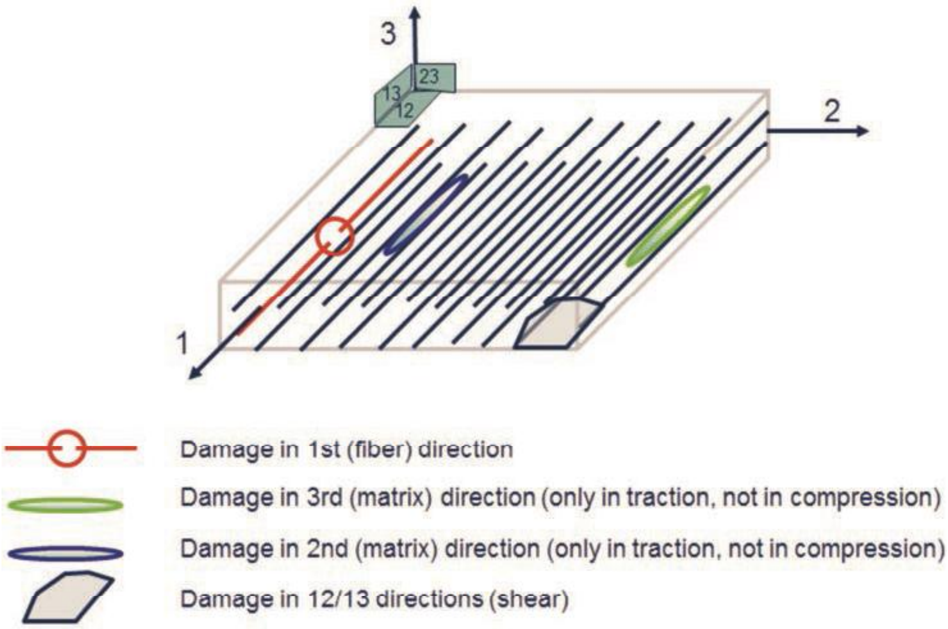

Figure 4: Damage inside the ply

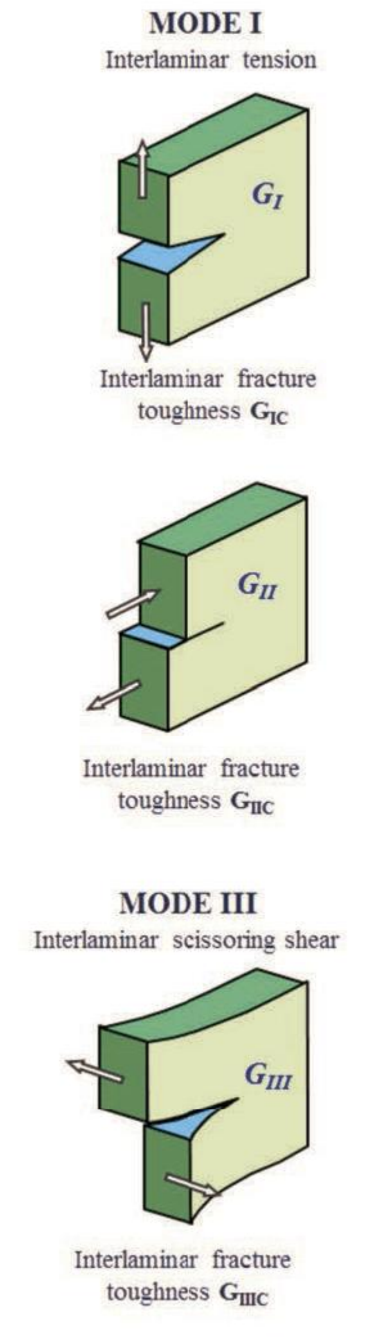

Figure 5: Damage between the plies

Crash modelling

In the automotive industry, the crashworthiness is one of the major driving attributes for vehicle development programs in general and for lightweight vehicle development in particular. Optimal balancing between conflicting design objectives such as weight, impact resistance and energy absorption capability is necessary. For transport applications, crashworthiness involves basically two different ways of expected component behaviour, namely components designed for optimal crash behaviour and components designed for optimal crush behaviour. The passenger compartment should provide passenger protection and should therefore resist to the high impact loads involved, meaning that the structural integrity is (approximately) conserved during a crash; it should hence show optimal crash behaviour. On the other hand, the large amounts of kinetic energy involved in such an accident should adequately be absorbed; this is most often achieved through adequate crush behaviour of front and back elements such as crush cones.

Predictive CAE of composites in automotive crashworthiness scenarios is not yet possible in an industrial context, which means that industry has to rely on expensive experimental tests for which the results become available only very late in the product development process. Internationally, much research effort has been devoted and currently still being dedicated to understand and simulate the behaviour of composite materials and composite structures under impact loading. Various aspects increase the simulation complexity of composites under dynamic loading conditions that make the necessary predictive property highly challenging. Also the behaviour of composite materials and composite structures under impact loading is being studied intensively [26]-[29].

However, it is a strong belief of many companies that currently, industrially relevant tools for adequately and accurately simulating the outcome of an impact are still in their "infancy". In the automotive sector, manufacturers like Mercedes-Benz for example state "that the state-of-the-art in the accuracy of prediction capabilities of current CAE tools for composites is the lowest, when durability and crashworthiness are concerned" [30]. Similarly Volvo "demands for better CAE for carbon composites, as crash simulation packages were originally designed with metallic structures in mind". "Regarding aluminium and safety, we have all of the tools we need and we can predict crash performance, but when it comes to CFRP the situation is quite different: CAE capabilities are much poorer; we don't have the tools yet – they are not mature enough" [31]. Depending on the exact nature of the involved types of impacts, the situation may be slightly different in other sectors, like aerospace or ballistic, but the general statements are also valid there [32].

The highly dynamic simulation of composite structures is challenged due to the high complexity of the damage mechanisms, geometrical non-linearities with contacts, multiple material combinations, stacking sequences. Furthermore the large number of impact scenarios (e.g lateral impact, axial impact or crushing) that manifest in numerous possible failure mechanisms (e.g. fibre/matrix debonding, fibre tensile failure and buckling, inter-ply delaminations) are characterized by a large number of associated model-specific physical or non-physical variables (e.g. fibre/matrix tensile strength, strain-rate coefficients, delamination mode coupling coefficient).

Manufacturing simulations

In order to fully cover the CAE-based virtual design engineering process for advanced lightweight materials such as composites, the process of manufacturing needs to be considered in the simulation chain. Various fabrication methods target different materials dedicated to applications that require specific properties, cost and cycle time. The large varieties of manufacturing processes have important influences on the mechanical properties of the composite components. The designed composite (micro)structure is often altered by manufacturing influences that result in scatter such as variations in local material properties, fibre misalignment or imperfections such as inclusions and voids. These factors have