The regulatory mandates for low carbon emissions and demand for vehicles with better fuel efficiency are driving the automotive industry to adopt weight reduction strategies. With their high strength-to-weight ratio, composite materials are an ideal replacement for, or complement to, current steel welded body-in-white (BIW) structures. While adopting these newer materials into vehicle development programs, engineering departments still rely heavily on experimental testing for the verification of the performance of these new designs due to gaps in predictive computer-aided engineering (CAE) tools.

Leveraging lessons learned in the aerospace sector, Siemens PLM Software is working with academic and industrial partners to address the composite simulation challenge for damage and durability; noise, vibration, harshness (NVH) and crash applications for the automotive industry. In support of composite manufacturing process decisions, Siemens PLM Software is also addressing the challenge of computer-aided design (CAD) integrated laminate composite model definition, allowing you to design composites in a shorter time using a design cycle that emphasizes weight and cost reduction, reduces prototype costs and reliance on prototypes. Furthermore, in order to reduce production costs, the solution provides more accurate simulation of part producibility for high volume automotive processes, such as draping.
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Executive summary

It is widely acknowledged among automotive original equipment manufacturers (AOEMs) that there is huge potential for better fuel efficiency and lower emissions by introducing the use of composite materials in body design. At the same time, high volume adoption of automotive mixed materials (metals and composites) is hampered due to economic and technological reasons.

Today automotive engineers rely heavily on simulation tools to conduct durability, NVH and crash performance evaluation for traditional body designs. At present, AOEMs have lots of experience working with steel or other metals. They have enormous experimental data accumulated since the 1970s. Since composite materials are relatively new, they lack this experience and experimental data. On top of that, with metals we can reproduce experimental measurements through simulation; with composites, it is not so straightforward. They are highly nonlinear, and reproducing similar results through simulation means existing simulation process and tools have to overcome this technological challenge.

Metallic structures built from homogeneous material display linear behavior while composite structures exhibit inherent nonlinearity. Composite nonlinear behavior creates uncertainty while evaluating performance. In order to account for this uncertainty, automotive design engineers tend to work with increased margins for safety. This ultimately leads to designs that weigh and cost more, decreasing the competitiveness of composites.

To deploy and exploit the potential offered by composites, existing engineering process, design and analysis standards, manufacturing facilities have to be reconfigured to take into account composite performance, producibility and recyclability. And in order to eliminate the composite structural over-dimensioning, engineers working on automotive performance applications need to predict with more certainty the nonlinear behavior. In other words, engineers need advanced and specific modeling tools and processes to be able to predict composite:

- Strength behavior through damage propagation studies
- Lifespan through durability studies
- Structural and acoustic performance through NVH studies
- Crash-worthiness through impact studies

This white paper presents state-of-the-art composite damage, durability, NVH and crash engineering tools and processes developed by Siemens PLM Software to help automotive engineers develop optimal composite designs so they can meet performance criteria. Such a process is depicted in figure 1.

![Figure 1: Composite engineering workflow highlighting structural design.](image)
Understanding the motivation

According to information presented by Audi at the IQPC Conference Automotive Composites in Munich, Germany in December, 2011, a weight savings of approximately 60 percent can be achieved on the body-in-white with the application of composite materials (see figure 2). The important advantage of composite car bodies is they have higher specific stiffness and strength or specific energy absorption capacity (see figure 3).

On the other hand, the composite engineering design and development process is limited by the lack of predictive modeling tools that can be used to accurately mimic the real-life behavior of lightweight material structures. This aspect is more apparent for design attributes, such as durability and damage, which require material predictions beyond the elastic limits (strength and damage under dynamic loading conditions). Expensive test procedures are currently undertaken to test composite body performances, however, a test-based methodology on its own, will not support the concurrent engineering practices prevailing in the automotive industry.

In order to address the performance simulation prediction challenge, Siemens PLM Software is leveraging its composites experience in aerospace to automotive domains, such as durability, strength and NVH. As composite fiber orientation plays an important role on the material performance, gateways are provided between tools from Siemens PLM Software and its partners, linking the manufacturing simulation data, such as fiber orientation, ply layup to performance prediction finite element tools.

The massive deployment of lightweight composite materials is limited by cost, profitability, scalability and other technological aspects prevailing in the automotive eco-system. In fact, industrial manufacturing processes for composites are very expensive compared to the metal-dominated manufacturing technologies. The economies of scale offered by metals are more lucrative. Composite manufacturing cannot benefit directly from the existing metal plant sunk costs. This indirectly means that manufacturing processes for composite materials, and joining techniques between composite and other components, still need to mature to the level of traditional automotive industrial applications.

Figure 2: © Audi, IQPC Conference Automotive Composites, Munich, Germany, December 7, 8, 2011.

Figure 3: © Insight Edition 2013, Daimler AG, November, 20 2013.
Achieving state-of-the-art status

To perform an effective simulation of the various automotive performance attributes such as strength, durability and crash-worthiness, the basic physical phenomena driving the behavior of the composite materials must be understood. Accurate predictions of stiffness as well as failure and damage in the composite materials are necessary to achieve a virtual CAE-based development process for composite-intensive vehicles. While stiffness prediction models are well developed, reliable and available in commercial finite element method (FEM) packages, the strength and damage predictions are still rather inaccurate because they are based on approximate descriptions of the relevant phenomena.

Currently, there is significant research being conducted on the study and analysis of composites mechanical behavior at different scales, including:

- Microscale focuses on the physical phenomena at the fiber level and fiber-matrix interface level
- Mesoscale is concerned with the details at the level of a representative volume element (RVE) or unit cell of a composite
- Macroscale focuses on the homogenized continuum.

As structures such as a car body need to be discretized into millions of finite elements for a proper CAE performance prediction, the macroscale modeling approach is currently the only feasible way to model the behavior of composite structures. As homogenized finite element modeling has its limitations in terms of the detailed representation of mechanical behavior, the authors believe that a breakthrough in predictive CAE of composite structures needs to be achieved by a multiscale modeling approach.
Composite materials exhibit complex failure mechanisms under static and fatigue loading. There are many theories used to describe the composite failure mechanism. Continuum damage modeling (CDM) is the current state-of-the-art for the progressive failure predictions of composite materials. The complex phenomena of damage initiation and propagation under static or dynamic loads can be efficiently modeled at the level of a homogenized composite cell. This macro level modeling approach for composite laminates captures both the intraply and interply damage evolutions by stiffness degradation laws. Figure 5 shows the typical damage modes in CDM models for ply damage (intraply).

Inter-ply (delamination) damage captures the stiffness degradation at the interface between plies (see figure 6).

The damage models from Siemens PLM Software enable the inclusion of intralaminar and interlaminar damage progression in complex composite layups. Specific models available in the software can be used to study the progressive damage inside the ply, accounting for fiber breaking, matrix cracking and fiber matrix decohesion. On the other hand, delamination can also be studied with the cohesive elements approach. Cohesive element models are based on continuum damage mechanics and offer a premium method to predict the complex delamination behavior. A new nonlocal model has been introduced, coupling the two kinds of damages: the transverse micro-cracking appearing inside the plies will influence the initiation of delamination at the interface of the plies. 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 nonlinear damage modeling of composites has been validated on different industrial structures. Figure 7 shows a comparison of damage propagation in a loaded design between test and simulation.
Following the state-of-the-art analysis\textsuperscript{9-10\textendash}11, one can state that fatigue models for composites are still in their early phase of development. The main approaches are based on S-N curves, a methodology used to characterize metal fatigue.

They are typically based on fatigue experiments in the main load direction. Modeling of fatigue in cross-ply laminates, especially for textile composites, is time consuming and expensive, as all models are based on experimental data for the full laminate, which requires that each change in the laminate structure or layup leads to expensive experimental programs.

Damage modeling in the context of dynamic fatigue of composites is an emerging field. Relevant publications refer to damage models that are based on the CDM approach\textsuperscript{12-13\textendash}14. Damage state variables are evolving as a function of the fatigue stresses and are typically linked to the degradation of the elastic orthotropic properties on the ply level. This approach has a number of advantages compared to the classical S-N approaches:

- Representation of the correct global behavior by stiffness degradation
- Cross influences between damages can be considered (multiaxiality)
- Stress redistribution can be accounted for during cycling
- No retesting is needed for a change in layup (while keeping the same ply properties)

The main challenge in this approach is to make it feasible for industrial applications in terms of computational efficiency. All state-of-the-art implementations are limited to simplified block loads. Compared to tangible complex load scenarios, large safety factors are applied to these simplified loads. This significantly reduces the advantages of composite materials.

Therefore, Siemens PLM Software addresses composite-specific fatigue and stiffness degradation with the most advanced simulation methodologies, accounting for complex, multiaxial, long-duration loading cycles typically encountered in automotive body and suspension applications\textsuperscript{15}. The technology can be applied to both short-fiber as well as continuous-fiber applications. It is based on combining progressive damage models with hysteresis operators. This facilitates an accurate and efficient fatigue-life prediction of composite structures.
NVH modeling

In the NVH domain, the main research focus is:

- Assessing the effect of the complex material geometry (for example, fiber orientations in continuous and short fiber composite structures, micro level material topology in poroelastic materials) on the stiffness properties and vibro-acoustic performances of lightweight material systems
- Dynamic correlation and updating of lightweight numerical models using experimental data
- Simulating the vibroacoustic properties of complex lightweight material systems, including noise and vibration control treatments

Through manufacturing simulations, highly accurate models of stiffness properties for composite components can be incorporated to augment the vibroacoustic prediction accuracy of numerical models. In order to further increase the fidelity of a dynamic model with 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 numerical models. In the next step, these models can be incorporated in system-level vibroacoustic 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 the combined dynamic behavior as compared to metal constructions. These observations have motivated the development of dedicated virtual prototyping tools for the efficient and accurate introduction of poroelastic noise control treatments in dynamic models.

To this end, three types of modeling strategies are offered:

- Using analytically determined transfer admittance relations, multi-layer noise control treatments consisting of poroelastic, viscoelastic and fluid layers can be incorporated in system-level, vibroacoustic models without incurring an additional computational cost
- For poroelastic materials that have either a very stiff or limp skeleton, equivalent fluid models can be used to describe poroelastic components as acoustic fluids with representative frequency-dependent material properties
- Finally, efficient formulations of the full Biot equations like the \((U,p)\) model can be used. While they come at a significant computational cost, these models describe the full complexity of the interactions between the two constituents of such materials

In a recent paper, 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 to reduce model sizes in computational dynamic analysis at both the component and system level. This has become an industrial norm for dynamic analysis of models. But many advanced materials that exhibit highly frequency-dependent behavior cannot be used with such approaches.

The modal superposition technique also fails when NVH and acoustics vibration control treatments, such as visco-elastic patches, are locally applied or when many composite components are assembled through bounding techniques in which the properties are both frequency- and position-dependent. To address these limitations, direct nonmodal model solution strategies are being developed.
Crash modeling

In the automotive industry, crashworthiness is one of the major driving attributes for vehicle development programs. It is critical to optimally balance conflicting design objectives, such as weight, impact resistance and energy absorption capability. Crashworthiness involves two different types of expected component behavior: optimal crash behavior and optimal crush behavior. The passenger compartment should provide passenger protection and, therefore, resist the high impact loads involved, meaning that the structural integrity is preserved during a crash; it should hence show optimal crash behavior. On the other hand, the large amounts of kinetic energy involved in such an accident should be adequately absorbed; this is most often achieved through adequate crush behavior of front and back elements such as crush cones.

The high complexity of the damage mechanisms, geometrical nonlinearities with contacts, multiple material combinations and stacking sequences and large number of impact regimes (for example, lateral impact, axial impact or crushing) manifest in numerous possible failure mechanisms (for example, fiber/matrix debonding, fiber tensile failure and buckling, interply delamination). These aspects significantly increase the crash and crush simulation complexity of composites and make the necessary predictive simulation capability highly challenging. Also, the behavior of composite materials and composite structures under impact loading is being intensively studied\textsuperscript{21-22,23-24}. However, there is a strong belief among many companies that the current industry tools for adequately and accurately simulating the outcome of an impact are still in the early phase of development. In the automotive sector, OEMs such as Volvo note a demand “for better CAE for carbon composites, as crash simulation packages were originally designed with metallic structures in mind.”\textsuperscript{25} Volvo further notes, “Regarding aluminum 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.”\textsuperscript{26}

Siemens PLM Software is teaming up with their academic and industrial research and development (R&D) partners in order to respond to the challenges related to the impact scenarios specific to the automotive industry. Here, one key ingredient is the extensive damage modeling knowledge available for both intra- and inter-ply damage modeling, which provides a solid basis for enhancing state-of-art crash and crush simulations.
Gateway to 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, including variations in local material properties, fiber misalignment or imperfections, such as inclusions and voids. These factors have a significant impact on mechanical performance. Therefore, a crucial point for accurately incorporating the complex microstructure of composite components on their structural stiffness and strength-related performance is the link between the manufacturing process used to construct such structures and their predicted mechanical properties.

The continuous fiber manufacturing simulation software for composites from Siemens PLM Software provides laminate definition with as-built fiber orientation information of composites for use in the FE models. For short-fiber composite parts, the injection molding results – fiber orientation tensors and stiffness properties – are transferred to FE codes by providing an interface with third-party software.

Figure 11: Gateway to manufacturing simulations.

Figure 12: Pictured is a draping simulation.
Conclusion

The automotive industry is undergoing a radical change to manufacture eco-friendly vehicles that meet ever more stringent emission and fuel norms. Producing lighter weight vehicles is one of the key strategies to meet these regulations. However, whether the automotive industry will be able to make high volume use of composites is dependent on developments on multiple fronts, including:

- Efficient and cheaper manufacturing processes
- Avoiding overly safe design of composite structures
- Reproducibility and manufacturability of composite structures on an industrial scale
- Improved and adapted out-of-the-box CAE methodologies and tools

To mitigate the risks, implementation costs and potential liabilities imposed by the transition to mixed material strategy, Siemens PLM Software is leveraging its multi-decade experience in the aerospace sector related to the advanced design and simulation of composites. Overdesign of composite structures can be accomplished by employing predictive simulation tools. Dedicated damage models for composites and gateways to manufacturing simulation from Siemens PLM Software and its partners are very promising for performing predictive strength, durability and NVH analysis. As part of the overall strategy, Siemens PLM Software actively partners with universities and technology institutes for addressing the remaining technological challenges in simulation of composite behavior.
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