MODULAR APPROACH TO MATERIAL CARD GENERATION ACCELERATING COMPOSITE PART DEVELOPMENT

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Abstract

A critical and often underappreciated factor in successful product development programs is the availability and validity of material card information. The term “material card” refers to the collection of input data, design engineers must enter into their simulation programs prior to modeling their designs. As the level of complexity of the design exercise increases, the amount and fidelity of the material card data must also increase to achieve an acceptable level of modeling predictability.

Recognizing that a lack of capable standardized material card data for automotive applications presented barriers to adoption of composites, Forward Engineering together with industry partners Hexion and Zoltek initiated a program to organize the testing procedures, develop a set of best practices and a methodology for translating test results into material card formats that are compatible with commercially available simulation solver programs.

The novelty of this program is the modular approach which allows users to extend and refine validity of the results depending on the stage of their development. The modules represent different stages of R&D from first static design estimations over more advanced approaches regarding crash behavior up to most advanced post-crash behavior.

This paper discusses the data generation and describes the calibration and translation into material card inputs. With the launch of this program, participants can now accelerate their composite part development, reduce program costs, as well as provide visibility to material testing budget and timing requirements for the evaluation of new materials and processes.

Background

In the framework of global CO_2 emission and fuel consumption legislation, lightweight material solutions become more and more attractive to OEMs and Tiers. Compared to most metals, fiber reinforced composites offer significant weight savings. A unique and powerful property of fiber reinforced polymer composites is the ability to tailor their behavior to specific performance requirements by combining suitable fiber reinforcements with matrix resins and defining a layup that matches a given load spectrum. However, due to the virtually unlimited combinations of these elements, composites are less standardized and, in many cases, less familiar and predictable to automotive industry design engineers.

The lack of capable standardized material cards for automotive applications presents a barrier to the adoption of fiber reinforced composites. Forward Engineering, Hexion, and Zoltek initiated a program based on carbon fiber reinforced epoxy composites to organize the testing procedures, develop a set of best practices, and methodology for translating test results into material card input data that are compatible with commonly used FEA solvers.

Modular FRP-Testing Program for Efficient Material Card Creation

The objective when developing the program was to set up a simple yet complete material testing structure to support capable simulation results at the various levels of detail required throughout an automotive product development program. When starting a project, a common challenge is identifying which material data are needed to simulate the required load cases. To eliminate these uncertainties at the beginning, the potential target load cases and necessary tests are classified into different levels: Some applications need to be analyzed regarding the elastic material values until first failure, however, when it comes to crash applications post failure properties are required as well. The resulting modular approach to material characterization is shown in Figure 1.

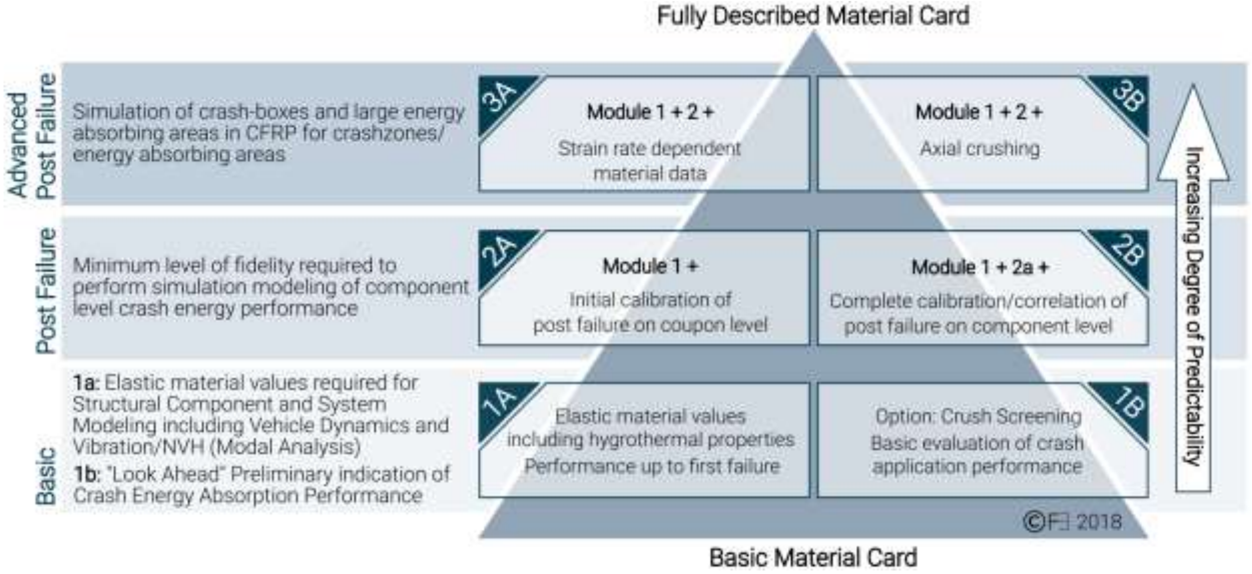

Figure 1: Modular Material Characterization Approach

At the base of the program, the Module 1a package provides basic material card information required for modeling simulation up to first failure of the material. These properties can be generated using standard tests for tension, compression and shear loads. For the most basic applications, where stiffness and dynamic loading before failure are the design constraints and the component or system is not factored into the overall vehicle crash performance Module 1a provides the minimum information required for basic part design. Testing for hygrothermal and damping properties can be added as required. The data from Module 1a material card testing are also an important input required for Vibration/NVH simulation (modal analysis) and vehicle dynamics simulations.

Module 1b ("Crush Screening") is a series of tests designed to provide a swift assessment of crash energy performance. For those materials where post failure crash performance is important, a quick and cost-effective Crush Screening evaluation can be performed to evaluate combinations of materials (resins, fibers, additives, etc.) to assess their relative crash energy behavior, and the general compatibility of materials.

For applications where understanding crash performance post 1st failure is a requirement, advancing to Module 2a and 2b will be required. These modules focus on the material behavior after the first failure when cracks begin to form and propagate through the material with increasing load and deformation. The level of fidelity derived from Module 2a testing will support initial structural component level crash modeling. To achieve a more accurate picture of the post failure energy absorption behavior Module 2b, a part-level hardware test of more complex three-dimensional components, is required.

Module 2a is comprised of several coupon-level hardware tests that will provide initial insight into post 1st failure performance based on crack energy release upon crack formation. Both fiber and matrix cracking are investigated. The level of fidelity derived from this testing will support initial structural component level crash modeling. While limited, this level of testing will provide a basic indication of how the material will perform under post-failure conditions. Example tests are Compact Compression and Compact Tension.

Module 2b provides additional results via component testing. Components can be any type of three-dimensional part geometry. Commonly, hat profiles or closed rectangular profiles in any type of 3-point/4-point bending test are used under quasistatic and/or dynamic load. Module 2a tests a series of failure modes with specific tests for each mode, whereas Module 2b test a combination of failure modes. This combined failure is the key to improved simulation correlation between sample testing and modeling results. The increased result fidelity supports accurate modeling of larger, more complex subsystems (e.g. Front-End Modules/Impact Zones). The step up from Module 2a to 2b results in a considerable increase in simulation forecast quality. Detailed information on Module 2 will follow in the result discussion section. Even though Module 2b provides expanded characterization of failure, coupon tests are still necessary to formulate the basis of the material properties. Module 2b is based on Module 2a.

Module 3a – Strain Rate Dependent Material Testing represents another addition to the already high fidelity of material data from Modules 1 and 2. The anisotropic nature of FRP also applies to strain rate. Specific test set-ups like drop tower and Split-Hopkinson bar are typically used. These tests are engineered to measure and match the strain rates of the particular application. The key item for Module 3a is then the solver specific result evaluation and material card enrichment. Both material model setup and hardware testing happen in close collaboration to ensure the simulation prediction quality.

Module 3b – Axial Crush testing is focused on emulating crash structure performance often seen in high speed vehicle crash testing. Module 2a and 2b are not sufficient to model this behavior. Therefore, Module 3 is comprised of further drop tower tests using generic or complex geometries to specifically recognize the energy dissipation capabilities of the material and the geometry through crushing. While the Crush Screening (Module 1b) describes the general suitability of the material, Module 3b captures the material behavior at energy levels common to full vehicle crash, and, depending on the application, realistic levels of strain rate.

At this advanced stage of testing the geometry of the test specimen has a considerable influence on crush energy release. Part curvature and overall complexity generally increase the crushing energy release rate. However, axial crushing not only refers to closed section profiles under longitudinal impact load but can also be observed in flat test specimen. For example, the side pole impact into a CFRP vehicle floor shows similar crushing effects to CFRP crash tubes used in frontal impact. Module 3b material cards refer to a very specific failure mode, and the engineer must decide the locations and parts where to use these material card carefully. A good default knowledge of the structural behavior and cross influences in full vehicle crash simulations is necessary to successfully implement Module 3b material data.

FEA Solvers and Material Models

Due to its broad use across the automotive industry, LS-DYNA was chosen as the base solver for the initial stage of the program development. Even within a given simulation software there are multiple material card options to choose. The choice of which card to use will depend on the customer's needs and simulation experiences as well as the simulation type that is required. For this specific project, and to be able to use the results for the most common material models, two LS-Dyna material cards were selected: MAT 58 and MAT 261.

The material cards MAT 58 and MAT 261 specify which material properties need to be tested. In many cases ASTM and ISO test methods define the test methodology to quantify the targeted properties and the preparation of the coupons to be tested. For the Module 2a level of MAT58, all test are directly derived from or based on ASTM standards. For material model MAT261, material tests like Compact Tension/Compact Compression do not follow official standards and are specific to the respective testing institute.

Calibration of material cards is done via FEA simulation of the proposed coupon and component tests. Simulation results are compared to test results like maximum force levels, strain at break or energy dissipation (and others). Through changing certain influence factors within the material card, correlation can be adjusted until an adequate level of performance is reached.

In general, the material properties generated from testing can be used to setup material models for other solvers. Most of the tests and the overall methodology are independent from the simulation software selected. Depending on the complexity of the material model, other solvers may require additional or less testing, and the transfer of test data must be validated. The basic calibration process to obtain a valid and accurate material card is the same for all solvers.

Materials

In order to generate data relevant to multiple automotive applications, a state of the art material combination was selected. The Hexion epoxy system EPIKOTE^{TM} Resin TRAC 06170 and EPIKURE^{TM} Curing Agent TRAC 06170 has been optimized for fast cycle RTM and LCM manufacturing of automotive composite parts and was combined with the internal mold release agent HELOXY^{TM} Additive TRAC 06805, enabling a high number of moldings without the application of additional external mold release. The glass transition temperature (T_g) of the epoxy system rapidly develops during curing which facilitates demolding without the need for cooling jigs or complicated part grippers. The Hexion reactive binder EPIKOTE^{TM} Resin TRAC 06720 enabled reproducible preforming with extremely high preform stiffness.

The use of carbon fibers in high volume automotive applications is motivated by lower part weight, higher part integration, and part consolidation, which can be achieved by composite materials. For serial supply into mass applications in the automotive sector the business case requirements must also be met which contain price, process-ability, supply commitment, and supply security. A long-term price which covers the entire program life is required and the price needs to be on a level competitive to aluminum solutions. The carbon fiber itself must be suitable for the application in mechanical performance as well as suitable for fast infusion and good drapeability. Lastly, supply into automotive also means a supply guarantee in which the very same raw materials can be supplied in the same quality from two independent and redundant facilities. The supply must also be flexible enough to cover any demand exceeding the forecasts. Zoltek^{TM} PX35 50k large tow carbon fiber can meet or exceed the above requirements and is therefore used in this study.

Table 1: Overview of Utilized Materials

Materials		
Product	**Name**	**Characteristics**
Fiber	Zoltek™ PX35 fiber	50k large tow for industrial applications
Fabrics	Zoltek™ UD300 NCF	0° unidirectional fabric with tricot stitch suitable for compression molding processes such as LCM, RTM, HP RTM
Epoxy Binder	EPIKOTE™ Resin TRAC 06720	Cross-linkable binder for parts made with liquid molding processes
Epoxy System	EPIKOTE™ Resin TRAC 06170	Very short cycle time, long resin injection window, excellent thermal and mechanical properties
	EPIKURE™ Curing Agent TRAC 06170	
	HELOXY™ Additive TRAC 06805	

These materials (Table 1) were processed using high pressure resin transfer molding (HP-RTM). In high pressure RTM mixing, the resin and hardener system are dosed under very high pressure into a small mixing chamber. The high velocity / kinetic energy of the respective components allow for very effective and rapid mixing. Typical HP-RTM mixing heads will operate between 100 and 200 bars. At the time of injection, computerized pumps accurately dose the chemicals, which then meet and mix thoroughly, converting their kinetic energy into turbulence and heat. The liquid system is then shot directly into the mold to permeate the reinforcement preform before the snap-cure epoxy fully reacts.

Test Matrix and Test Results

Using the materials from table 1, HP-RTM plaques were manufactured for test coupon production. Table 2 gives an overview of the test approach for each material models MAT58 and MAT261.

Table 2: Test Matrix

Module	Description	Standard	Load	Result	
1A	Base linear testing	ASTM D 3039	Tension	Tensile strength and modulus	
		ASTM D 6641	Compression	Compression strength and modulus	
		ASTM D 7078	Shear	Shear strength and modulus	
1B	Crush Screening	Testing institute specific	Crushing	Crush stress	Crush Compression Ratio (CCR)
		Testing institute specific	Double dogbone compression	Compression strength	
2A	MAT58 testing	ASTM D 3518	Shear	Shear damage and plasticity	

	MAT261 testing	Testing institute specific	Compact Compression (ENKINK)	Fracture toughness for longitudinal fiber compressive failure mode
		Testing institute specific	Compact Tension fiber (ENA)	Fracture toughness for longitudinal fiber tensile failure mode
		Testing institute specific	Compact Tension matrix (ENB)	Fracture toughness for intralaminar matrix tensile failure mode
		Testing institute specific	End notched flexure-transverse (ENT)	Fracture toughness for intralaminar matrix transverse shear failure
		Testing institute specific	End notched flexure – longitudinal (ENL)	Fracture toughness for intralaminar matrix longitudinal shear failure
		ASTM D 6671	Mixed Mode Bending (MMB)	Coupling factor G% between mode I and II
		Testing institute specific	Charpy	Validation for Compact Tension/Compact Compression test

In the case of design applications where post-first failure performance is a design consideration, material card data from Modules 1a, 1b and 2a can be applied to any project independent of geometry.

Material Card data from these modules provide a powerful set of tools required by the material and application development engineers to complete their preliminary designs. Proactive completion of this testing accelerates the design and development of FRP composite parts.

Depending on the results of initial testing and the needs of the particular application additional modules can be completed to provide a higher level of resolution to the expected post failure performance. This step by step approach allows design engineers to further refine the solution at the component, module-, and system levels, enabling the development of robust designs capable of successful validation testing.

Basic Material Data

Test results from Module 1a for MAT 261 are shown in the Table 3. The material cards for MAT 58 and MAT 261 can be shared within client projects.

Table 3: Module 1a Elastic Material Property Test Results

Material Properties [normalized to 51% fiber volume fraction][1]			
Tensile modulus in fiber direction	E_{11t}	GPa	**115.83**
Compressive modulus in fiber direction	E_{11c}	GPa	**97.54**
Matrix tensile modulus	E_{22t}	GPa	**7.99**
Matrix compressive modulus	E_{22c}	GPa	**6.35**

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[1] *The information provided herein was believed by the authors to be accurate at the time of preparation or prepared from sources believed to be reliable. The information is supplied for informative purposes only and should not be considered certified or as a guarantee of satisfactory results by reliance thereon*

Material Properties Continued			
Poisson Ratio in plane	v_{12}	-	**0.30**
Shear modulus in plane	G_{12}	GPa	**3.15**
Tensile strength in fiber direction	X_t	MPa	**1496**
Compressive strength in fiber direction	X_c	MPa	**942**
Tensile matrix strength	Y_t	MPa	**53**
Compressive matrix strength	Y_c	MPa	**155**
In plane shear strength	S_{12}	MPa	**64**

The material properties were normalized to 51% fiber volume fraction. Fiber volume fractions were established through calculation by measuring preform stack weights and test plate thicknesses. The mean fiber volume fraction of all test plates was used as starting point for normalization.

The above elastic data contains the combined influence from many sources of deviation, tolerance, and error. For example, the fabric areal weight varied by ±5% of its target value. Further, the manufacturing process induced fiber distortion from cutting, stacking, and during the injection itself. There are also thickness tolerances form the RTM tool and the resin curing. As well, the specific tolerance stackup from the individual sample preparation and test equipment setup can impact the observed results.

Crush Screening

The analyzed CCR (crush compression ratio; Module 1b) for this resin fiber combination (Table 2) shows a high potential of specific energy absorption and the expected sensitivity to fiber angle distribution and stacking sequence.

Due to the fast and uncomplicated implementation of these tests, a biaxial fabric material with a comparable layup to the UD material was also analyzed. The failure modes were similar to the UD material. The usage of multiaxial fabrics provides increased efficiency in layup compared to UD only stacking at comparable crash performance and behavior.

Figure 2 shows crushed coupon examples from the Crush Screening program.

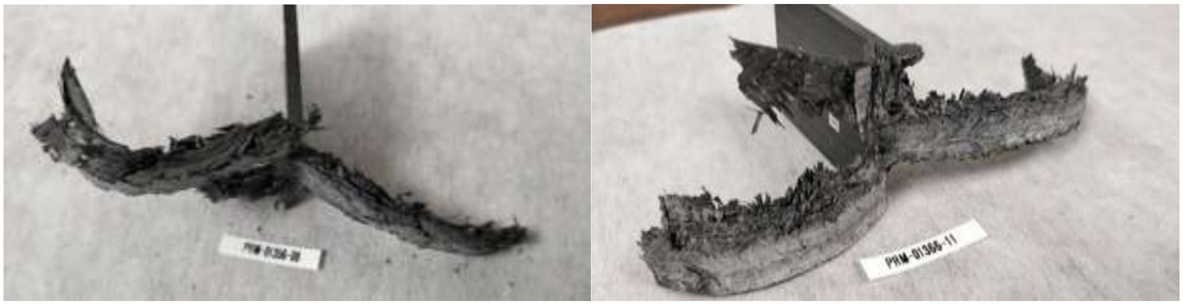

Figure 2: Crush Screening sample results

Module 2a Correlation Results for MAT261

Testing and simulation have to be correlated to create a usable material card. Within this project, correlation and material card enhancement was done for Compact Tension and Compact Compression, as well as, all the basic tests from module 1 (Table 2).

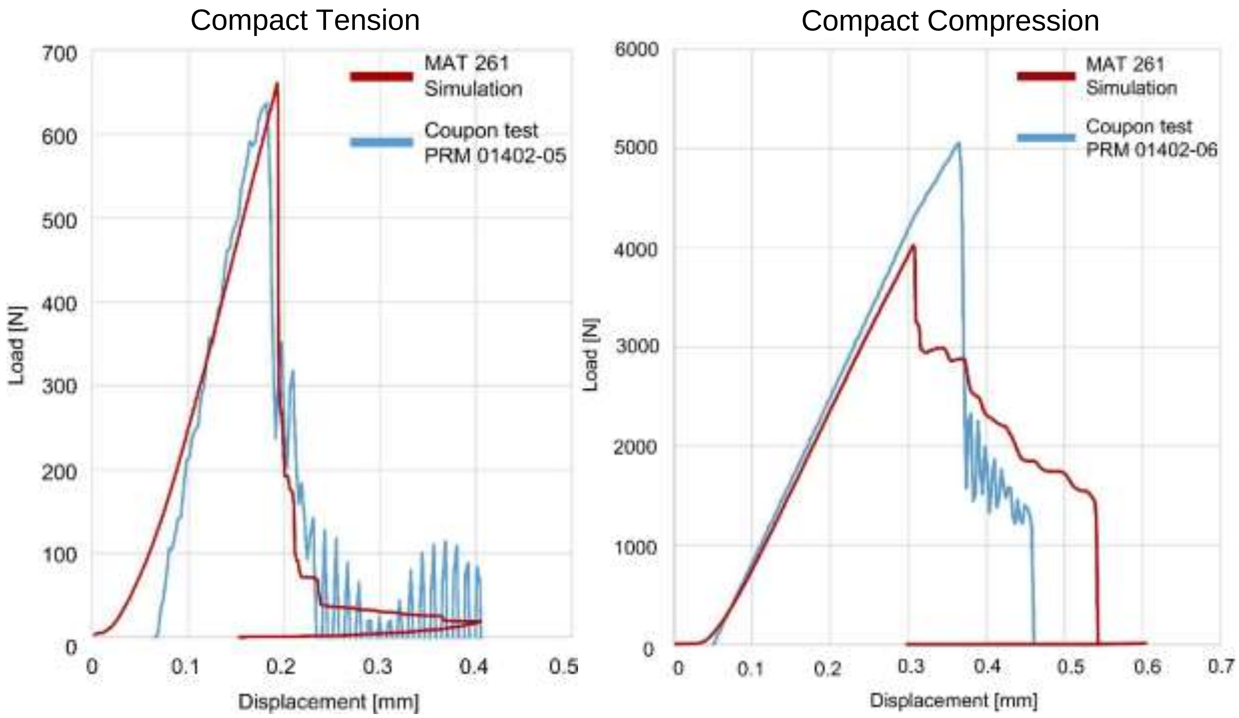

Figure 3: Correlation of Compact Tension and Compact Compression: Coupon Test vs. Simulation

The compact tension validation shows very good overall correlation. Peak load, stiffness and dissipation energy very closely match between model and test.

Compact Compression correlation shows some deviations in maximum force and displacement, however the sum of energy release captured in the areas under the graphs closely match.

As an initial material card calibration on coupon level (module 2a), the results are capable of predicting the material post failure characteristics at a reasonable level of certainty.

Additional Testing for MAT 261 Characterization

Figure 4 shows the test setup for mixed mode bending. Coupon bending test results of ENB, ENT, ENL and MMB, represent the key input values for the MAT261 material model in terms of intralaminar fracture toughness.

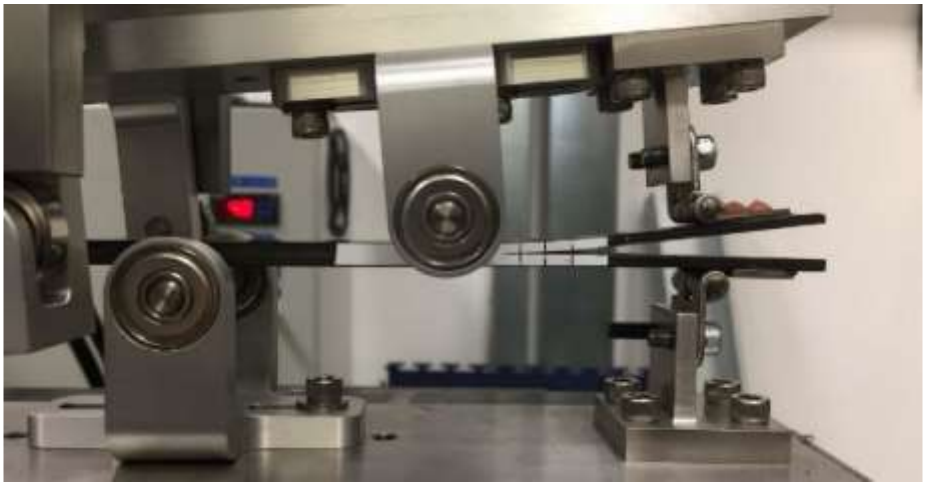

Figure 4: Test Setup for Mixed-Mode Bending

The following section will compare the results of coupon level testing (module 2a) and component testing (module 2b). Component testing with increased test specimen complexity provides more accurate results required for post failure simulation correlation.

Detailed Review of Module 2 Testing and the Influence on Simulation Prediction Quality

While the basic Module 1 FRP material characteristics are suitable for initial concept work, advanced FEA simulations associated with detailed vehicle design require a deeper insight into the material post failure behavior. Figure 5 shows the FEA result comparison between coupon level and component level post material cards in terms of force/displacement and energy dissipation.

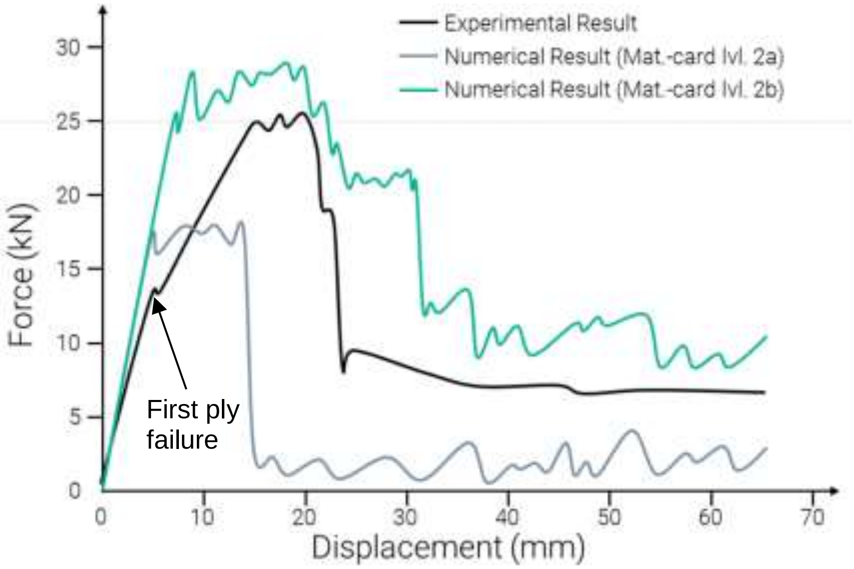

Figure 5: Comparison Between Simulated Coupon-Level, Simulated Component-Level, and Experimental Result of a Quasistatic 3-Point-Bending Test Using a Closed-Section CFRP Profile

The coupon-level material card can give a first impression of the post failure behavior but cannot accurately capture both energy dissipation (area under the curve) and maximum force levels (shape of the curve). A (full vehicle) crash simulation using a Module 2a material card for FRP parts can only give a limited insight into the viability of the vehicle structure.

Material cards based on coupon testing are surpassed by the test results derived from 3D component testing of Module 2b using hat-shapes or closed profiles. From Figure 5 we see the maximum achievable force levels and dissipated energy match more closely to the experimental results.

The difference between test curves and simulation depends on the following factors:

- Capability of material model in combination with the simulation solver to show post failure mechanics and to allow for material calibration and enhancement
- Test setup and measuring equipment
- Component geometry
- General manufacturing quality of coupons (base plates) and components

Generally speaking, component testing should not be bound to a specific geometry and testing method. Component testing should always closely relate to the expected real-world load cases as a much as possible. This applies for the component geometry, the test setup and the load case interaction that needs to be shown.

However, for general use, there are a couple of test types that yield good results. For module 2b characterization we recommend quasistatic and dynamic (impact) 3- or 4-point-bending setups (Figure 6). Impact speeds and impactor geometries can also be varied and adjusted to increased the fidelity of test results.

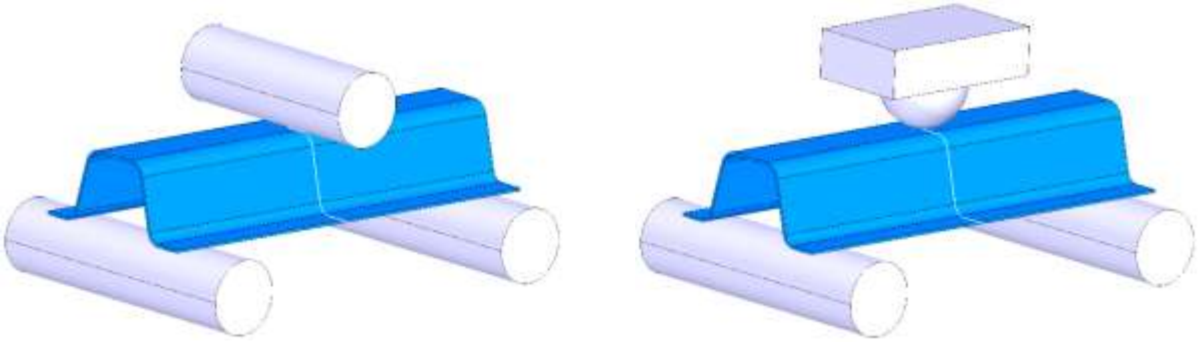

Figure 6: Component Test Setup for 3-Point-Bending Using the Standard Beam Impactor (Left) and a Specialized Spherical Shape Impactor (Right)

The enriched material card of level 2b matches the real-world force/displacement in a much better way because more than one failure mechanism is tested and simulated simultaneously in a controlled environment.

Component testing with failure mode interaction is the key ingredient for successful material card enrichment. However, coupon tests are still necessary to prepare test setups and to provide the groundwork for advanced calibration tasks.

Use Case

The modular material card data development approach was applied to a recent automotive industry project providing real world insights on the benefits of the program.

The scope of this two-phase project was the development of a specific automotive structural CFRP part from initial concept design up to detailed series design, including prototype production and testing. A compressed design-to-market schedule and the use of a novel material presented challenging conditions for the project team.

Within the concept design phase, the early availability of usable and proven material data had a very positive impact on milestone planning. Uncertainties in material selection could be discussed faster and solutions were found earlier. The clear approach enabled an overall better understanding and acceleration of the project.

In its initial stages, the project used Module 1 basic material properties, which had proactively been prepared during product development, to assess and pick a best-of-all concept via fundamental FEA simulations. The clear module/result definition of the testing program provided insight into the planning of necessary expanded characterization for the specific client material. Employing the modular approach, the design phase including simulations and material characterization can run in parallel, conclusions can be drawn earlier, and engineers are able to focus on the main structural design path.

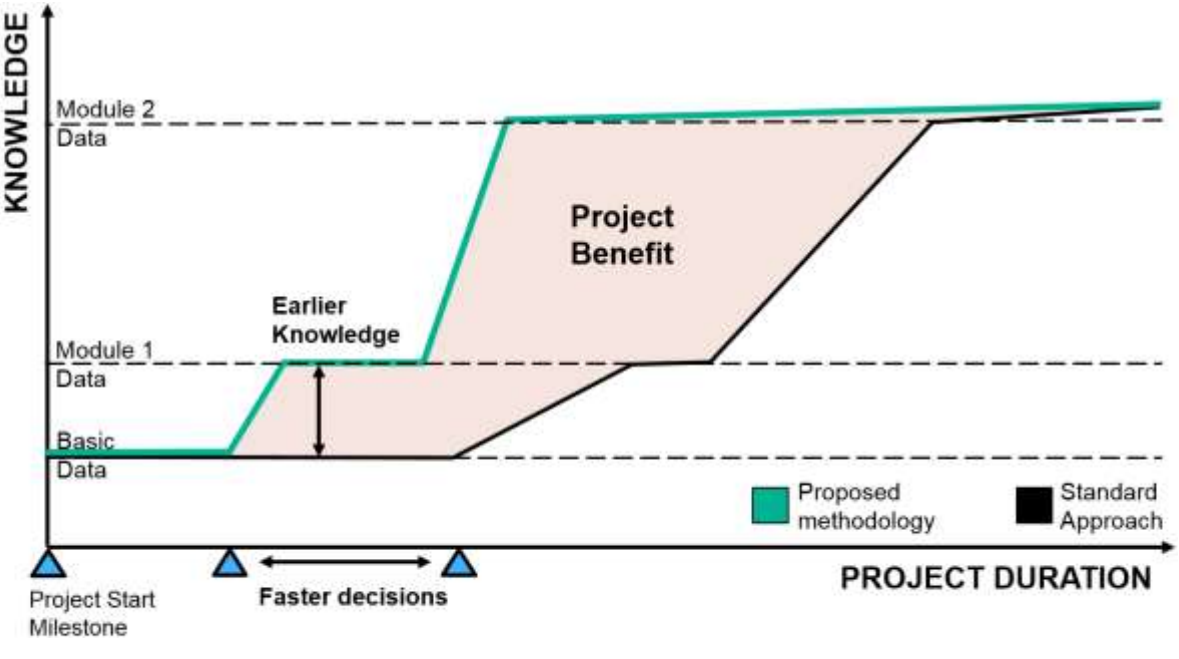

Figure 7: Project Time over Material Knowledge: Speedup and Budget Savings Potential

Furthermore, an Abaqus ply fabric user material card from testing results was performed within this use case project. First trials indicate that this conversion process was successful, and the derived Abaqus material card can be used in the project.

To summarize, the modular material card development program provided the client with a clear path to generate capable material card data for preliminary design which they were able to already use in the early stages of the project. The immediate availability of the basic material card data was not only an accelerator but can be seen as a key enabler for the project endeavor. Early knowledge and fast decisions removed budget restrains that otherwise would have hindered the advance in concept design and ultimately led to project success.

Summary and Next Steps

A structured methodology to FRP material card generation for the automotive industry was developed. The system is separated into modules, each representing a certain level of material data knowledge. Automotive industry projects benefit from the clear timing (“when do we need what kind of data”), and the increased transparency in handling FRP material data.

The partners Forward Engineering, Hexion and Zoltek continuously work on refining the material characterization methodology for fiber reinforced polymer composites. It is planned to test more standard materials and generate a material data and material card toolkit to broaden the applications where automotive industry can accelerate their product development.

The insights gathered from applications of the modular material card development program will lead to an even more straightforward characterization approach for the automotive industry. Entrance barriers into the world of fiber reinforced plastics can be removed and the complexity of those materials will be even more manageable.

By removing constraints from FRP usage in the automotive industry, potentials for cost & mass saving as well as performance increase can be leveraged.

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