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Modular approach to composite material card generation

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Accelerating the adoption of fibre-reinforced composite parts in automotive applications requires a better evaluation and testing of composite designs. To address this challenge, a new modular approach for generating material card data was developed, tested and used in an actual industry project to confirm its viability.

The automotive industry is facing significant challenges to address new and very different customer requirements driven by dramatically shifting trends in vehicle powertrain and the demands of integrating complex Automated Driver Assistance Systems. Compared to most metals, fibre reinforced composites offer significant design freedom and the ability to seamlessly integrate functionality while reducing mass and improving overall vehicle performance (Range, NVH, Comfort, etc). This design freedom comes with the unique and powerful ability to tailor the behaviour of fibre reinforced polymer composites to specific performance requirements by combining suitable fibre 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 available standardized material cards for automotive applications presents a barrier to the adoption of fibre-reinforced composites. The term "material card" refers to the collection of input data design engineers must enter into their simulation programs prior to modelling their designs. As the level of complexity of a composite design increases, the amount and fidelity of the material card data must also increase to achieve an acceptable level of modelling predictability. To overcome this barrier to composite adoption, materials suppliers need to develop testing procedures, a set of best practices, and a methodology for translating test results into material card input data that are compatible with commonly used FEA solvers. The following represents a modular approach for material card data generation that allows users to extend and refine the validity of the results depending on the stage of composite development. Three modules represent progressively more advanced stages of R&D from static design estimations to crash behaviour to post-crash behaviour. The objective when developing this approach was to set up a simple yet complete material testing structure to support simulation results at the various levels of detail required throughout an automotive product development programme. When starting a project, a common challenge is identifying which tests are needed to simulate the required load cases. To eliminate these uncertainties, the potential target load cases are classified into different levels. Some applications require analysis of the elastic material values until first failure. Crash applications, however, require post-failure properties to be addressed. To increase the modelling predictability, test module levels are added to the classification. The resulting modular approach is shown in Figure 1.

Modular approach

The Module 1a package provides basic material card information required for modelling performance up to first failure of the material.

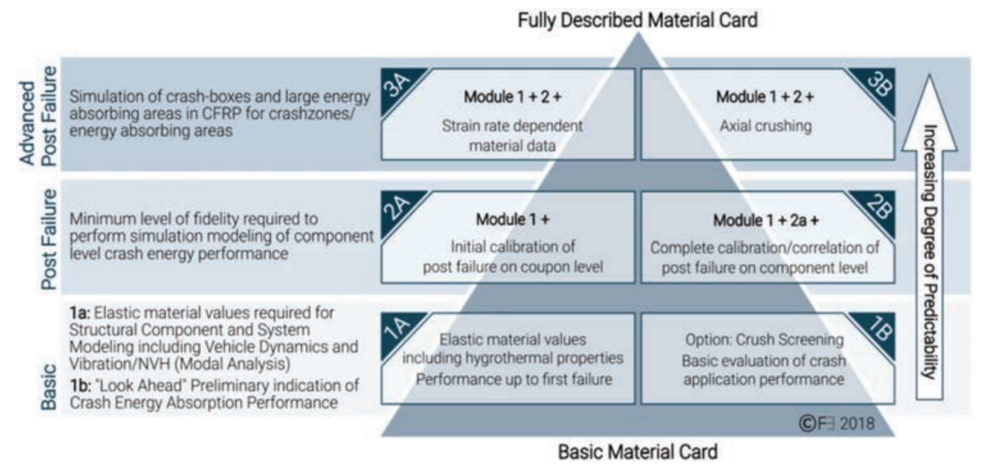

Fig. 1: Modular material characterization approach

These properties can be generated by 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 is also an important input required for vibration/NVH (noise, vibration, harshness) simulation (modal analysis) and vehicle dynamics simulation. 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, fibres, additives, etc.) to assess their relative crash energy behaviour.

For applications where understanding crash performance post first failure is a requirement, Modules 2a and 2b apply. These modules focus on the material behaviour after the first failure when cracks begin to form and propagate through the material with increasing load and deformation. Module 2a testing supports initial structural component level crash modelling. To achieve a more accurate picture of post-failure energy absorption behaviour, 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 provide initial insight into post-first failure performance based on crack energy release upon crack formation. 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 component testing results. 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 quasi-static and/or dynamic load. Module 2a tests a series of failure modes with specific tests for each mode, whereas Module 2b tests a combination of failure modes. This combined failure is the key to improved simulation correlation between sample testing and modelling results. This supports accurate modelling 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. 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 a further addition to the already high fidelity of material data from Modules 1 and 2. The anisotropic nature of FRP makes strain rate testing critical. Specific test setups like drop tower and Split-Hopkinson bar are typically used to measure and match the strain rates of the particular material, enriching material card data. Both material model setup and hardware testing take place in close collaboration to ensure the simulation prediction quality.

Module 3b – axial crush testing – is focused on modelling crash structure performance seen in high-speed vehicle crash testing. Modules 2a and 2b are not enough to model this behaviour. 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 behaviour at energy levels common to full vehicle crash, and, depending on application if possible, even realistic levels of strain rate.

In advanced post-failure Module 3b 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 specimens. 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 determine the applicable locations and parts carefully. A good default knowledge of the structural behaviour and cross influences in full vehicle crash simulations is necessary to successfully implement Module 3b material data. To ascertain the validity of this approach to material card data generation for composite materials – and gauge its compatibility with commonly-used FEA solvers – the following testing programme was implemented.

FEA solvers and material models

Due to its broad use across the automotive industry, LS-DYNA was chosen as the base solver. Even within a given simulation software (solver), there are multiple material card options from which to choose. Which card to use depends on the customer's needs and simulation experience as well as the simulation type that is required. For this 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.

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

The calibration of material cards for this testing programme was done via FEA simulation of the proposed coupon and component tests. Simulation results were compared to test graphs, and certain influence factors were changed within the material card until a good correlation was achieved.

In general, the material properties generated from this 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 testing, and the transfer of test data has to 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™ Resin TRAC 06170 and EPIKURE™ Curing Agent TRAC 06170, which is optimized for fast-cycle RTM and LCM manufacturing of automotive composite parts, was combined with the internal mould release agent HELOXY™ Additive TRAC 06805, enabling a high number of mouldings without the application of additional, external mould release agents. The glass transition temperature (T_g) of the Hexion epoxy system rapidly develops during curing, which facilitates demoulding without the need for cooling jigs or complicated part grippers. The Hexion reactive binder EPIKOTE™ Resin TRAC 06720 enabled reproducible preforming with extremely high preform stiffness.

Tab.1: Materials used

Product	Name	Characteristics
Fibre	Zoltek™ PX35 fibre	50k large tow for industrial applications
Fabrics	Zoltek™ UD300 NCF	0° unidirectional fabric with tricot stitch suitable for compression moulding processes such as LCM, RTM, and HP RTM
Epoxy binder	EPIKOTE™ Resin TRAC 06720	Cross-linkable binder for parts made with liquid moulding 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	

The use of carbon fibre-based composites in high-volume automotive applications is motivated by lower part weight, higher part integration, and part consolidation. For serial supply into mass applications in the automotive sector, the business case requirements must also be met including price, processability, supply commitment, and supply security. Long-term pricing for the life of the entire programme is required, and the price needs to be on a level competitive to aluminium solutions. The carbon fibre itself has to be suitable for the application in terms of mechanical performance as well as capable of fast infusion and good drapeability. Finally, supply guarantee, in which the very same raw materials can be supplied in the same quality from two independent and redundant facilities, is mandatory. The supply must also be flexible enough to cover any demand exceeding the forecasts. Zoltek™ PX35 50k large-tow carbon fibre can meet or exceed the above requirements and is therefore used in this study.

These materials (see Table 1) were processed using high-pressure resin transfer moulding (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 resin materials allows 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 chem-

Tab.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	MAT 58 testing	ASTM D 3518	Shear	Shear damage and plasticity	
	MAT 58 testing	Testing institute-specific	Compact compression (ENKINK)	Fracture toughness for longitudinal fibre compressive failure mode	
		Testing institute-specific	Compact tension fibre (ENA)	Fracture toughness for longitudinal fibre 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/compression test	

Tab.3: Module 1a elastic material property test results

Material properties [normalized to 51% fibre volume fraction]			
Tensile Young's modulus in fibre direction	E_{11t}	GPa	115.83
Compressive Young's modulus in fibre direction	E_{11c}	GPa	97.54
Matrix tensile Young's modulus	E_{22t}	GPa	7.47
Matrix compressive Young's modulus	E_{22c}	GPa	6.13
Poisson's ratio in plane	V_{12}	-	0.30
Shear modulus in plane (Tests differ comparing material cards)	G_{12}	GPa	3.04
Tensile strength in fibre direction	X_t	GPa	1.40
Compressive strength in fibre direction	X_c	MPa	150.01
Tensile matrix strength	Y_t	MPa	49.61
Compressive matrix strength	Y_c	MPa	150.01

The information provided herein was believed by the authors to be accurate at the time of preparation and for informative purposes only.

icals, which then meet and mix thoroughly, converting their kinetic energy into turbulence and heat.

The liquid system is then shot directly into the mould to permeate the reinforcement preform before the snap-cure epoxy fully reacts.

Test matrix and test results

Table 2 gives an overview of the test approach for each material model.

For 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 into 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 Table 3.

The material cards for MAT 58 and MAT 261 can be shared within client projects.

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

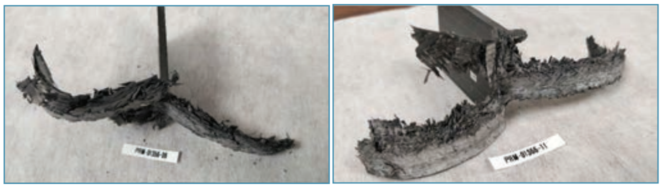

Fig. 2: Crush screening sample results

The elastic data above reflects the combined influence of 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 fibre distortion from cutting, stacking, and during the injection itself. There are also thickness tolerances from the RTM tool and the resin curing. The specific toler-

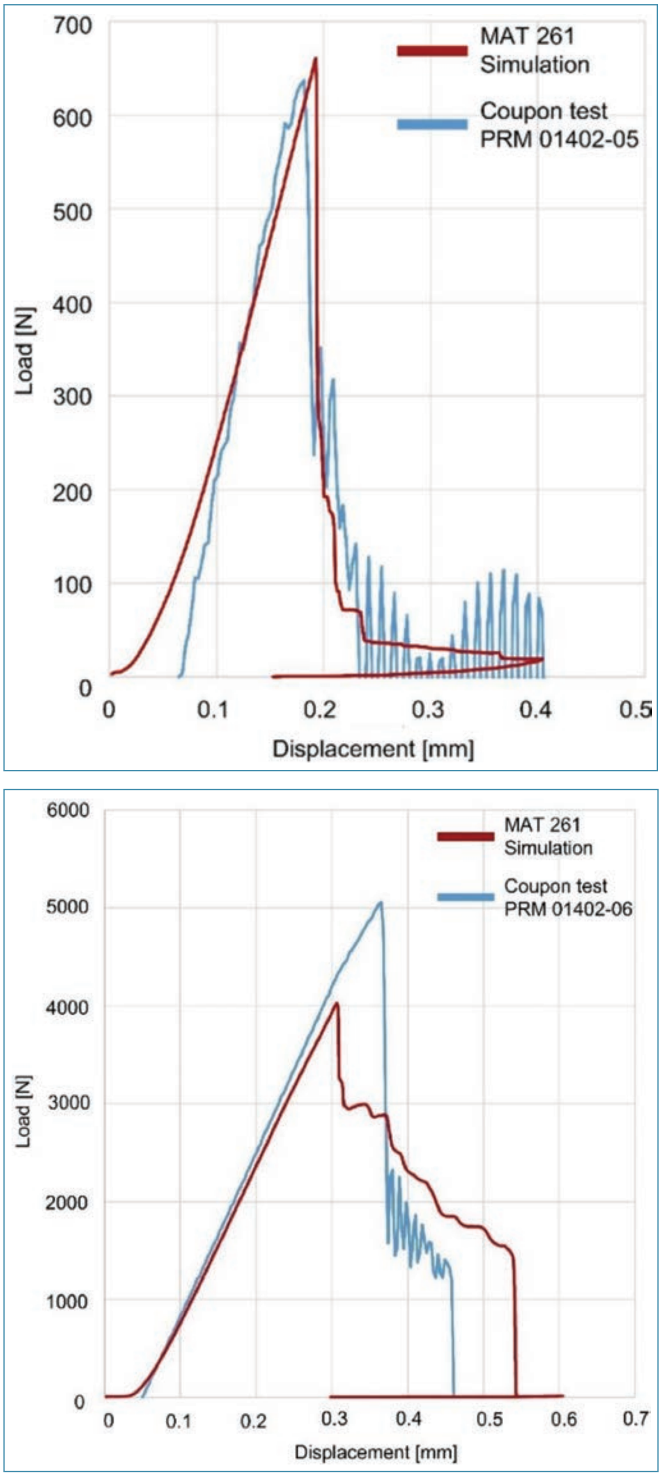

Fig. 3: Correlation of compact tension and compact compression: coupon test vs. simulation

ance stackup from the individual sample preparation and test equipment setup can impact the observed results as well.

Crush screening

The analysed CCR (crush compression ratio; Module 1b) for the resin/fibre combination tested in this project shows a high potential for specific energy absorption but also a certain sensitivity to changes in the layup. Due to the fast and easy implementation of these tests, a biaxial fabric material with a comparable layup to the UD material was also analysed. The failure modes were similar to the UD material, but it is assumed that the biaxial fabric material may be preferred in components that need a significant reinforcement perpendicular to the crush direction. Figure 2 shows crushed coupon examples from the crush screening programme.

Module 2a correlation results for MAT 261

Testing and simulation need to be correlated to ensure a usable material card. For this project, correlation and material card enhancement were done for compact tension and compact compression, as well as for all the tests from module 1 (see Table 2).

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

Compact compression correlation shows some deviations in maximum force and displacement. However, the energy release rates captured closely match. For an initial material card calibration on coupon level (Module 2a), the results can predict the material's post-failure characteristics at a reasonable level of certainty.

Additional testing for MAT 261 characterization

Figure 3 shows the test setup for mixed-mode bending. Together with coupon bending tests ENA, ENB, ENT and ENL, MMB test results provide key input values for the MAT 261 material model.

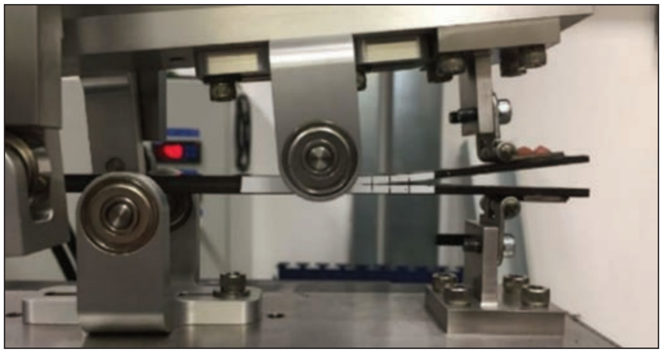

Fig. 4: Mixed-mode bending test setup

The following section compares the results of coupon-level testing (Module 2a) and component testing (Module 2b). More complex component testing provides the more accurate results required for post-failure simulation correlation.

Detailed review of Module 2 testing and influence on simulation prediction quality

While the basic Module 1 FRP material characteristics are suitable for initial concept work, the advanced FEA simulations associated with detailed vehicle design require a deeper insight into the material's post-failure behaviour.

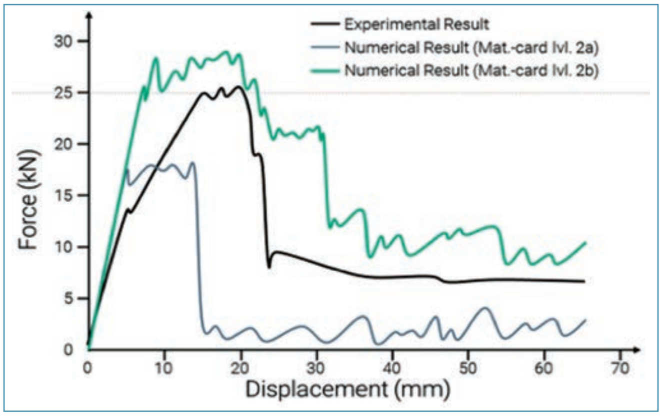

Fig. 5: Comparison between simulated coupon-level, simulated component-level, and experimental results of a quasi-static 3-point bending test using a closed-section CFRP profile

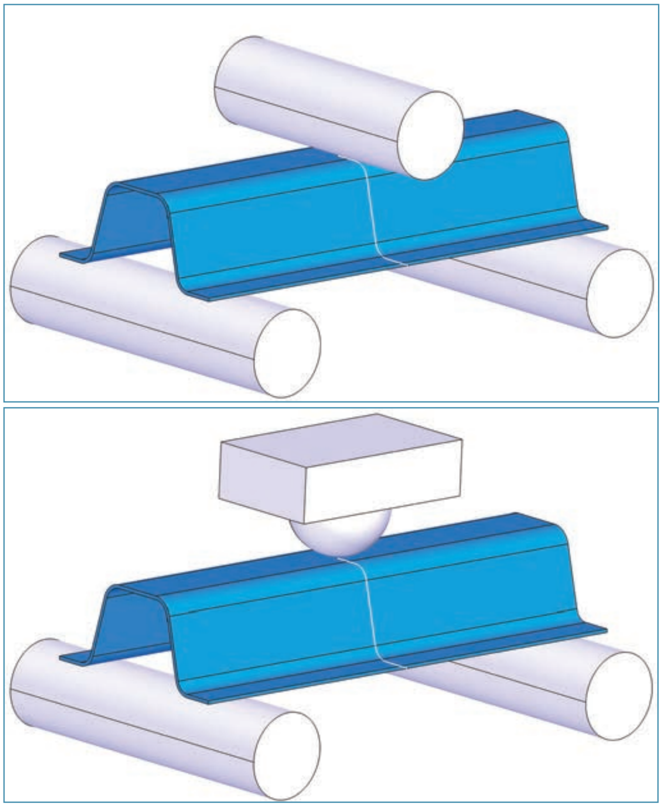

Fig. 6: Component testing setup for 3-point bending using a standard beam impactor and a specialized spherical shape impactor

Figure 4 shows the FEA result comparison between coupon-level and component-level post-material cards in terms of force/displacement and energy dissipation.

The coupon-level material card can give a first impression of the post-failure behaviour 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.

The material card test results derived from the 3D component testing of Module 2b using hat-shapes or closed profiles are much more robust. Figure 4 shows that the maximum achievable force levels and dissipated energy match much more closely the experimental results.

The difference between test curves and simulation can be attributed to the following factors:

- Capability of the 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 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, quasi-static and dynamic (impact) 3- or 4-point-bending setups (Figure 5) are recommended. Impact speeds and impactor geometries can also be varied and adjusted to increase the fidelity of test results. The enriched material card of Module 2b matches the real-world force/displacement much more closely 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.

One of the major benefits of the structured module material card development programme is the reduction in the amount of coupon testing required. Through the development of capable component-level testing in Module 2b, an equal or better level of resolution and correlation can be achieved with fewer coupon-level tests.

Use case

The modular material card data development approach was applied to a recent automotive industry project, providing real-world insights into the benefits of the programme.

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 very challenging conditions for the project team.

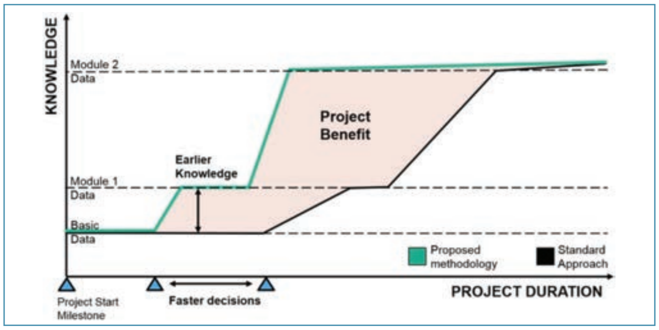

Fig. 7: Project time over characterization effort: speedup and budget saving potential

In 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 programme 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.Furthermore, an Abaqus ply fabric user material card from testing results was generated within this use case project. The first trials indicate that this process was successful.

In summary, the modular material card development programme provided the client with a clear path to generate capable material card data for preliminary design, which they were able to 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. Early knowledge and fast decisions removed budget restraints that otherwise would have hindered the advance in concept design, and ultimately led to project success.

Conclusions 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 benefited 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 are continuously refining the material characterization methodology for fibre-reinforced polymer composites.

They plan to test more standard materials and provide a material data and material card toolkit to broaden the applications where the automotive industry can accelerate their product development. The insights gathered from the application of the modular material card development programme will lead to an even more straightforward characterization approach for the automotive industry. Entrance barriers for fibre-reinforced plastics can be removed and the complexity of these materials will be even more manageable. By removing constraints from FRP usage in the automotive industry, the potentials for cost and weight savings as well as performance increases can be leveraged. ◻

More information:
www.hexion.com
www.forward-engineering.com
www.zoltek.com

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