



AUTOMOTIVE PLASTICS News



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14th - Annual SPE Automotive Composites Conference & Exhibition

This year's **SPE® Automotive Composites Conference & Exhibition** (ACCE) returns **September 9-11, 2014** to The Diamond Banquet & Conference Center at the Suburban Collection Showplace in Novi, Mich. in the Detroit area. Now in its fourteenth year, the show is the *world's leading forum for automotive composites* and draws over 900 exhibitors, speakers, and attendees from 15 countries on five continents. This year's theme is **Composites: Meeting Today's Automotive Needs**.

Dr. Michael Connolly, program manager - Urethane Composites at Huntsman Polyurethanes, 2014 SPE ACCE conference co-chair explains, "Our conference has been fortunate to experience some pretty significant growth in the past few years, thanks to a rebound in the North American automotive industry along with considerable interest among all transportation OEMs on the subject of *lightweighting* and the role composites can have in helping them achieve mass-reduction goals. That means our committee is working harder than ever to ensure we provide a strong technical platform for discussing the latest advances in transportation composites as well as an expanding our exhibition area with suppliers from all parts of the automotive composites supply chain."

Antony Dodworth, managing director, Dodworth Design and the 2014 SPE ACCE co-chair adds, "This year's conference theme reflects our commitment to show automakers that composites aren't just something to solve *future* transportation issues. The composites supply chain is actively engaged in solving problems today by improving cost, weight, aesthetics, and safety performance of cars and light trucks."



An Engineer's Life...

by Roger Assaker

CEO, e-Xstream engineering and
Chief Materials Strategist, MSC Software

I was born in Lebanon in October of 1968 as the youngest of three brothers. I grew up and lived in Lebanon until the end of high school in 1987 when I left to go abroad for university. In my home country, we are basically encouraged to get a good education, and most choose a career in either medicine or in engineering. I went the route of engineering. My father was a landscape architect who was passionate about math. One of my brothers, Richard, who is 11 years older than me, is a professor of Neurosurgery in Lille, France and has invented many medical devices. My other brother, Dany, who is 8 years older than me, holds a Master's degree in Civil Engineering and a Ph.D. in Aerospace Engineering. These days he is a manager at the Goodyear Technical Center in Luxembourg.

I finished a combined Bachelor's/Master's degree in Aerospace Engineering in 1992 at the University of Liège in Belgium. While I was working on that degree, my brother Dany worked at Solvay's headquarters in Brussels and helped me get the opportunity to do a couple of summer internships at the company. That proved to be my first contact with plastics. After graduating, I continued my education by following in Dany's footsteps and pursuing a Ph.D. degree at the University of Louvain, also in Belgium. My doctorate was in MagnetoHydroDynamics in Semiconductors. I chose Aerospace Engineering because it sounded exciting and because it was strongly computational mechanics and simulation based, and I loved that kind of work. While I was pursuing my Ph.D. degree, I did some teaching in solid mechanics and strength of materials, and that's where I met my future business partner, Professor Issam Doghri, who had recently left California after working for a software company for some years. A decade later, we co-founded e-Xstream engineering.



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Before I'd even finished my Ph.D., I started my first full-time job as a Senior R&D Engineer in the Computational Mechanics Group at the Goodyear Technical Center in Luxembourg. Once again, my brother Dany arrived before me and helped me obtain an interview for a job that I was offered. It really was nice to be able to work with him and a team of friends. My work there was focused on developing methods and software for the effective and efficient modeling and simulation of tires. Our company, as many other major corporations, had invested millions of dollars in finite-element analysis (FEA) simulation working with all the major commercial software codes. However, when it came to material modeling for those commercial packages, we found that this area of work was underfunded and underdeveloped. To do my job, I mainly collaborated with Sandia National Laboratories in the U.S. and with different FEA software vendors working on topics such as fluid-structure interaction and uncertainty quantification. My work at Goodyear gave me the opportunity to issue a couple of trade secrets related to advanced modeling of tires. While working there, I completed my Ph.D. dissertation and then started work on an M.B.A. by taking evening classes at Sacred Heart University's John F. Welch College of Business in Luxembourg. I graduated as valedictorian in the Class of 2002. During my time as an M.B.A. student, I worked on a business plan to start e-Xstream engineering. After 5-1/2 years at Goodyear, I took a big risk and walked away from a nice career plan, and a comfortable salary and benefits at the end of 2002. I wanted to focus on starting my own company with my long-time colleague, Issam Doghri, whose research at University of Louvain focused in



An Engineer's Life CONTINUED FROM PAGE 12

material modeling and micromechanics. Interestingly, the business plan I wrote for e-Xstream won 2 competitions at regional (123GO) and European (Eurowards) levels of competition, and that helped us not only get a lot of free publicity, but also to meet two of the three investors who eventually would help fund the company's startup.

We began operations in May of 2003 and our first office was in Belgium. Less than a year later, we set up a second office in Luxembourg. Issam stayed at University of Louvain but worked as a consultant for us as head of R&D, a position he still holds. e-Xstream engineering is a software and engineering services company that is 100% focused on multi-scale modeling of reinforced plastics and composites. The company has been experiencing double-digit growth for the past decade and today is a key player in the materials modeling segment. Automotive is our most important market, followed by aerospace. It's funny but we see automotive moving from plastics toward composites, and aerospace moving from composites toward reinforced plastics, so we think we are positioned well to help both industries, since their needs overlap our core competence.

While I worked to build e-Xstream, I continued my education studying entrepreneurship (at Massachusetts Institute of Technology's Sloan School of Management), negotiation (Harvard Business School and Harvard Law School), and innovation (Louvain School of Management - UCL). In 2007, I won the Creative Young Entrepreneur award in Luxembourg. I love flying all over the world to visit with customers, learning about the problems they face, and helping them find creative custom solutions that we develop from scratch. However, as much as I love technology, I would never want to spend all my days sitting behind a desk and making the same report 10 times to my boss and my boss' boss, and so on. I get bored really fast if my work is repetitive.

In September of 2012, e-Xstream engineering was acquired by MSC Software. We continue to focus exclusively on modeling of advanced materials. After the acquisition, I kept my position as CEO of e-Xstream but added a new job as Chief Material Strategist at MSC, where "materials" are one of three strategic pillars, the other two being "parts" and "systems." My job is to help MSC make the connection between each of those three areas for our customers.

Today I am married to Florence, whom I tutored in math when we were both at university and she was studying Economics. Together, we have a 12-year-old daughter called Anouk, who is crazy about horses, and is showing great aptitude in math as well as early indications of an entrepreneurial spirit, since she wants to start a horse ranch. I like all kinds of outdoor and water sports, including scuba diving, sailing, snowboarding, and running — that is, when I'm not on a plane.

And my two brothers? Although we aren't working together at the moment, when we play golf we come up with 10 new ideas an hour. My surgeon brother has brought me in to help design a new medical device that replaced titanium with PEEK/carbon fiber composite for an intervertebral disc replacement. Who knows what the future will hold?

ABOUT ROGER ASSAKER

Roger Assaker, a tech entrepreneur, is CEO and co-founder of e-Xstream engineering, a software and engineering-services company that is 100% focused on advanced materials modeling. Since September 2012, he is also the Chief Material Strategist of MSC Software. He holds both Ph.D. and M.S. degrees in Aerospace Engineering with a strong focus on nonlinear computational mechanics – an area of expertise where he now has 20 years' experience. Assaker has complemented his engineering education with an MBA in International Business, plus has taken additional advanced business and technology entrepreneurship courses from prestigious universities such as Massachusetts Institute of Technology and Harvard. In addition to growing e-Xstream engineering into global leadership in advanced composite modeling, Assaker is also Vice-Chair of NAFEMS' Composite Working Group and an active member of other technical material associations such as SPE and SAMPE.

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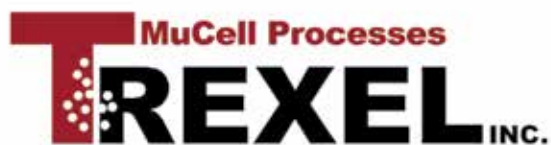
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Novi, MI, Sept 9-11, 2014



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CONTENTS

ACCE 2014	1, 4
Automotive Division Calendar	2
Chair's Message	3
Call for Part-Competition Nominations	4
Call for Student Scholarship Nominations	5
Batter's Box	8-9
An Engineer's Life	12-13
ANTEC Chair's Report	15-18
Service through Science	20-21
Membership Report	23
Innovation Awards Gala & Competition 2014	26-27
Call for Hall of Fame Nominations	27
Call for Vehicle Engineering Team Award Nominations	28
TPO 2014	29
Technical Paper	31-39
Councilor's Report	41-42
Social Report	43-44
Treasurer's Report	44
Secretary's Report – Dec. Board Meeting Minutes	45-46
Board of Directors / Directory	48

AUTOMOTIVE DIVISION MEETING SCHEDULE & SPECIAL EVENTS CALENDAR



AUTOMOTIVE

Auto. Div. Board Meeting

American Chemistry Council - Auto. Ctr. 5:30 - 7:30 pm
Troy, MI USA April 14, 2014

SPE ANTEC Conference

Rio All Suites Resort & Casino ALL DAY
Las Vegas, NV USA April 28 - 30, 2014

9th-Annual SPE AutoEPCON Conference

MSU Management Education Center ALL DAY
Troy, MI USA May 6, 2014

Auto. Div. Board Meeting

American Chemistry Council - Auto. Ctr. 5:30 - 7:30 pm
Troy, MI USA June 16, 2014

14th-Annual SPE Automotive Composites Conference & Exhibition (ACCE)

Diamond Center ALL DAY
Novi, MI USA Sept. 9 - 11, 2014

16th-Annual TPO Automotive Engineered Polyolefins Conference

Troy Marriott ALL DAY
Troy, MI USA Oct. 5 - 8, 2014

First Round -

Automotive Innovation Awards Judging

Celanese Corp. 8:00 a.m. - 5:00 p.m.
Auburn Hills, MI USA Oct. 2 - 3, 2014

Second Round / Blue Ribbon -

Automotive Innovation Awards Judging

Celanese Corp. 8:00 a.m. - 5:00 p.m.
Auburn Hills, MI USA Oct. 13, 2014

44th-Annual SPE Automotive Innovation Awards Gala

Burton Manor 5:00 - 11:00 p.m.
Livonia, MI USA Nov. 12, 2014

Automotive Division Board of Directors meetings are open to all SPE members. All events are listed on our website at

<http://speautomotive.com/ec>

Email Yvonne Bankowski Merritt at

auto-div-chair@speautomotive.com for more information.



Multi-Scale Modeling of High Cycle Fatigue of Chopped and Continuous Fiber Compounds

Thierry Malo, Laurent Adam, Roger Assaker
e-Xstream engineering

Tsukatada Matsumoto, Riccardo Giacomini
Toyota Motor Europe

Abstract

The structural durability of an automotive component is one of the most expensive attributes to test, thus one of the most appealing for CAE. Fatigue modeling of chopped and continuous fiber polymer composites is challenging due to their anisotropic, heterogeneous and viscous material properties as well as their process-dependent microstructure. In this context, the ability to model high cycle fatigue (HCF) of fiber reinforced composites was developed in Digimat®.

A first model, based on macroscopic S-N curves and using the pseudo-grain modeling technique, was developed and implemented for chopped fiber reinforced plastics (FRP). It enables computing the S-N response for any fiber orientation state.

A second fatigue model, based on damage evolution in the matrix phase, was developed to address failure of continuous fiber reinforced plastics (CFRP).

The two micro-mechanically based composite fatigue models will be presented and discussed in this paper.

The macro pseudo-grain fatigue model was applied to an automotive plastic part, made of a nylon 6.6 material reinforced by short glass fibers. Experimental fatigue testing was performed both on test coupons and parts. To define the fatigue models, and evaluate their accuracy and robustness, specimen testing was done at different R ratios; a focus on $R=-1$ will be made. The developed models enable computing the S-N curves locally in every element of a finite element (FE) model and provide that information to fatigue software that compute the fatigue lifetime of the part. The presentation will aim at describing the model and its ability to accurately compute high cycle fatigue by showing correlation between finite element analysis (FEA) and experimental data.

Thierry Malo, engineering services team leader at *e-Xstream engineering*, an MSC Company, was named a *Best Paper Award* winner by the peer-review committee for the **SPE® Automotive Composites Conference & Exhibition (ACCE)**. Malo was lead author (along with Laurent Adam and Roger Assaker, also of *e-Xstream engineering*, and Tsukatada Matsumoto and Riccardo Giacomini from Toyota Motor Europe) on a paper entitled *Multi-Scale Modeling of High Cycle Fatigue of Chopped and Continuous Fiber Composites*. Malo's colleague, Kurt Danielson, accepted a special plaque for excellence in technical writing on his behalf during opening ceremonies at the thirteenth-annual SPE ACCE on September 11, 2013 and presented the paper in the *Virtual Prototyping & Testing* session on September 12 from 8:00-8:30 a.m.

Aside from Malo's current responsibilities as team leader for the engineering services group at *e-Xstream*, he also is involved in all initiatives at the company on fatigue modeling of composites. He joined *e-Xstream* in 2009 as a project engineer. Before that, he worked for Rhodia Engineering Plastics on the development of state-of-the-art composite modeling techniques.

Introduction

Composites are increasingly being used in structural automotive parts, both chopped FRPs as well as CFRPs and hence a clear understanding of composites behaviors is mandatory. This heightens the demand for accurate simulation tools to predict structural performances. In particular, HCF is critically important over these materials as barely visible damage can appear, over the lifetime of a car, in multiple structural parts submitted to small but repeated loads.

Dealing with composite materials, heterogeneous and anisotropic in nature, requires an even better understanding of fatigue phenomena along with rigorous fatigue modeling solutions accounting for their microstructure. The modern metal approaches based on strain based fatigue developed since the 1970's are able to handle plasticity effects especially relevant in the framework of low cycle fatigue problems. However, for HCF problems, more common stress based approaches like critical plane methods are commonly used in the industry. Extensions of stress based approaches to predict polymer fatigue are generally used whereas strain based approaches are more problematic [1] [2]. While standard tests and databases are in place for metals, polymers offer a complex set of challenges that remain to be solved such as fatigue testing methods, proper handling of their anisotropic character and understanding of their sensitivity to mean stress.

Numerous process simulation codes can compute fiber orientation resulting from the manufacturing process such as injection molding, drape molding, compression molding and resin transfer molding. The microstructure determines the anisotropic character of the material. By interfacing with processing data as well as structural FEA codes, Digimat® software bridges the gap between the process and the structural part performances, offering multi-scale material modeling tools capable of modeling the anisotropic, nonlinear, strain-rate dependent and other specificities of composites in FEA.

The purpose of this paper is to illustrate how multi-scale material modeling can be applied in the field of high cycle fatigue modeling to obtain a state-of-the-art accurate fatigue modeling solution for composites.

This paper first presents the main characteristics of composites submitted to fatigue loadings, focusing more specifically on chopped FRP. Then it describes how their HCF behavior can be modeled thanks to micromechanics and the failure models developed in Digimat® by e-Xstream engineering. Finally it presents the validation study carried out jointly by Toyota Motor Europe and e-Xstream engineering on specimens as well as an automotive oil cooler bracket submitted to fully reversible ($R=-1$) fatigue loadings.

Fatigue Modeling of Composites

At the microstructural level and under static loadings, various and complex damage mechanisms exist, including debonding at matrix/fiber interfaces, fiber breakage, fiber pull-out, matrix drawing, matrix crazing and micro-cracking, shear cracks, nucleation, growth and coalescence of voids. These mechanisms depend on the fiber nature and their orientation with respect to the applied load.

If a uniaxial load is applied transversely to the main fiber alignment of a short fiber reinforced plastic (SFRP), one can observe debonding and matrix drawing as seen in Figure 1 [3]. If a uniaxial load is instead applied along the main fiber alignment of a SFRP, mechanisms such as debonding at the fiber tips, fiber pull-out, fiber failure, shear crack formation at the fiber interface and void coalescence are observed as shown in Figure 2 [3].

In CFRPs, the failure mechanisms directly depend on the fiber orientation with respect to the applied load. If this angle is less than 5 to 10 degrees, the failure is mainly driven by the fibers via local fiber-matrix debonding (in tension) and via micro-buckling (in compression). The adhesion of fibers to the matrix, as well as the in-plane stresses other than the longitudinal stress, influences these two failure modes. If the angle is greater than 10 degrees, micro-cracking parallel to fibers and fiber-matrix debonding often occur. These damage mechanisms are driven by transverse and shear stresses and often lead to a progressive stiffness reduction. Globally, stresses in HCF problems of CFRP materials are low enough such that the damage in the fibers is negligible, the dominant source of HCF failure being the matrix itself and possibly the interfaces between the polymer matrix and the fibers.

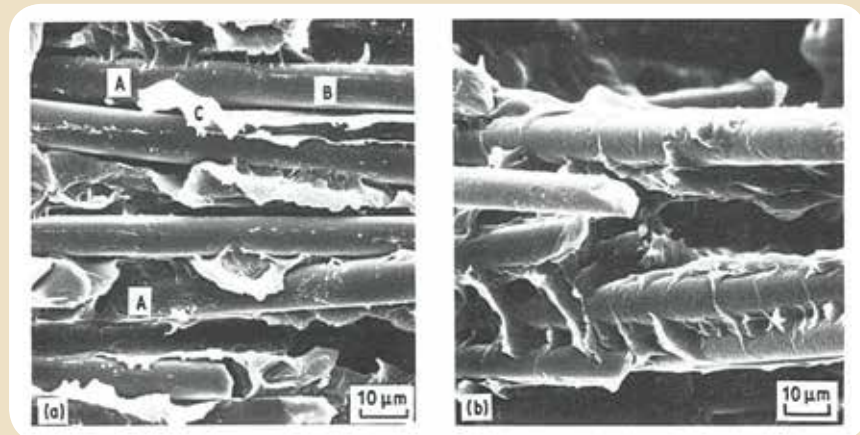


Figure 1. Fractographs revealing failure mechanisms when the load is applied across the main fiber alignment including A. microvoid formation B. extensive debonding C. matrix drawing and b) fast fracture.

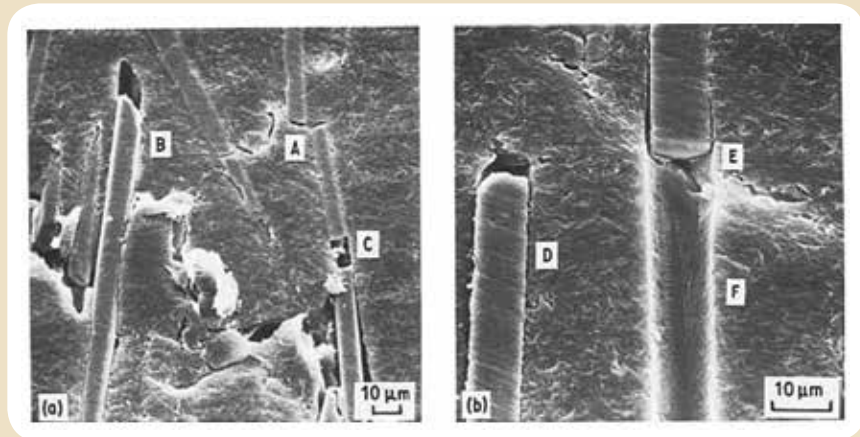


Figure 2. Fatigue damage when the load is applied along the main fiber alignment including A. debonding at fiber tip B. fiber pull-out C. fiber failure D. shear crack formation E. stress concentrations due to sub-surface fibers and F. microvoid coalescence.

FRPs are characterized by a strongly anisotropic character in stiffness. As an extension, the fatigue life of fiber reinforced plastic is also anisotropic and must be characterized by a range of varying S-N curves, with greater fatigue life in the longitudinal than in the transverse direction of the loading to the fibers [4].

To prevent self-heating of polymers, fatigue tests are performed at low frequencies, hence increasing both the testing cost and duration. Some studies investigated means of reducing the amount of tests needed to fully characterize in fatigue a composite. One of the proposed solutions consists in normalizing measured S-N curves by their corresponding ultimate tensile strengths (UTS) which can be measured for the same fiber directions [4], [5]. Such method provides some level of fitting between S-N curves measured at different fiber directions, but is not accurate enough to be predictive within a decade of cycles in fatigue life.

Mean-Field Homogenization Theory

Composites are by definition a combination of two or more constituents to obtain improved material properties in comparison to the base constituents. As composite properties depend on the material microstructure including fiber amount and orientation, they are adequately modeled from micromechanics, in particular with mean-field homogenization techniques. This technique allows computing the anisotropic composite properties based on the properties and the microstructure of the underlying constituents of a multi-phase material. In other words, the original heterogeneous material is represented by an equivalent homogeneous one. Implemented in the Digimat® software [6], this technology has proven to be effective for a broad range of materials.

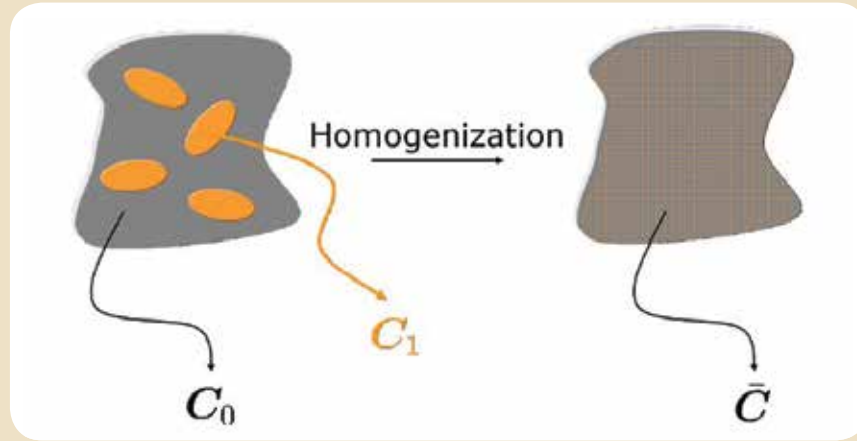


Figure 3: Heterogeneous material (left) from which its equivalent stiffness \bar{C} is computed from homogenization.

Fatigue Modeling

Ideally, all fatigue damage mechanism would be modeled to ultimately predict fatigue life of composites. At the moment, this is not possible and it would probably involve the execution of a far too large number of tests to identify all the parameters such models would contain. As of today, two routes are proposed to model failure: micro-scale modeling of the damage occurring in fatigue, often focusing on the polymer matrix phase, and macroscopic modeling of the composite fatigue life.

HCF Model for CFRPs

As the fatigue of CFRPs is being primarily driven by the damage occurring in the matrix, e-Xstream implemented in Digimat® a matrix based non-linear fatigue model. It is based on the evolution of damage into the matrix phase, following the two scale scheme proposed by Desmorat et al. [7] for thermo-mechanical composites (Figure 4).

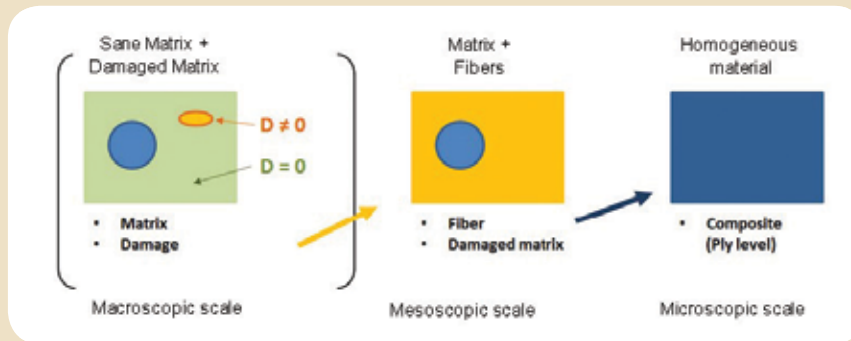


Figure 4: Two-scales damage based fatigue model.

At the microscopic scale, the matrix is decomposed into:

- A sane phase: It plays the role of the embedding medium;
- A damaged phase: It is constituted by local damages appearing in the matrix and modeled as spherical inclusions.

The damaged matrix behavior is described by an elastoplastic law with isotropic damage D . Damage accumulates as plasticity appears, and the fatigue life is determined once a critical damage value, defined by the user, is reached. By considering isotropic damage the “sane” (undamaged) stress tensor $\bar{\sigma}_\mu$ is defined from the damaged stress tensor σ_μ with a simple relation:

$$\bar{\sigma}_\mu = \frac{\sigma_\mu}{1 - D}$$

Involving plasticity, the whole micromechanical scheme must be iteratively computed at each fatigue load cycle for the prescribed macroscopic stress amplitude, until failure is declared. Such process is prohibitive in CPU time for large numbers of cycles, hence a stepped method is implemented breaking down the logarithmic space of loading cycles into N groups of cycles. Within each group of cycles, the increments of accumulated plastic strain and damage are considered constant and cumulated linearly. However, the increments of accumulated plastic strain and damage are updated upon completion of each group of loading cycles.

Overall a strength of this model is its capacity to handle multi-axial loadings, in comparison to simpler matrix-based failure models based on a kinetic theory of fracture and that are mainly uniaxial [8]. Moreover, it updates the composite stiffness based on the damage accumulating in the matrix. More details about its mathematical description are provided in the Digimat® documentation [6].

HCF Model for Chopped FRPs

Fatigue damage mechanisms in chopped FRPs are numerous, complex and dependent upon the composites microstructure. As a consequence, e-Xstream engineering developed a linear elastic phenomenological HCF model that doesn't explicitly model each damage mechanism individually, but captures them on a macroscopic level.

Multiaxial failure criteria developed for CFRPs, such as Tsai-Hill, have proven to work accurately under static loads; their use can also be extended to compute the fatigue life of composites [9]. These failure criteria account for the dependency of the composite strength on the fiber alignment. The Tsai-Hill 3D criterion was selected to elaborate the phenomenological HCF fatigue model and is expressed as follows:

$$FC(N_c) = \left(\frac{\sigma_L}{S_L(N_c)} \right)^2 - \frac{\sigma_L(\sigma_{T1} + \sigma_{T2})}{S_L(N_c)^2} + \frac{\sigma_{T1}^2 + \sigma_{T2}^2}{S_T(N_c)^2} + \left(\frac{1}{S_L(N_c)^2} - \frac{2}{S_T(N_c)^2} \right) \sigma_{T1}\sigma_{T2} + \frac{\sigma_{LT1}^2 + \sigma_{LT2}^2}{S_{LT}(N_c)^2} + \left(\frac{4}{S_T(N_c)^2} - \frac{1}{S_{TT}(N_c)^2} \right) \sigma_{TT}^2 \quad (1)$$

where

- σ_L denotes the longitudinal stress amplitude,
- σ_{T1} and σ_{T2} the transversal stress amplitudes,
- σ_{LT1} and σ_{LT2} the shear stress amplitudes in between the longitudinal direction and the two transverse directions, and
- σ_{TT} the shear stress amplitude in the plane normal to the longitudinal direction.

The $S(N_c)$ terms refer to the composite's fatigue lives in the different directions with respect to the main fiber alignment, using the same indices. To minimize the number of experimental input, a transverse isotropy assumption, valid for fiber reinforced composites, is applied and leads to handling on three experimental input measurements. The composite fatigue life, under any triaxial stress state, is triggered when the criterion reaches 1.

The application of a Tsai-Hill criterion implies the assumption of uniformly aligned fibers in the composite, which is in opposition with the complex misaligned orientation state that characterizes chopped FRPs. Hence, this problem is solved by an e-Xstream proprietary numerical decomposition of a representative volume elementary (RVE), defined by a complex orientation tensor, into a set of so-called pseudo-grains (PGs). Each PG is by design a two-phase composite simpler than the composite at the RVE level. The solving strategy consists in computing, in each PG, the anisotropic stiffness matrix thanks to the Mori-Tanaka homogenization method and the fatigue life thanks to the Tsai-Hill criterion. Upon computation of these over all PGs, homogenization of the global RVE stiffness and fatigue behaviors is performed.

The HCF model being linear elastic, it is used in combination with the Miner's rule to sum the damage throughout the cyclical loading. The input to this HCF model is three S-N curves measured at different main fiber alignments with respect to the loading direction. The fatigue specimens are thus machined out of injection molded plaques; the typical angles are 0°, 90° and some intermediate angle like 30° or 45°.

The general computation workflow applied by Digimat is summarized in Figure 5.

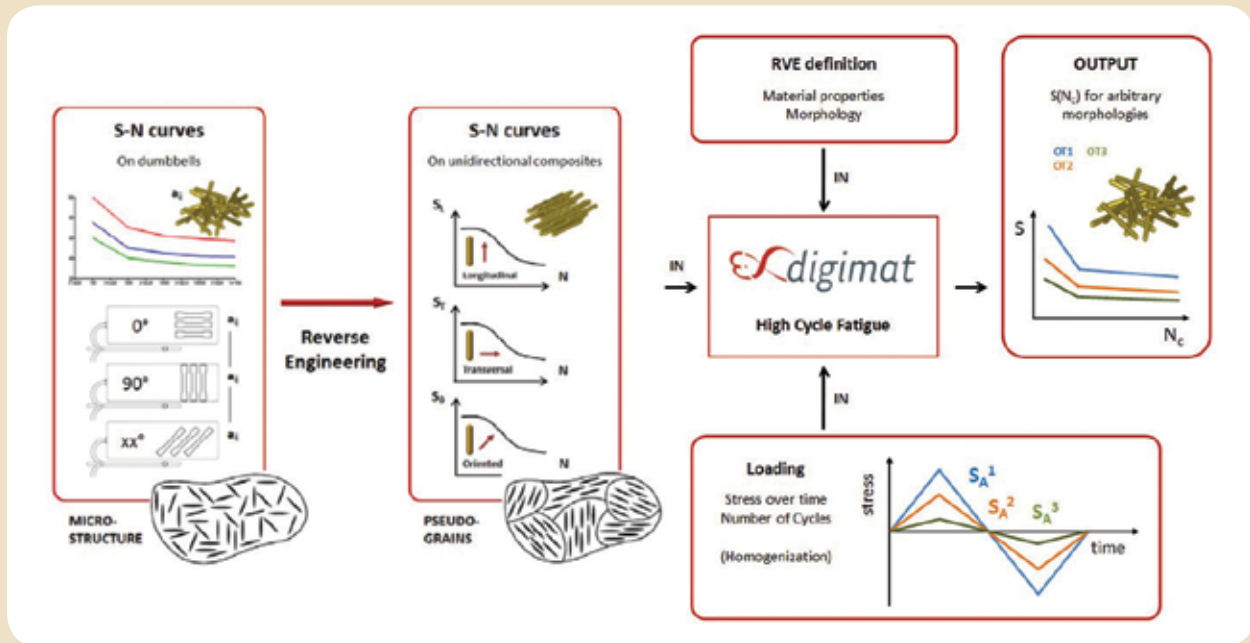


Figure 5: Fatigue computation workflow using the composite PG HCF model.

This fatigue modeling solution is available for standalone computation on one material point (i.e. RVE) as well as in structural interfaces to fatigue codes such as Virtual.Lab Durability and nCode DesignLife; interfaces to FEMFAT and Nastran Embedded Fatigue are under development. The fatigue FE interfaces serve at computing the lifetime prediction of composite parts taking into account the local anisotropic behavior of chopped FRPs.

Validation of the Proposed Fatigue Modeling Technology

e-Xstream engineering collaborated for a long time with Toyota Motor Europe to develop the fatigue modeling technology described above. The developments were validated against uniaxial fatigue specimens and an oil cooler bracket component. The material considered in this validation work is the TECHNLY A218 V35 Black 34NG grade supplied by Solvay Engineering Plastics, nylon 6.6 reinforced by 35% weight fraction of short glass fibers.

Testing Campaign

Two testing campaigns were carried out, one by Axel Products at the specimen level and one by TME at the part level. A focus was made on testing these components under a fully reversible cyclic load involving tension and compression (i.e. $R=-1$). Specimen buckling is a major risk under such reversible load and must be properly controlled; this was successfully achieved by Axel Products through a precise alignment of the grippers. To avoid self heating effects from the polymer, tests were performed at a frequency of 3 Hz. The test conditions selected are 23°C, dry-as-molded. Nylon is extremely sensitive to humidity. Significant care was brought in controlling the humidity level and maintaining the material dry-as-molded, both by drying properly the specimens in an oven and by storing them in sealed bags with desiccant until testing.

The fatigue test results on the specimen show consistency in the measurements as illustrated in Figure 6, with an emphasis on the fatigue behavior between 1,000 and 1 million cycles. Few data points were measured at 1 million cycles since the S-N curves are relatively flat in that area of the cycling range, meaning that fatigue failure hardly happens. Verifications using strain gauges on both sides of the specimen confirmed that no buckling occurred.

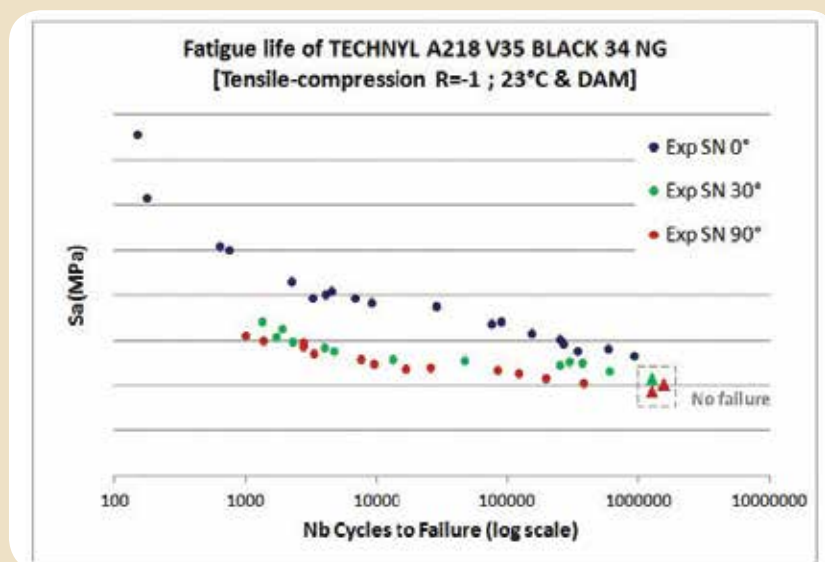


Figure 6: S-N curves measured at 0°, 30° and 90° on the Solvay TECHNYL A218 V35 Black 34NG grade.

At the component level, an out-of-plane reversible load was applied. Damage in the form of cracks was recorded in four different locations. The locations numbering does not relate to the order of appearance of these cracks.

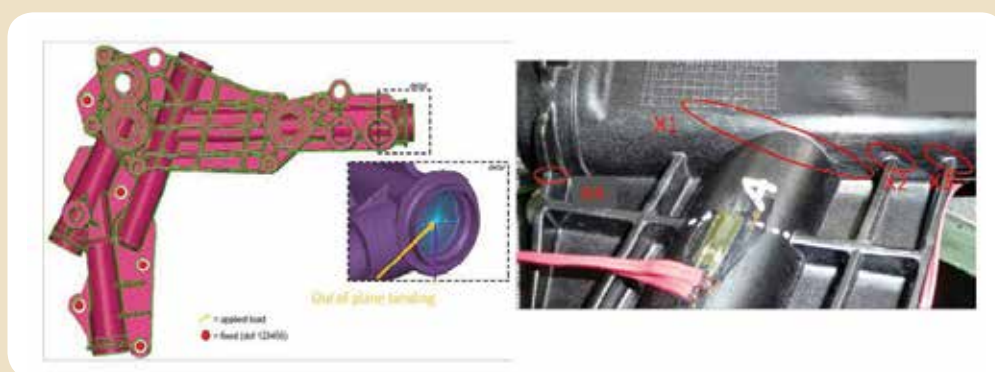


Figure 7: Oil cooler bracket component with indications about the load setup (left); Crack locations recorded during the fatigue tests (right).

FEA Correlation

From the experimental S-N curves measured, a fatigue model was created in Digimat®. The quasi-static (QS) unit load case was computed coupling Digimat® with an implicit FE solver, accounting for the fiber orientation tensor (OT) data computed from injection simulation and mapped onto the structural FE meshes. From these stress results, fatigue FE simulations were performed coupling Digimat® with a fatigue FE solver. In this interface, the Digimat® fatigue model replaces the isotropic S-N model commonly defined in the fatigue software, and Digimat® takes care of computing the S-N local responses in every element of the mesh dynamically throughout the fatigue simulation.

A fatigue computation method called “maximum absolute principal” is selected. This method considers the complete stress tensor, feeding as such the Tsai-Hill 3D criterion used by Digimat®. It is also a computationally cost-effective method in comparison to methods such as the critical plane one. The overall workflow here described is illustrated in Figure 8.

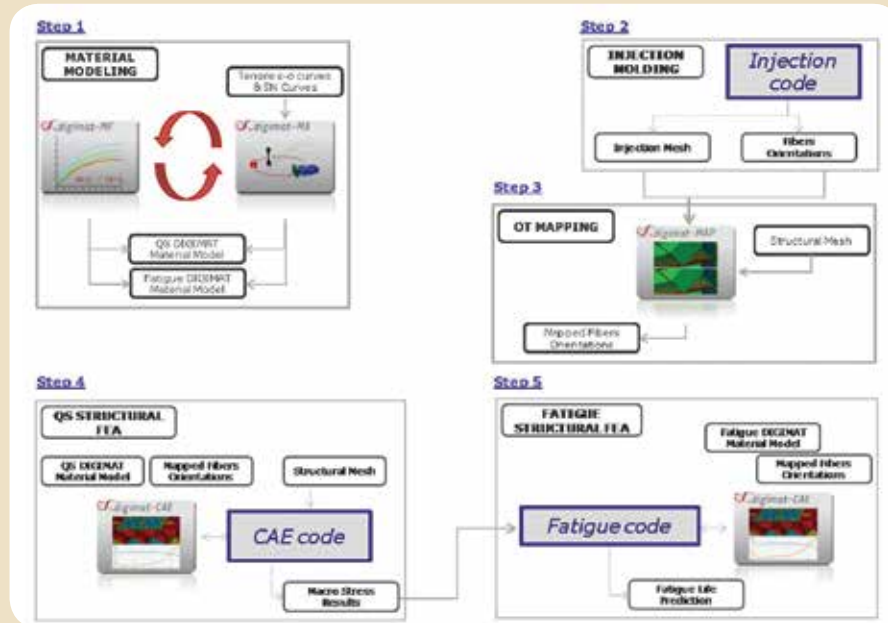


Figure 8: Workflow to numerically compute the fatigue life behavior of a structural part.

The fatigue model was first validated on the numerical FE models of the fatigue specimens. Fatigue life was recorded on the most damaged element of the specimens. This approach is conservative but at the specimen level, fatigue cracks usually propagate quickly (brittle failure). The high cycle fatigue behavior successfully correlates for all three loading angles with respect to main fiber alignment, results being slightly conservative for 30° and 90° angles.

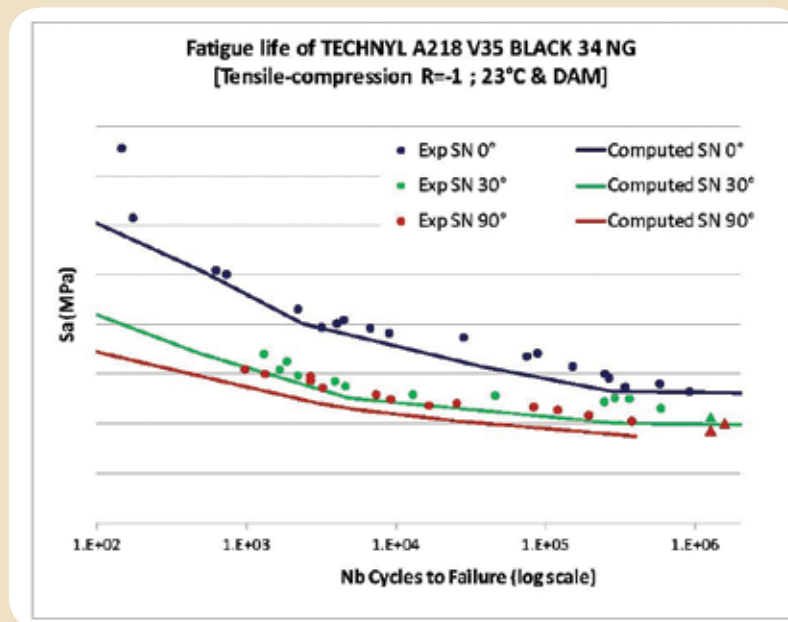


Figure 9: Correlation of the HCF behavior on tensile-compression uniaxial specimens.

The correlation work was then extended to the oil cooler bracket component. The few locations where cracks were experimentally observed are properly identified. The prediction of crack initiation in the most critical rib (location X3) matches the timing at which stiffness reduction was first recorded in experiment as a consequence of local damage occurring in ribs. The experiments, carried out over a larger number of cycles than first crack initiation, lead to large crack propagation in location X1. Though propagation cannot be directly predicted from fatigue simulation since stress redistribution isn't accounted for, fatigue simulation predicts damage occurrence in location X1 and suggest the later occurrence of crack propagation in locations X1, X2 and X4.

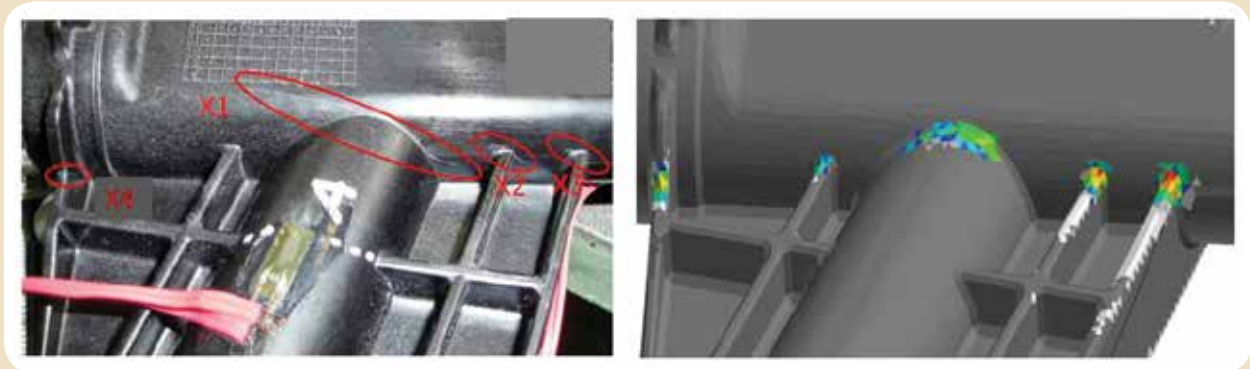


Figure 10: Fatigue life prediction in most critical locations (right) compared to the measured crack locations.

Conclusions

The design of high quality, light and energy efficient vehicles is crucial for success in the automotive industry. The use of composites is essential for achieving that objective and, though very challenging, accurate modeling of their high cycle fatigue behavior is required to optimize designs without compromising the lifetime and security of structural automotive components.

This paper presented two fatigue models developed in the Digimat® software that, combined with mean-field homogenization techniques and the multi-scale modeling approach, accurately predict the high cycle fatigue life of chopped and continuous fiber reinforced plastics. Both models account for the anisotropic character of composites that derive from the composite microstructure, specifically fiber orientation in the resin.

The HCF model developed for chopped fiber reinforced plastics is now available in structural FE simulation coupling Digimat® with fatigue FE solvers. The model was validated on an industrial part from Toyota Motor Europe. It has proven to be accurate both at specimen and part levels. Additional correlation studies are expected on the same fatigue model in the coming months; similar correlation studies, using the damage based fatigue model, will follow on continuous fiber reinforced composites upon identification of partners to help carrying them out.

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