ICME SOLUTION TO PREDICT LIFETIME OF SHORT FIBER REINFORCED THERMOPLASTIC PARTS

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Abstract

Short fiber reinforced thermoplastic parts subjected to mechanical and cyclic loading during a long period of time eventually fail. To prevent premature failure in service, predictability is key when designing load bearing components. The lifetime depends obviously on the nature of the thermoplastic material but also on the amount of reinforcement, the type of reinforcement and the set-up of the injection process. All these ingredients make the fatigue modeling of short fiber reinforced plastic parts highly challenging.

Dedicated solutions at several stages of the modeling workflow are thus required. The ingredients needed are (a) an accurate material model for any orientation tensor~~s~~ and any loading~~s~~, (b) a reverse engineering procedure allowing to identify the model parameters from a reduced set of experimental data in order to reproduce the measured lifetime at specimen level, (c) efficient structural and fatigue solvers enabling to predict life-time for various type of loading conditions (constant amplitude, random signal, frequency/time domain loadings, …) and (d) an overall methodology able to account for stress gradients so to deliver accurate predictions for any part geometry and mesh.

In this paper, an ICME (Integrated Computational Material Engineering) solution is presented, leading to accurate predictions of the fatigue life of short fiber reinforced parts for any type of experimental signal. The framework combines engineering tools that enable design engineers to predict fatigue life of engineering plastics applications, including material anisotropy and nonlinear behavior. This paper highlights the key features of the framework and demonstrates its ability to predict the response of a representative demonstration part.

Background and Motivation

Short fiber reinforced thermoplastics are used since many years in the automotive industry to replace metal material and lighten parts. The influence of the manufacturing process must be accurately accounted for in order to correctly predict the performance of the final part. Optimization of the design will not be limited to the geometry but will integrate the manufacturing process too.

The manufacturing process governs the orientation of the fibers in the mold, the weld line position, the residual stress, the warpage etc. The final part performance is linked to all these characteristics. Depending on the part, different performances must be evaluated like stiffness, strength, lifetime, creep, damping etc. The part efficiency is related to its design but also to the material performance and its microstructure.

In this paper, fatigue is the performance targeted. Fatigue modeling is more complex for plastic materials than for metals. The first step to accurately predict lifetime of SFRP's is to properly understand and model the mechanisms that lead to long-term failure. In general, for thermoplastics one can distinguish three failure mechanisms: i) plasticity-controlled failure, related to creep or to the accumulation of plastic strain, ii) slow crack growth, controlled by gradual crack propagation, and iii) molecular degradation [1,2]. With all three having different origins, each is affected differently by loading conditions, such as load magnitude, load amplitude or load ratio, and frequency [3-5]. This work focuses on the first two failure mechanisms.

The second step is to capture the anisotropic material behavior, induced by the local glass fiber orientation resulting from the injection molding process. The local alignment of fibers can easily induce variations in stiffness and strength of a factor of 1.5 to 2 [6]. Hence, one needs to accurately capture the local glass fiber orientation after processing and properly model the resulting anisotropic material behavior. In addition to modelling the failure mechanisms and anisotropy, taking into account some additional features like local stresses, stress gradients and local load ratios make our ICME solution even more precise.

Material Modeling approach: Mean-Field homogenization

Short fiber reinforced thermoplastic material is assumed to be made of two major constituents: the resin and the fibers. For the fibers, the material model selected will be elastic. For the resin, two material models will be used, an elastic one for the calibration of the fatigue card and an elasto-plastic one for the static analysis. Besides the selection of the material model for the fibers and the resin, the composite microstructure must be described by specifying the volume or mass fraction of fibers, their orientation and their size.

Mean-Field Homogenization

Mean-Field homogenization combines the properties of the underlying constituents of a multi-phase material so that the original heterogeneous material is represented by an equivalent homogeneous one. Implemented in the Digimat software [7], this technology has proven effective for a broad range of materials. This semi-analytical solution shows the advantage to be very fast in computing the composite material behavior. It can be used for various type of performances: stiffness, strength, failure, lifetime, NVH and creep. Nevertheless, it is based on some assumptions that can be sometimes not respected in the real material. Assumptions are:

- Fibers are ellipsoidal.
- Fibers are uniformly distributed in the resin, no cluster.
- Fibers stick perfectly to the resin.

Mean-Field homogenization is performed in three main steps as illustrated in Figure 1:

- Step 1: the localization: The per-phase strain is computed from the strain applied on the composite.
- Step 2: the stress computation at micro-level: The stress in each phase is computed from the strain obtained at the step 1.
- Step 3: the averaging of stress: The stress at the macroscopic level is computed through an averaging approach based on the stress at the phases level.

The results provided by the Mean-Field homogenization are limited to the average stress and strain in the composite and in each phase (resin & fibers). This approach does not capture the peak of stress that can be observed locally in the composite at the tip of the fibers for instance.

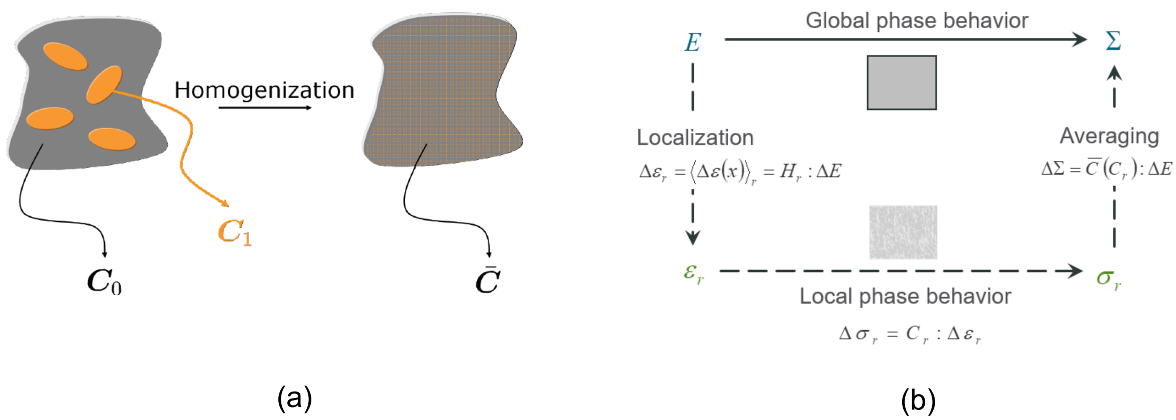

Figure 1: (a) Heterogeneous material (left) from which its equivalent stiffness $\bar{C}$ is computed from homogenization. (b) Three steps in the Mean-Field homogenization procedure : localization, per-phase stress computation and averaging.

Fatigue modeling

Fatigue damage mechanisms in chopped FRPs are numerous, complex and dependent upon the composite's 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 [8]. These failure criteria account for the dependency of the composite strength on the fiber alignment. The Tsai-Hill 3D transversely isotropic criterion was selected to elaborate the phenomenological HCF fatigue model and is expressed as follows:

$$\mathrm{FC}(\sigma) = \left(\frac{\sigma_{11}}{X}\right)^2 - \frac{\sigma_{11}(\sigma_{22}+\sigma_{33})}{X^2} + \frac{\sigma_{22}^2+\sigma_{33}^2}{Y^2} + \left(\frac{1}{X^2} - \frac{2}{Y^2}\right)\sigma_{22}\sigma_{33} + \frac{\sigma_{12}^2+\sigma_{13}^2}{S^2} + \left(\frac{4}{Y^2} - \frac{1}{X^2}\right) \qquad (1)$$

where

- σ_{ij} are the component of the stress amplitude tensor
- X denotes the axial tensile strength amplitude,
- Y denotes the in-plane tensile strength amplitude,
- S denotes the transverse shear strength amplitude.

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 element (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 overall PGs, homogenization of the global RVE stiffness and fatigue behaviors is performed. The main advantage of this workflow is that only three parameters are enough to enable accurate predictions for any loading and any orientation. The loading sensitivity is obtained by the shape of the Tsai-Hill envelope. The orientation sensitivity is coming from the pseudo-grain mechanism which leads to a different fatigue behavior for each orientation tensor by using a dedicated combination of pseudo-grains with specific weight and orientation.

The above framework enables to model the fatigue behavior for a given single load ratio, called reference load ratio (Rref) hereafter. An additional tool is needed to cover the load ratio sensitivity, also called mean stress sensitivity. The S-N curve at a given load ratio can typically be obtained by scaling the S-N curve at the reference load ratio by a single value. The latter can be computed as the ratio between the stress amplitude, Sa(R) and the stress amplitude, Sa(Rref). This ratio is computed either at a single N or as an average at various N. Digimat enables to define the scaling value for each load ratio through a table.

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 2.

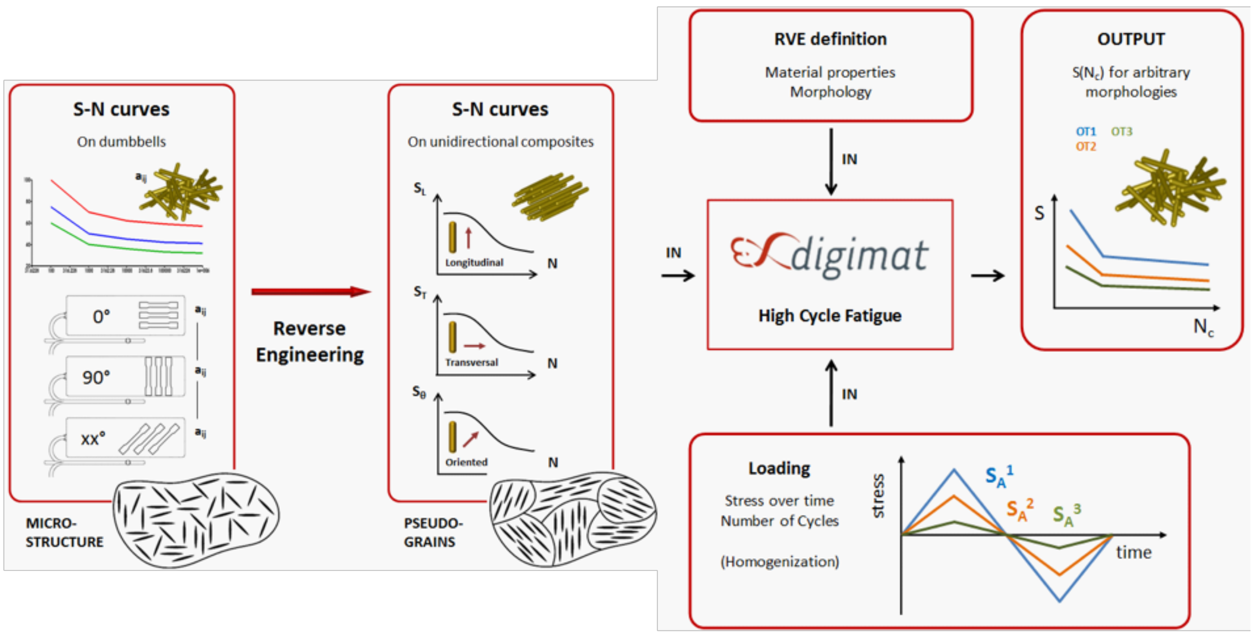

Figure 2: Fatigue computation workflow using the composite PG HCF model.

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 CAEfatigue and nCode DesignLife. The fatigue FE interfaces serve at computing the lifetime prediction of composite parts taking into account the local anisotropic behavior of chopped FRPs.

From experimental data to accurate failure predictions at structural level

The standard set of experimental data contains stress-strain curves for three loading angles at a static strain rate, S-N curves for three loading angles at single load ratio and additional S-N curves at other load ratios to identify the mean stress sensitivity. A single S-N curve per additional load ratio is typically enough. The choice of additional load ratios depends on the application. For Material Supplier, it is key to consider a wide range of load ratios to cover the multitude of applications from their customers. A minimum range of load ratios would range between -1 and 0.5. For Tier1 and OEM that want to use the material model on a single application, it is important to cover load ratios around the targeted macroscopic load ratio. The influence of the pre stress can indeed lead to a local load ratio which is significantly different from the macroscopic one as shown in [9].

Calibration procedure

The calibration is done following two steps. The first one is the calibration of the stiffness properties, while the second step involves calibration of the fatigue criteria.

In order to obtain the most accurate results, the static analysis will be run with an elasto-plastic material model, called EP in the rest of the article, having a non-linear behavior calibrated on quasi-static experimental data. The matrix's non-linear behavior and the fibers' aspect ratio are reverse engineered. An automated reverse engineering draw upon the best practices and the experience of e-Xstream is offered as well as a semi-automated workflow where the user has a full flexibility on the optimization.

The fatigue calibration can then be performed using an elastic material model which is obtained by downgrading the EP material model to keep the same linear and aspect ratio properties. The fatigue calibration consists in calibrating the three parameters of the Tsai-Hill 3D transversally isotropic criteria for each number of cycles, N, for which experimental data are provided. A full calibration is performed for a first value of N. For other N values, the parameters are estimated from the results at the first N value and from the slope of the experimental data. This is done in an automated step for all N values. The user can then perform an additional calibration to fine tune the parameters.

A key ingredient of the calibration is to use S-N curves which are representing what happens locally. During experimental material characterization, force and displacement are recorded and subsequently converted to nominal stress and strain. For fiber reinforced materials, stress and strain often localizes in specific regions of the test specimen and, naturally, the local values will deviate from the nominal. Since in the FE analyses the local values are computed, this must be considered to ensure consistency between experiment and simulation.

To efficiently do so, a localization factor is computed that transforms the macroscopic nominal stress values to local values. The stress-based localization factor is defined as the ratio between the local stress at the hot spot and the nominal stress in the experiment. Its magnitude is computed for each fatigue load case and is used to scale the SN-curves from nominal to local, before calibrating the final fatigue model, as displayed in Figure 3.

In order to have a material model ready to be used for any applications, the user needs to manually define a mean stress sensitivity as explained in the Fatigue modeling section. The resulting material model is elastic with fatigue criteria and will be called E+Fatigue material model in the remaining part of the paper.

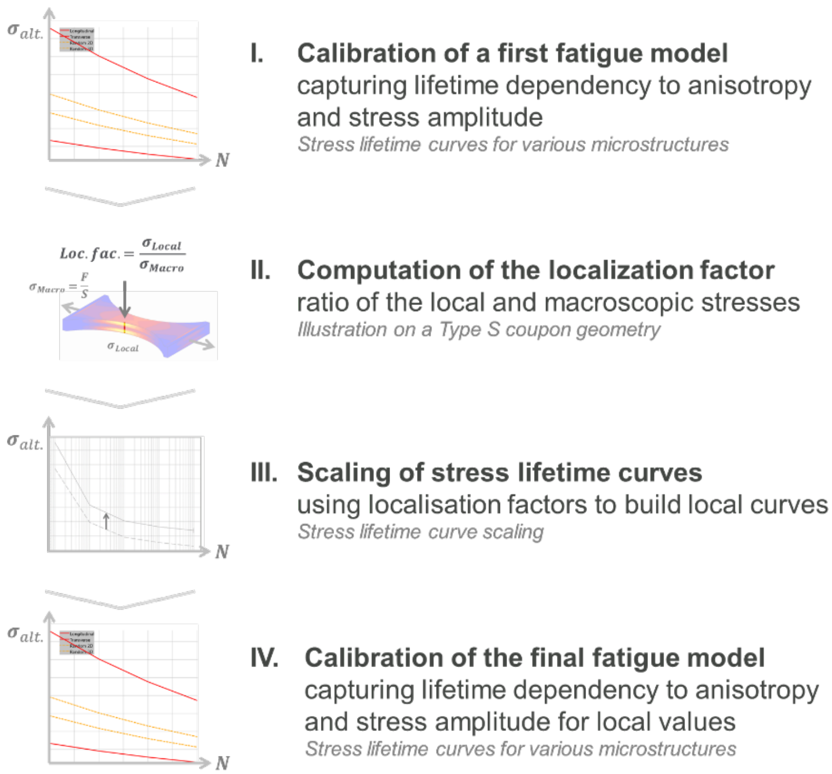

Figure 3: Illustration of the workflow to correct for the localization factor

Model reduction

The result of the calibration is a material model that performs mean-field homogenization to predict the composite behavior. A direct use of the material model leads to prohibitive simulation time for a typical customer application. A model reduction is therefore performed prior to the structural simulation. This reduction has to be done only once for a material model.

The reduced model is a macroscopic model which is calibrated through virtual tests performed with mean-field homogenization [7]. The obtained model is matching the mean-field homogenization results for all standard configurations of microstructure and loadings.

Structural application for Constant Loading Amplitude

Running a structural application requires the mapping of the manufacturing data from the injection mesh to the simulation mesh. For Fatigue, the procedure is limited to the local fiber orientation information in the structure. For other performance, other factors can also be accounted for, such as the initial stress, weld lines, local porosity, local aspect ratio and fiber volume fraction variation. Manufacturing data can be mapped from solid injection mesh to solid and shell structural mesh as well as from shell injection mesh to shell structural mesh. The material response at each integration point is then computed using the reduced model for the corresponding local orientation.

Structural application for Constant Loading Amplitude can be further handled by the Fatigue Post Processing tools. The user needs first to launch a static simulation with either the E+Fatigue or EP material model. Various static simulations can be performed in function of the workflow. If there is no pre-stress, the user can run a simple static simulation up to the maximum force (Fmax) since there is no need to extract the local load ratio. As soon as there is pre-stress, the user needs to define a way to extract the local load ratio. The easier solution is to run a full cycle simulation that goes up to Fmax then goes down to the minimum force.

The extraction of the local load ratio is done by selecting respectively the increments at which the maximum forces and the minimum forces are reached. The local load ratio is then automatically computed from the stress tensor at these two increments. This allows to automatically detect:

- the influence of the pre-stress on the local load ratio;
- the scenario for which the stress at the maximum force is the minimum stress and not the maximum stress;
- the scenario for which R is bigger than 1 instead of being lower than 1.

Furthermore, in the RP\Fatigue Post Processing tools, the user can use a plasticity correction with the EP material model if he runs its static simulation with the E+Fatigue material model. This plasticity correction allows to account for plasticity effects without requiring a new static simulation. The user can also use a numerical correction to handle stress gradients and obtain results which are globally mesh independent [9].

Structural application for non-constant loading amplitude

As soon as the design constraints required to handle non-constant loading amplitude as block loading or Vibrational Fatigue, an additional tool is required, a dedicated Fatigue software. Digimat is interfaced with nCode and recently with CAEfatigue. The interface to nCode enables to do any kind of fatigue. The interface to CAEfatigue is currently limited to time domain with single channel for solid elements.

These interfaces enable to take into account all the advanced features of the fatigue modeling and the calibration, i.e. the sensitivity of the fatigue behavior to the loading, the orientation and to the load ratio calibrated on the local S-N curve. These interfaces do not allow for the plasticity correction yet, but plasticity can be taken into account during the static analysis. The numerical corrections are also currently not interfaced.

An example with CAEfatigue at the specimen level

A validation of most of the ingredients of the methodology, using a generic material representative of a PA6GF50, has been presented on the DSM Load bracket two years ago [9]. Since then, the plasticity correction has been added to further improve the results for static analysis run with the E+Fatigue material model, as shown on Figure 4. The focus on this section is on the new interface to CAEfatigue. The current paper only shows results at the specimen level, but results on the DSM Load Bracket will be shown during the conference presentation.

A validation step is performed by comparing RP/Fatigue post-processing results with CAEfatigue for Constant Loading Amplitude. Results are shown for various load ratio and force level on Table 1. The Maximum Principal workflow is used in CAEfatigue using the E+Fatigue material for both the static and the fatigue computation. It can be observed that the results are the same for both software. The scenario have been chosen to illustrate the robustness of the solution for a wide range of number cycle through several load ratio and scale factors.

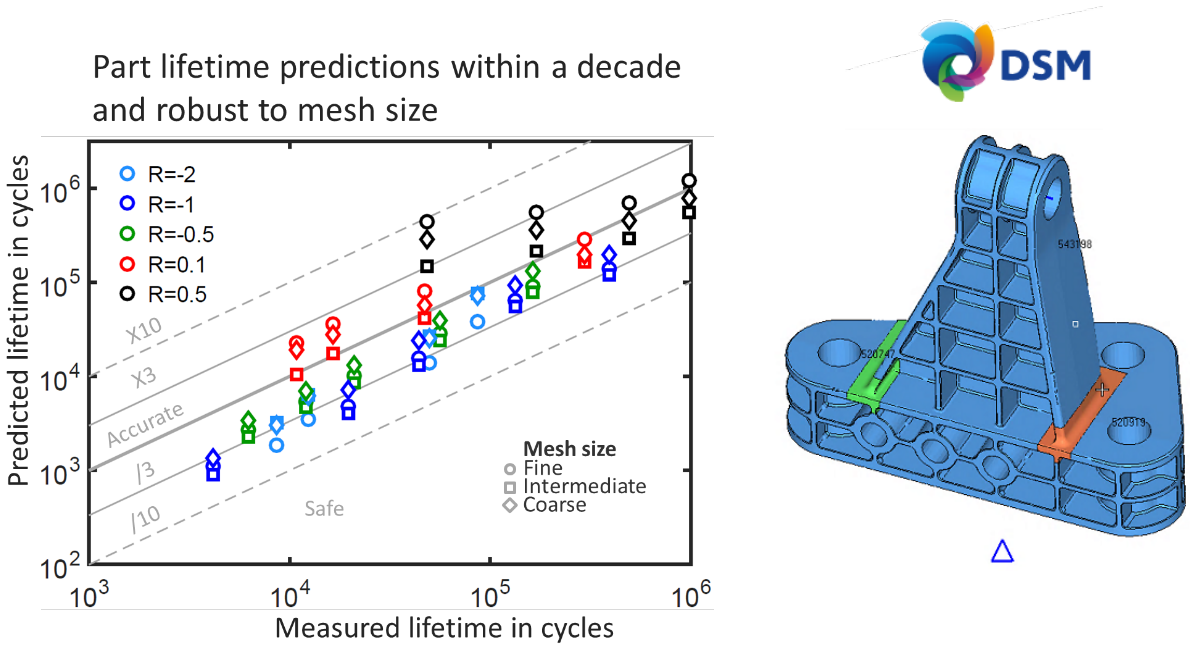

Figure 4 : Typical results obtained with plasticity correction and stress gradients on a Constant Loading amplitude with RP/Fatigue Post-processing, illustrated here on the DSM Load Bracket

Table 1 : Comparison of lifetime prediction between RP\FatiguePostProcessing and CAEfatigue for various load ratio and scale factor on a specimen.

Load Ratio	Scale Factor	RP\FatiguePostProcessing	CAEfatigue
R=-1	1	856	850
R=-1	0.8	205400	202000
R=-0.5	1	202	199
R=-0.5	0.7	6324	6291
R=0.1	0.5	1596000	1606000
R= 0.5	0.6	614	603

Sanity results are then shown for a two events simulation, also called Block loading, where results are shown for various combinations of cycles at load ratio =0.1 and -1 on Table 2. It can be observed that the individual results of each block are the same as for the similar constant loading scenario. The influence of each repetition is therefore correctly taken into account.

Table 2 : Prediction of the number of repetition for combined events when performing block loading simulation with two events with CAEfatigue

# repetition R=-1 and scale factor 1	# repetition R=0.1 and Scale factor 0.5	# repetition of event 1	# repetition of event 2	# repetition of combined events
1000	1	0.85	1606000	0.85
100	1	8.5	1606000	8.5
10	1	85	1606000	85
1	1	850	1606000	849.8
1	10	850	160600	846
1	100	850	16060	807
1	1000	850	1606	556

Perspectives

Our goal for the conference is to show the results on the DSM Load Bracket using a unit load in CAEfatigue. Results have been already obtained and validated using a full cycle load. An on-going development is required to show the improved efficiency with a unit load using multiple channels and a static load to take pre stress into account.

Conclusions

The ICME, Integrated Computational Material Engineering, offers a great environment to investigate the behavior of composite material, to predict the behavior of the material in various condition and to represent the material as accurately as possible at the part and assembly level.

In this paper, ICME has been used to predict the fatigue behavior of short fiber reinforced thermoplastic material from a limited set of inputs: three quasi-static data, three S-N curves at a single load ratio and additional S-N curve at other load ratio, the fiber behavior and the microstructure information. The paper focus on showing the equivalence of results between the new interface to CAEfatigue and the RP/Fatigue post-processing tools for which the accuracy has been shown in a previous paper [9].

The next steps will be to support multiple channel, frequency domain and the plasticity correction in the interface between Digimat and CAEfatigue. The support of multiple channel is required to extract the local load ratio for application which has a pre load that lead to a significant pre stress at the critical area. The support of the frequency domain is needed to support Vibrational Fatigue. The plasticity correction is needed to be able to obtain accurate prediction using a unit load loading. In order to obtain the most accurate predictions, the current workflow in CAEfatigue requires to run a static simulation with an elasto-plastic material up to the maximum force.

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