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Parametric Optimization of CAE Material Models for Carbon-Fiber-Reinforced Polymer (CFRP) Composites

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Abstract

Carbon-fiber-reinforced polymer (CFRP) composites have been increasingly employed in aerospace, automotive, and civil engineering applications due to its high strength-to-weight ratio. However, the anisotropic properties across the layers of composites, resulting from different fiber orientations, create challenges in modeling the CFRP parts by themselves, and when integrated into larger structural systems. This challenge is particularly evident with the simulation of CFRP material undergoing crush type loading conditions as might be seen in an automotive crashworthiness event. For one CFRP material, typical coupon tests were conducted to obtain basic properties in and out of fiber directions, such as the elastic moduli, strains at failure, and plastic moduli among others. Furthermore, CFRP parts with different geometries were manufactured from this same material and quasi-statically tested under multiple loading conditions. These tests were simulated using a continuum damage mechanics material model in LS-DYNA. It was observed that significant discrepancies existed between the simulated results and the experimental data when property values obtained solely from coupon tests were employed. This has to do with the fact that during crush conditions, material properties of CFRP parts change significantly, unlike their metal counterparts, due to factors such as the de-bonding, the load-transferring nature of the layers, temperature-related softening, and residual stiffness of the fibers after failure among others. In CAE models of CFRP composites it is necessary and even critical to correctly calibrate certain material properties to accurately correlate the crush test data with simulation. These parameters include the ones in material cards to account for the residual stiffness after failure, static and dynamic friction coefficients between the CFRP parts and the testing fixtures, as well as the criteria for element deletion. This paper presents a systematic approach to identify optimal material model parameters based on a

methodology incorporating CAE models and numerical optimization. An adaptive meta-model based global optimization strategy with the objective to match the force-time characteristics of multiple crush experiments simultaneously has been established to calibrate the CFRP material model parameters. The resulting composite crush simulations show a good quantitative as well as qualitative agreement between simulations and experiments at a level that is difficult to be achieved solely with engineering best practice.

1. Introduction

Carbon fiber-reinforced polymer (CFRP) materials are growing increasingly popular in the automotive industry today as they have the desirable characteristics of being light-weight yet extremely strong. In fact, CFRP has one of the highest strength-to-weight ratios among common automotive construction materials. Thus, there is great potential in utilizing CFRP in designing light-weight automotive body structures. In order to virtually design body structures which utilize CFRP, the material's behaviour during impact and crashworthiness loadings must be accurately predicted through finite element (FE) modeling. Of particular interest for crashworthiness simulations is the accurate prediction of the energy absorbed by the CFRP material. This can be a significant modeling challenge as this typically occurs through repeated progressive failure of the CFRP material. While many models exist to accurately predict a first ply failure within a CFRP layup, the damage and failure that occur after this can be a challenge to accurately predict. To capture this progressive failure, material parameters are needed which are not typically obtained through standard coupon testing. This paper presents an approach to determine these parameters through testing a set of different geometries under multiple loading conditions and determining through optimization a single unique set of material parameters that provide the best correlation to all tests.

2. Methodology

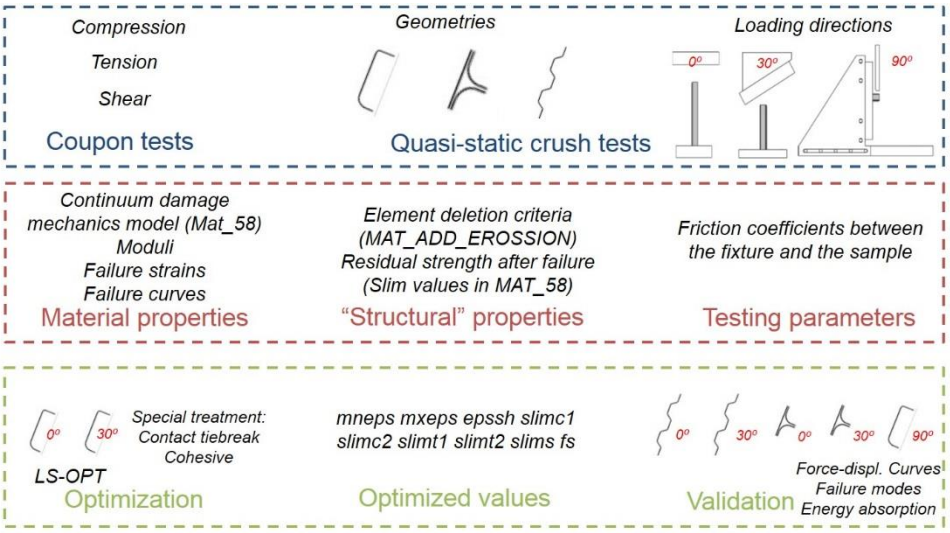


Figure 1: Schematic view of the methodology for CFRP model parameter identification.

A schematic view of the proposed methodology for CFRP model parameter optimization is depicted in Figure 1: . The methodology comprises three main parts: testing, modeling and optimization. It starts with coupon tests in compression, tension, and shear to investigate the basic material properties of CFRP materials. These coupons are created from plaques where the fibers in each layer lie in the same direction. Material properties such as elastic moduli and failure strains can be derived from this test data and applied in material models for simulation. In addition to the coupon tests, specimens made of CFRP materials with various geometries are crushed quasi-statically in the test laboratory. The crushes are conducted in three different directions: 0 degree (straight down), 30 degree (angled), and 90 degree (transverse shear). Simulations of these tests are performed to reproduce the displacement-force curve characteristics and crush modes. However, by simply using the material parameters obtained from coupons in a typical continuum damage mechanics model (Schweizerhof et. al., 1998), there exist significant discrepancies between the simulations and the testing data, which is shown in Section 3. The reason is that CFRP composites should be treated as a structure rather than one particular type of material uniformly distributed over the part.

The responses measured in the tests are reactions of the structure constructed by fibers oriented in different directions layer by layer and the resin matrix in between. The way fibers and matrix fail are dependent not only on the stress and strain states of each part but also the interaction between them. When fibers fail, the strength of the fibers do not disappear altogether immediately due to the support from the matrix. Additionally, the temperature generated during the tests and the strain rates of the composites' deformation could affect

the response of the material. Some of this structural response can be accounted for in continuum mechanics damage model, for example, slim values in Mat_58 (Matzenmiller et. al., 1995) in LS-DYNA [1]. Others need to be considered by introducing additional element failure and deletion criteria, such as maximum strains before deletion in MAT_ADD_EROSSION in LS-DYNA. Testing conditions and some artefacts need to be addressed as well. The friction between the upper fixture and the samples is important in deciding the crush force, especially the peak force when the first contact takes place (Dong et. al, 2016).

The ultimate goal of this project is to find a set of values for the above-mentioned parameters, slim values, maximum strains for deletion, and friction coefficients, so that the structural reaction of CFRP composite materials can be accounted for accurately. Although these parameters have physical meanings, in reality they are not easy to evaluate or quantify. Tuning those parameters by trial-and-error can be very time-consuming and ineffective. Therefore, in this methodology algorithms and tools from computational optimization are adopted to seek for an optimal set of CFRP material parameter values, so that the respective simulation model generalizes well to different crush scenarios and part geometries.

2.1 Experimental Tests

The coupon tests and quasi-static crush tests on CFRP composite samples have been carried out by Gemini Composites, LLC. The experimental set-ups for the crush tests are shown in Figure 2: . Three different directions are adopted: 0 degree (straight), 30 degree (angled), and 90 degree (transverse). Each test is conducted with the top piece moving down at 1 mm/s constant speed and they last approximately for 100 seconds. The bottom plate is fixed and the specimen is placed in the slots shaped to the specimen cross-section. Crush force and the displacement of the top piece are measured.

[1] http://www.lsdynasupport.com/

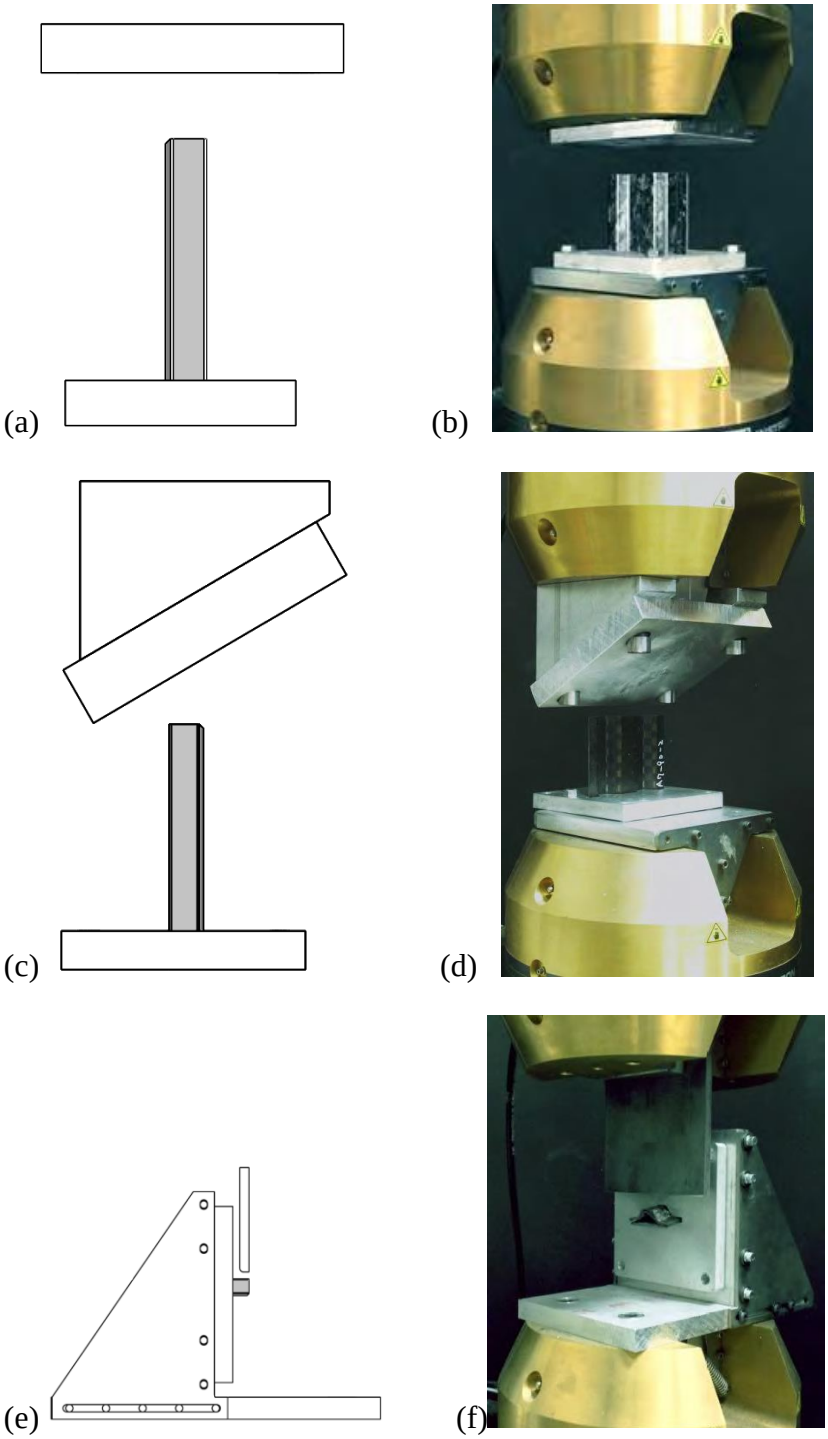


Figure 2: Crush test set-up: (a) and (b) 0 degree crush; (c) and (d) 30 degree crush; (e) and (f) 90 degree crush (Gemini Composites, LLC, 2014).

The sample parts are manufactured using the Vacuum assisted Resin Transfer Molding (VaRTM) process to infuse dry carbon fibers with liquid resin. Specimen with different geometries have been manufactured and tested, three of which are used in this paper: C channel, corrugated single thickness, and corrugated double thickness. The cross-sections are shown in Figure 3: .

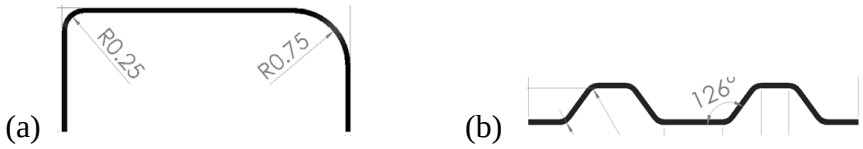


Figure 3: Geometry of tested parts: (a) C channel; (b) Corrugated (Gemini Composites, LLC, 2014).

2.2 Modeling

Modeling of the CFRP composites is conducted in LS-DYNA using the continuum damage mechanics model MAT_58. The composite layers are modeled using shell elements with each layer represented by an integration point as shown in Figure 4: . Different layers can be accounted for separately and the fiber orientation of each layer is defined in a *Part_composites card. Material properties in and out-of fiber directions are assigned in MAT_58, including the Young's modulus, Poisson ratio, and failure strains among others. The moving and support plates are modeled as rigid bodies and a velocity is prescribed to the top plate to crush. The force is measured with the bottom plate and the displacement with the top plate.

Baseline models were built by simply applying the material properties that are obtained from the coupon tests without considering the structural response from the characteristics of the CFRP composites' construction. This method creates significant discrepancies between the simulation and test results. Then, the structural response (such as the residual of the strength of the fibers after failure) are taken into account by activating slim values within MAT_58 and introducing element deletion criteria. This allows the elements to exceed the failure criteria but to stay existing until they totally lose functionality. This greatly improves the match between tests and simulations, which will be shown in section 3.1.

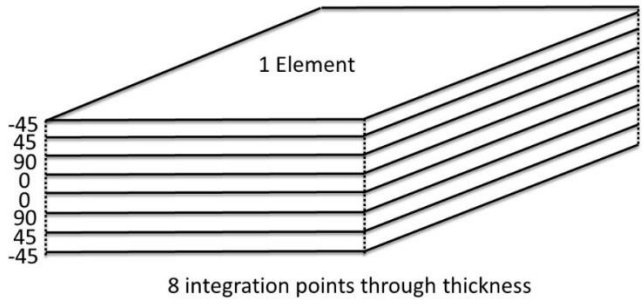


Figure 4: Shell element in LS-DYNA for modeling CFRP composite materials.

2.3 Optimization

For the simulation of larger structures of CFRP composite materials, e.g., as being used for the design of the body-in-white (BIW) structure of a passenger car, the developed material models are expected to be robust with respect to small variations of the applied crush loads. A slight change of the loading conditions must not lead to a degradation in the accuracy of the simulation model. However, the free parameters of the CFRP are rather sensitive to the actually test modality, and manually tuning of the free parameters in order to achieve a good match between simulation and experiment can be a cumbersome and time-consuming task.

In the following a multi-objective parameter identification approach is used to tune the free parameters to multiple crush modalities simultaneously. The resulting parameter set and the respective simulation setup is expected to generalize better to new test modalities. In this approach, a large number of crush simulations is required until an optimal parameter set can be found. Meta-models are used as surrogates of the expensive crush simulation throughout the optimization in order to minimize the overall computational expense and to speed up the search process.

The flow chart in Figure 5: depicts the overall optimization strategy for CFRP material parameter identification. Given a constrained design space, by means of upper and lower bounds of the free material parameters under consideration, in each iteration a space filling sampling algorithm (Ye, Li, & Sudjianto, 2000) is used to generate variations of the material cards by means of different material parameter sets. The sampling step targets a uniform sampling of the parameter space by maximizing the minimum distance between design points for a given number of samples.

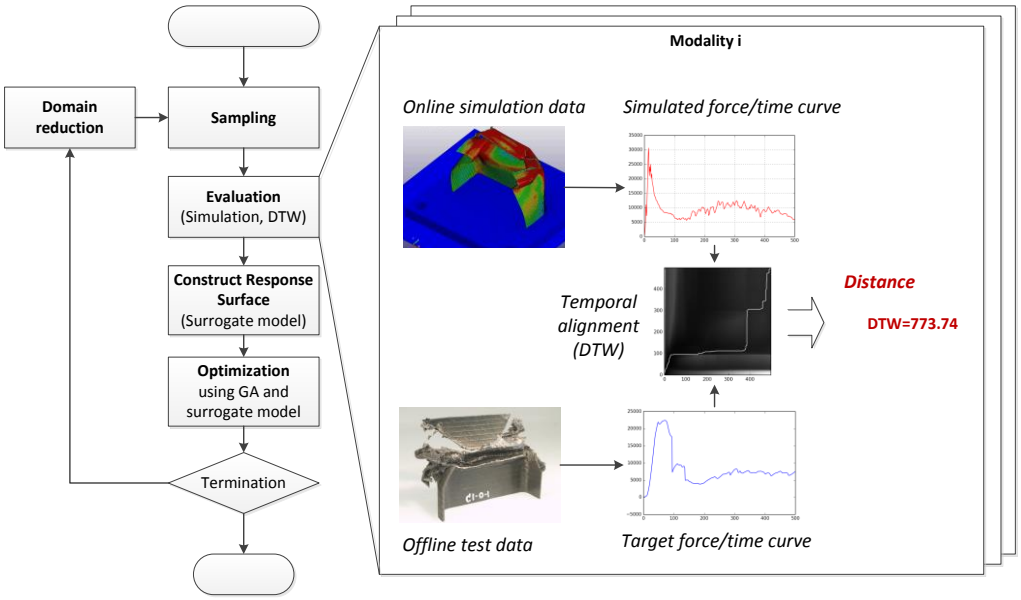


Figure 5: Outline of the multi-objective surrogate assisted optimization strategy used for CFRP material parameter identification.

FEM simulations for each sample and for all considered crush modalities are carried out using the same material model. The resulting force-time curves are compared to the expected target curve derived from an experiment by means of calculating the Dynamic Time-Warping (DTW) distance. The DTW distance quantifies the match of the simulation with the experiment. DTW is an established and one of the most relevant distance measures in time series analysis, originally developed for speech recognition (Sakoe & Chiba, 1978). In contrast to the use of the Euclidean distance, that compares measurements at exactly the same point in time, the DTW distance relies on an a priori optimal non-linear alignment (warping) of the measurements. This makes the DTW less sensitive to small timing variations with respect to crush speed when comparing simulation and test results.

The number of simulated crush modalities and the respective distance values defines the number of objectives for the overall optimization process. The different distances are combined using a weighted superposition approach to formulate the objective for the overall optimization strategy. Let $DTW_i\left(F_i^{Sim}(t), F_i^{Target}(t)\right)$ be the distance between the simulation and the expected target force time curve for crush modality i, the overall objective is defined as $\min_{x\in \mathrm{X}}(\sum_{i=1}^{N} w_i \cdot DTW^i\left(F_{Sim}^i(t), F_{Target}^i(t)\right)$, with Ndefining the number of modalities and $x \in \mathrm{X}$ the free material parameters to be tuned. The weights for the different modalities can be adjusted according to the relevance of the individual crush scenarios.

In order to reduce the computational expense of the overall optimization procedure, response surface models are utilized to estimate DTW based on different material parameter configurations. In the given framework, the results from the initial sampling and simulation steps are used to construct a Kriging (Bakker, 2000) model, which is utilized in the successive optimization step as an evaluation method to search for optimal CFRP material parameters. The computational costs of the Kriging approximation model are negligible compared to the expense of the finite element simulation. In order to seek for the global optimal configuration using the derived Kriging surrogate models, a Genetic Algorithm (GA) (Goldberg, 1989) with real value encoding is used. After termination of the GA, typically after a pre-defined number of iterations, the final solution is verified using the high-fidelity finite element simulation.

Before the next iteration of the overall optimization loop starts with the sampling of new solutions a domain reduction scheme (Stander & Craig, 2002) is applied by means of varying the lower and upper bounds of the material parameters. The domain reduction scheme is used to increase the search pressure towards optimal solutions, which potentially leads to a faster convergence of the overall optimization approach.

The overall procedure iterates until a pre-defined stopping criteria is met, typically after a predefined number of iterations or when the user manually stops the optimization run. A crush modality that has not been used during the optimization procedure can be used for evaluating the robustness of the derived optimal CFRP material based simulation setup.

3. Results

3.1 Simulation with and without considering structural response

Baseline models do not consider the structural response from the characteristics of the construction of the CFRP composites. This creates some problem in the force-displacement curves as shown in Figure 6: . The figure shows a comparison between test data and simulations for the C channel 0 degree crush. Clearly, the simulation curves have significant discontinuities. The force drops to zero as the top plate crushes down causing layers of elements to fail and immediately deleted. The plate is, for the height of that row of elements, pushing against nothing and therefore the force drops to zero. The force increases again once the plate hits the next row of elements.

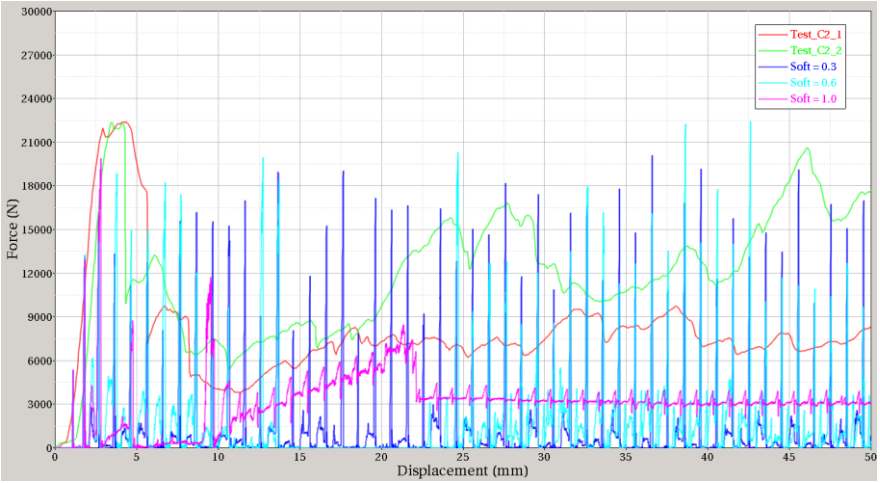


Figure 6: Comparison of the results from test and simulation when structural response is not considered.

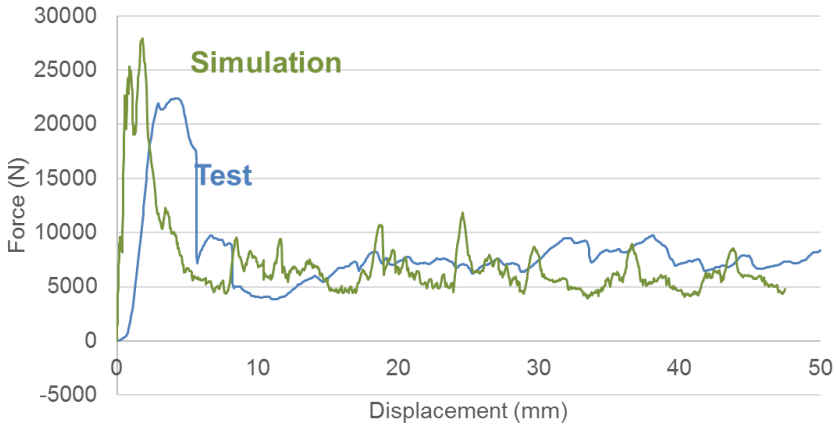


Figure 7: Comparison of the results from test and simulation when the structural response is considered.

When structural responses are taken into consideration, the simulation is improved significantly, as shown in Figure 7: . The elements, although failed, can still contribute to the structure by boasting residual strength and are not deleted until they are completely twisted or lose their functionality. This is a much closer approximation to the real tests. Although improved in this loading case, the results are still not considered as a close match to the test data. The reason is that the set of parameter values that account for the structural response are selected without a solid basis of reasoning or abundant experiences referred to in the literature. That is when optimization is considered to determine the values for those parameters.

3.2 Computational Optimization Results

The main goal of the following computational optimization studies is to investigate how far the optimal CFRP material parameter values depend on the crush modality under consideration. It is studied, how in general such an optimal parameter set can be defined and the degree to which the material model's parameters need to be updated once the geometry of the structure or its loading changes.

LS-OPT[2], a commercial optimization framework developed and distributed by LSTC[3], is used to setup and run the above described multi-objective surrogate assisted optimization strategy for parameter identification. Three different optimization runs are conducted using the same search strategy but considering different crush modalities. Given the objective to match the experimental force-time curve with the simulation, the target of each optimization run is to find an optimal set of parameters regarding the slim values, maximum strains for deletion, and friction coefficients. Overall 10 parameters have been tuned as shown in Figure 9: . Using the sample size and respective simulation budget for 24 solutions per iteration, each optimization was stopped after nine iterations in total. A list of the considered crush modalities used either during optimization or for validation purposes is given in Table 1: .

Table 1: Crush modalities used for optimization and validation.

Order	Geometry	Load direction
1	C channel	0 degree
2	C channel	30 degree
3	Corrugated single thickness	0 degree
4	Corrugated single thickness	30 degree
5	Corrugated double thickness	0 degree
6	C channel	90 degree

Using the C channel geometry, two single-objective optimizations are conducted with the objective to match the 0 degree (optimization a) and 30 degree (optimization b) test respectively. A third optimization (c) is carried out where both modalities are considered simultaneously and simulated in parallel.

The overall best solutions from each optimization are compared with respect to the DTW distance of both tests, 0 degree and 30 degree, in Figure 8: The respective parameter values are depicted in Figure 9: . The results clearly reveal that the material parameters which are tuned to a single crush modality, e.g. results from the 0° crush (Opt. 0°), don't generalize well to the other crush

[2] http://www.lsoptsupport.com/
[3] LSTC Inc. – Livermore Software Technology Corp.

modality. Therefore, it is required to derive the parameters with respect to the objectives of both cases.

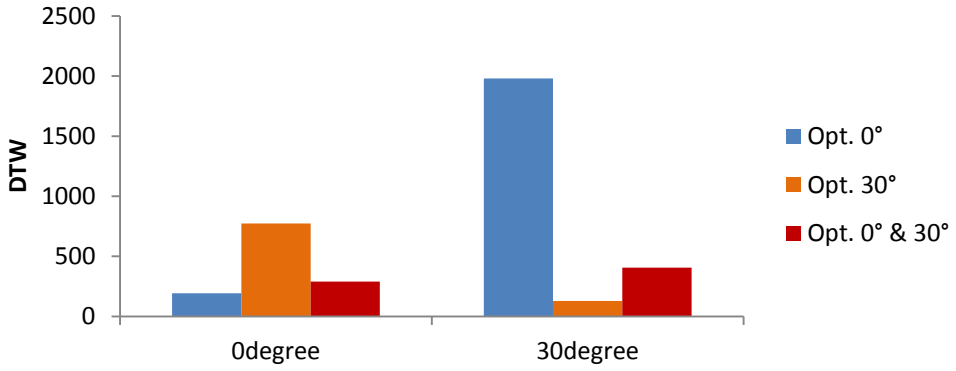


Figure 8: Comparison of the results from the different optimization runs.

When running the optimization under consideration of both crush modalities simultaneously, an adequate agreement for both modalities can be achieved. The performance is slightly worse compared to the optimal parameter set found in optimization a) and b) respectively. In Figure 9: , it can be seen that considering both crush modalities a different set of optimal parameters is found compared to the single-objective optimization runs. The optimal set of run c) is not just a simple re-combination of the optimal parameter values from a) and b).

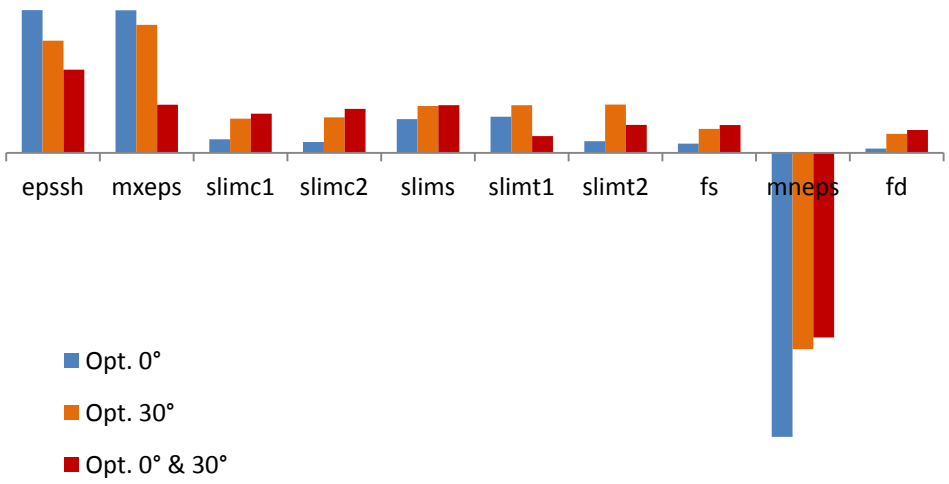


Figure 9: Comparison of normalized parameter values from the different optimization runs.

In the following, the optimal parameter set from optimization c) are adopted and used to build a simulation model for other crush modalities as listed in Table 1.

3.3 *Simulation results and model validation*

To evaluate the cases, the failure mode of the composite samples and/or the force-displacement curves are utilized for comparison. Case 1 and 2 use the results from the parallel optimization (c) and this optimized set of parameters are then input to other cases listed in Table 1 for validation. This section will present some of these results.

Case 1: C channel 0 degree

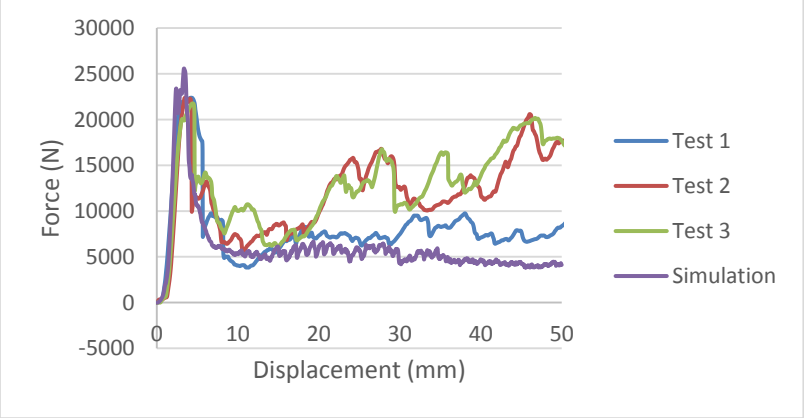


Figure 10: Comparison of simulation and tests for the C channel 0 degree crush.

Three 0 degree tests were conducted and a fair amount of the discrepancies can be observed between different tests after the initial peaks. The reason is that, the part fails in the form of a buckle or breaking at the peaks of the curves. Whether the failed pieces stay in the load path influences the magnitude of the crush forces in the remaining duration of the tests. It can be seen that the simulation correlates to the test curves well, especially in capturing the peak of the crush force.

Case 2: C channel 30 degree

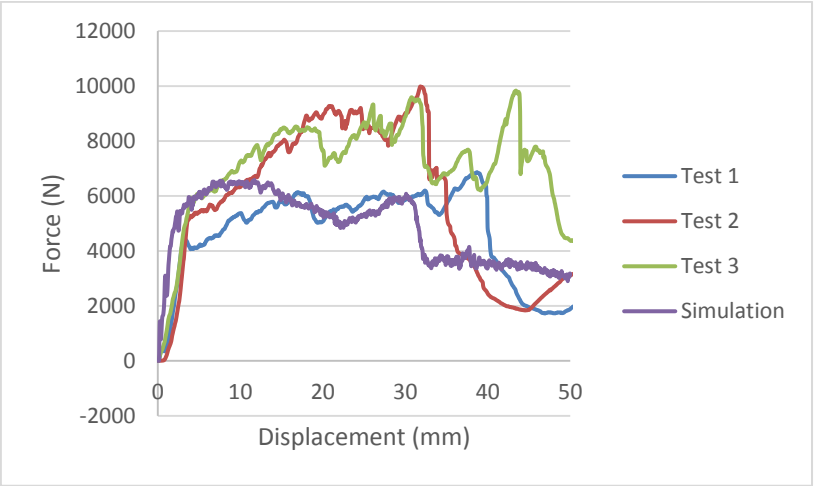


Figure 11: Comparison of simulation and tests for the C channel 30 degree crush.

Three tests were conducted for 30 degree C channel, and again, some variation exist in the test data. For 30 degree crush, the sample is pushed until it buckles or snaps at around 30 or 40 mm displacement depending on the tests. The variation mainly comes from the manufacturing variation on the thickness of the samples. The simulation is able to match the test that was targeted for optimization.

Case 3: Corrugated single thickness 0 degree

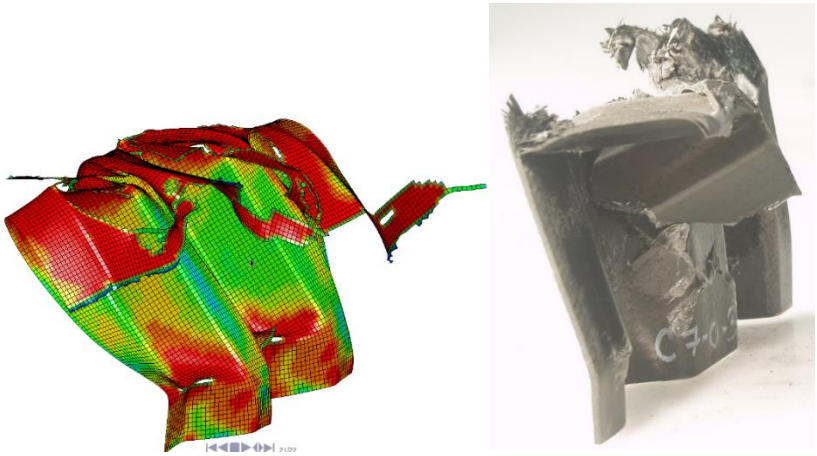


Figure 12: Comparison of simulation and tests for the corrugated single thickness 0 degree crush.

The failure modes of the test and simulation are compared for the corrugated single thickness 0 degree case. It is evident that the model captures the failure at the tip and the at the root of the CFRP part well.

Case 4 Corrugated single thickness 30 degree

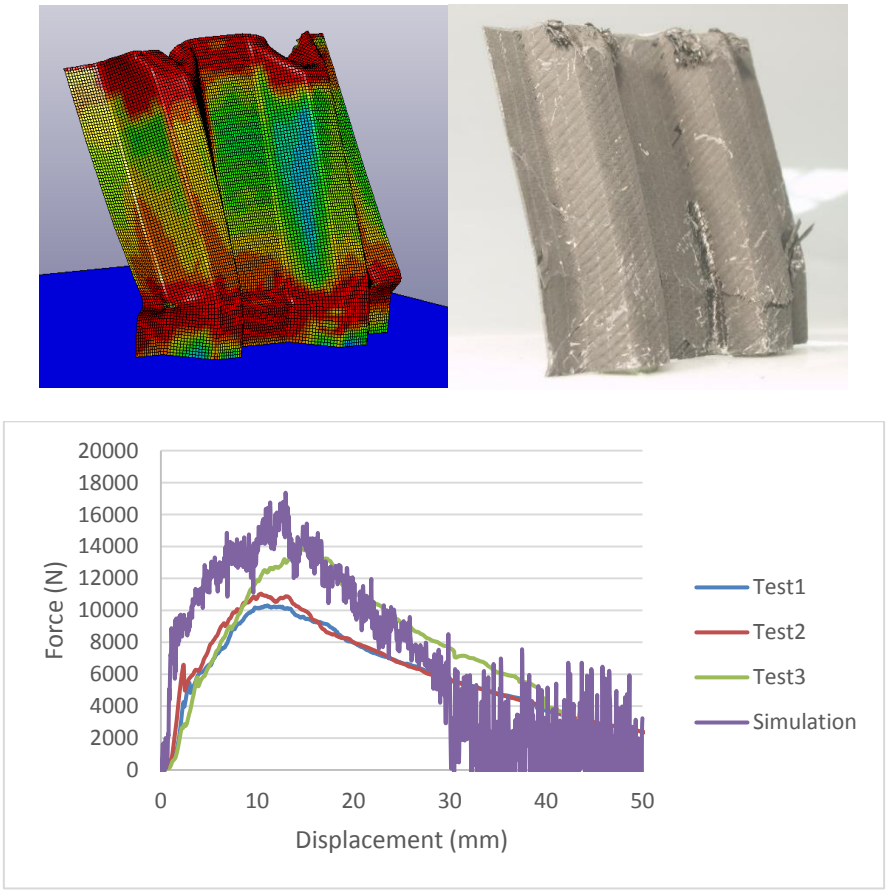


Figure 13: Comparison of simulation and tests for the corrugated single thickness 30 degree crush.

Both the failure modes and force-displacement curve show a close match between the simulation and the tests. The simulation curve has some level of noise due to the element size.

Case 5 Corrugated double thickness 0 degree

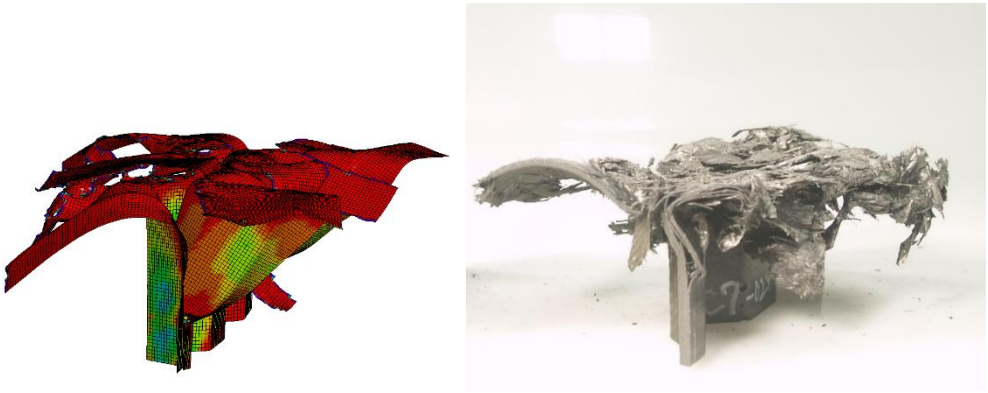
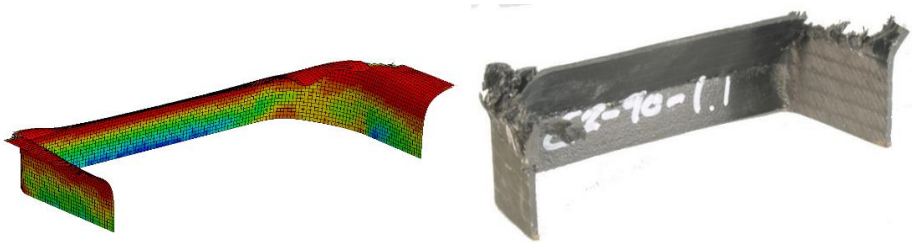


Figure 14: Comparison of simulation and tests for the corrugated double thickness 0 degree crush.

In this case, in addition to using the opitmized parameters, a special treatment was implemented in the model to capture the delamination of the layers. The shell elements are divided into two slabs with tiebreak contact connecting the two sides. The delamination modeling technique shows a close match with epxerimental restuls.

Case 6 C channel 90 degree



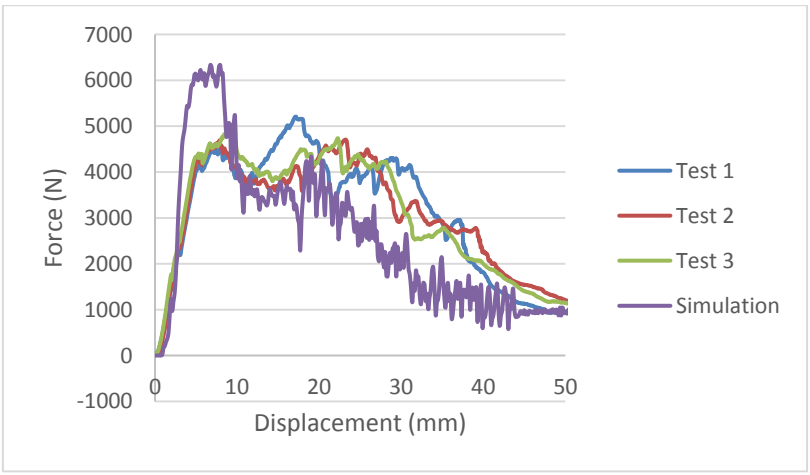


Figure 15: Comparison of simulation and tests for the c channel 90 degree crush.

Both the failure modes and force-displacement curve are well matched between the simulation and the tests. The peak value of the force does not match perfectly due to the fact that in the tests the loading block bends slightly when the crush initiates, while in the simulation the same block is modeled as a rigid body with no movement allowed except in the crush direction. Being ideally rigid in the simulation enables it to predict a higher peak force than the tests.

4. Discussion

The set of parameters that were derived from the parallel optimization of the c channel 0 and 30 degree crush loadcases appear robust in that they are provided good correlation with the cases considered for validation. The work so far indicates good confidence in this approach, which not only introduces parameters that take the structural properties of CFRP materials into consideration, but also provides a set of values for those parameters that work for different cases with various geometries and loading conditions.

5. Concluding remarks

The use of carbon-fiber-reinforced polymer (CFRP) composite material creates modeling challenges for CAE engineers. It was found that the properties obtained from coupon tests alone usually do not work well when utilized in crushing component simulations of different geometries and loadings. The reason lies in the fact that composite materials should be treated as a structure rather than a material due to the interaction between the fiber and matrix. This paper proposed a set of parameters that takes into consideration the structural response of CFRP parts so that the simulation can match the tests with regards to force-displacement curves and failure modes. An optimization is conducted in order to search for the values for these parameters that can work for cases with different geometries and loading conditions. Results show that the values derived from parallel optimization of the c channel 0 and 30 degree cases have good performance when used in other cases.

Acknowledgments

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