Modeling of Carbon-Fiber-Reinforced Polymer (CFRP) Composites in LS-DYNA® with Optimization of Material and Failure Parameters in LS-OPT®

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Abstract

Carbon-fiber-reinforced polymer (CFRP) composite material has gained increasing popularity in aerospace, defense, automotive, and civil engineering. Its high strength-weight-ratio makes it efficient as a structural component. However, the structure of the layers of fibers oriented in different directions, together with the bonding matrix polymers, create challenges in crashworthiness modeling of CFRP parts as a standalone piece, not to mention when they are integrated into larger mechanical systems. This paper presents work done in modeling CFRP composite parts using MAT_58, a continuum mechanics damage material model in LS-DYNA. The parts are manufactured into different geometries, and have been crushed quasi-statically in axial and angled directions. The basic material properties in and transverse to the fiber directions, such as the elastic moduli, strains at failure, and plastic moduli among others are determined by simple coupon tests in tension, compression, and shear. However, by simply inputting values obtained from coupon tests in crush models of CFRP parts, there exist discrepancies between the simulations and tests. CFRP composites should be deemed more as structures rather than materials due to factors such as the bonding structure of the layers, the temperature-related softening, and the residual stiffness of the fibers after failure among others. In MAT_58, SLIM values of tension, compression, and shear are designated for capturing the residual strength of the material after failure as well as the temperature-related softening, both in and out of the fiber directions. Furthermore, MAT_ADD_EROSSION is added to activate element deletion based on individual tension, compression, and shear failures. As presented in this work, the system identification capabilities of LS-OPT can be used to calibrate such parameters to improve the correlation between the simulations and the tests. For an efficient optimization of the material parameters with LS-OPT a meta-model based optimization strategy with domain reduction has been applied. The objective for the optimization has been set to minimize the Dynamic Time Warping (DTW) distance between the force-time curves resulting from simulation and test, respectively. By using an LS-OPT setup that considers the match of multiple crush scenarios simultaneously an optimal parameter configuration can be identified that is more specific for the CFRP material characteristics and less sensitive to individual crush tests.

Introduction

Carbon fiber-reinforced polymer (CFRP) materials has one of the highest strength-to-weight ratios among common automotive construction materials. This equipped them to be increasingly popular in the automotive, aerospace, and civil engineering. Thus, there is great potential in utilizing CFRP in designing light-weight automotive body structures with high energy absorption per weight. Of interest for crashworthiness simulations is the accurate prediction of the energy absorbed by the CFRP material. To achieve such performance in real applications, different levels of samples of CFRP materials has been manufactured, tested, and simulated. This creates challenges for CAE engineers using repeated progressive failure of the CFRP material. While many models exist to accurately predict coupon level test results, the damage and failure that occur of a scaled-up element samples can be a challenge to accurately predict, not to mention the component level. To capture failure of CFRP at larger scales, more parameters are needed which are not typically obtained through standard coupon testing. This paper proposes such parameters to account for the structural response of element level

CFRP composites. The values of such parameters are derived by optimization based on testing a set of different geometries under multiple loading conditions.

Schematics

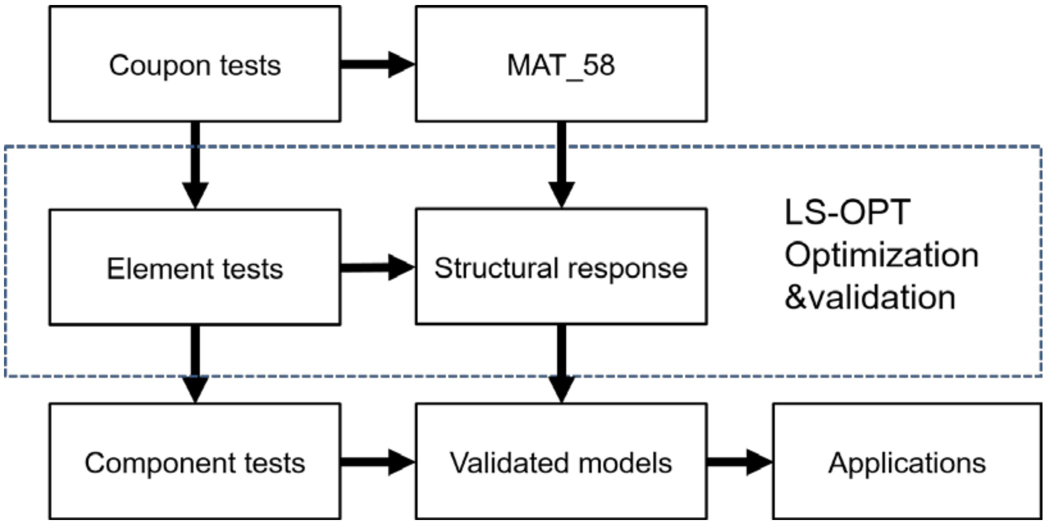

Figure 1: Schematics of this work.

The schematics of this work is shown in Figure 1 . To create components or parts that can be practically used in automotive, aerospace, or any other applications, Carbon fiber-reinforced polymer (CFRP) materials are usually manufactured and put through different levels of tests, modeling, and validation. Firstly, coupons test samples are cut from CFRP plagues that are manufactured with different lay-up designs. Coupon tests are then conducted in compression, tension, and shear directions. Basic mechanical properties, for instance elastic modulus and failure strains, can then be derived to represent the behavior of such coupon samples under the three loading conditions till failure. Such properties can be used to populate the parameters for Mat_laminated_composite_fabric in LS-DYNA, which is a type of continuum mechanics damage model (Schweizerhof et. al., 1998).

Furthermore, element samples are one scale up than coupon samples. Such elements, usually cut from a bigger piece made with careful draping, have different cross-section shapes (C-shape, T-shape, or corrugated) with lengths that are in the same order of scale as the widths of the samples. These samples are then tested quasi-statically or dynamically under different loading conditions for investigation of their performance when crushed. In this paper, the crushing tests are conducted in three different directions: 0 degree (straight down), 30 degree (angled), and 90 degree (transverse shear), the illustration of which are shown in Figure 2 .

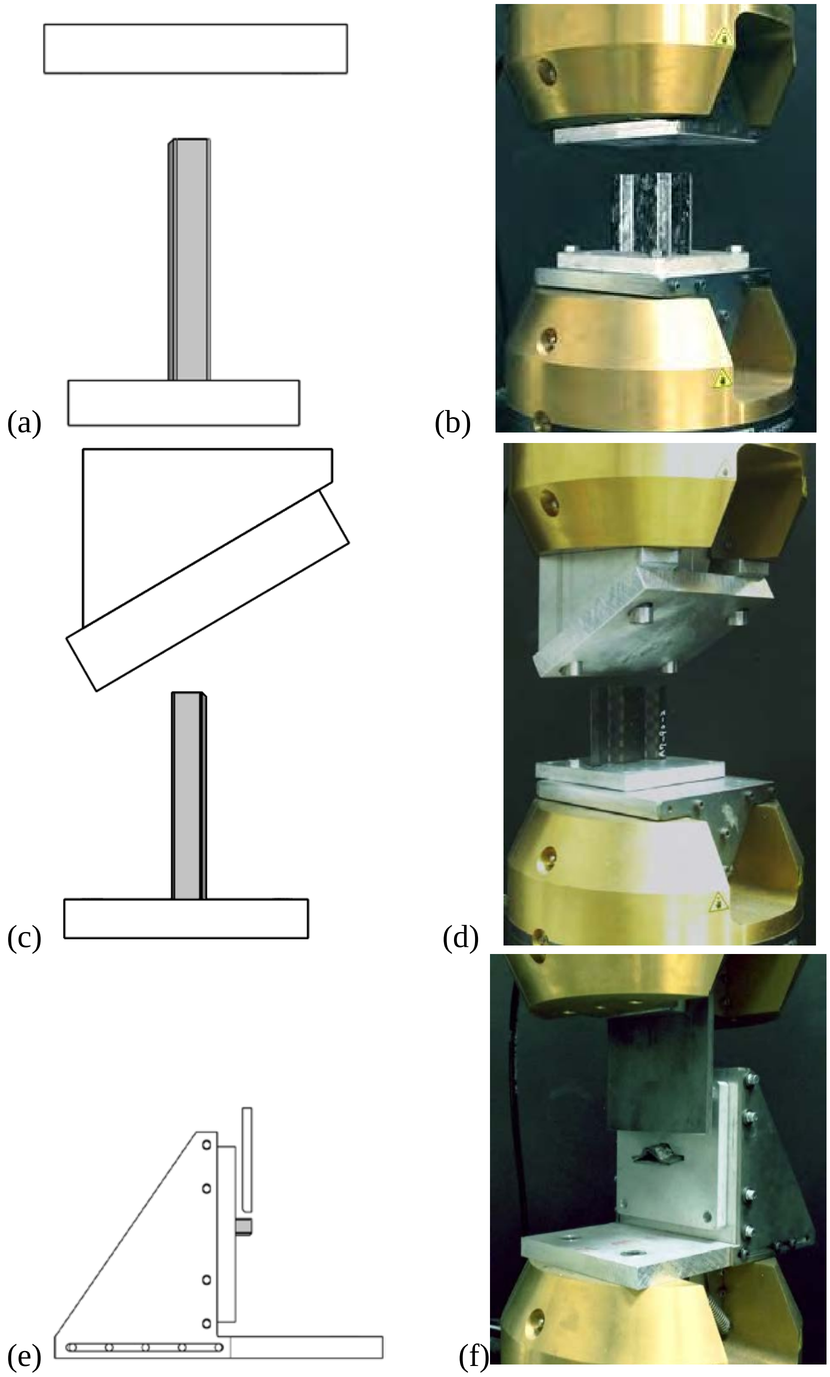

Figure 2: Crush test set-up: (a) and (b) 0 degree crush; (c) and (d) 30 degree crush; (e) and (f) 90 degree crush (Gemini Composites, LLC, 2014).

Displacement-force curves are measured for the duration of the crushing, which is used as a key parameter to evaluate the accuracy of the model. In addition, the crushing and failure mode of the samples are also investigated. Models are created based on Mat_58 that were derived from the coupon tests, however, there exist significant discrepancies between the simulations and the testing data by using Mat_58 directly. Composite materials behave closer to a structure than materials like metals or rubber, due to that different components act drastically differently.

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. 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, 2017).

To search for value for such set of parameters in the LS-DYNA model, an optimization is performed in LS-OPT. The goal is to use the least number of optimization cases to find the values but use the most case to validate such value set. To start with, the first crushing case is used and one set of values is found by matching the force-displacement curves of such case. Such set then is implemented in the rest case for validation. If the set does not work for a certain case, then such case is added to the first case for a parallel optimization in search for a second set of values. The procedure continues until all cases can be accurately modeled.

Modeling

For single thickness samples, there are eight layers with different fiber orientations. The composite sample is modeled as a single layer of shell elements with Mat_58 in LS-DYNA. As shown in Fig. 3, the sample is C shape cross sectioned. Each of the eight layers through thickness is then represented using *Part_composites with fiber orientation defined relative to the material direction and element direction. The fiber direction is shown in white lines.

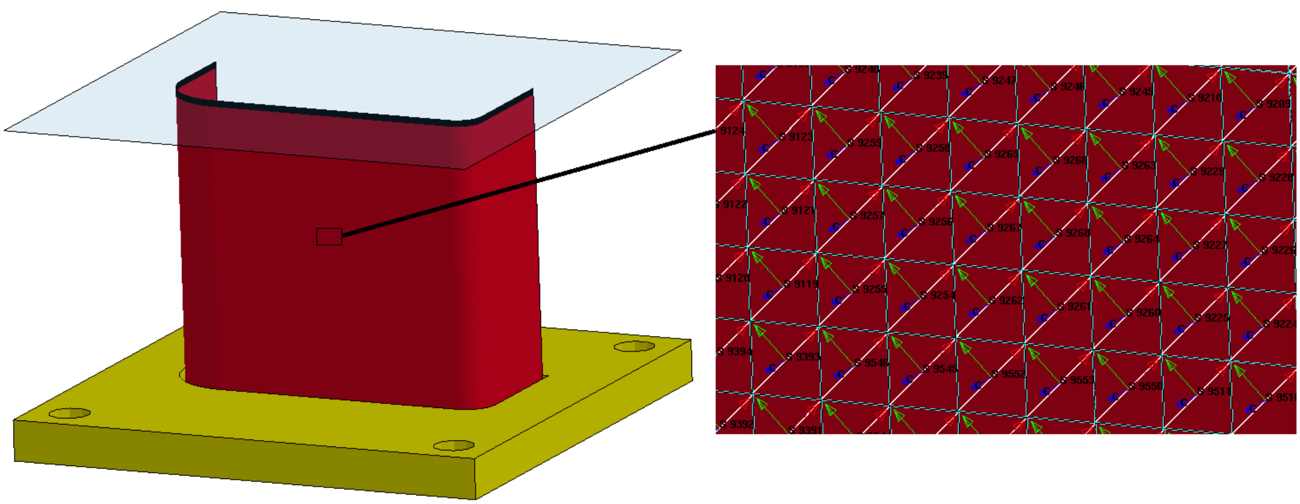

Figure 3: Model of crushing C shape cross-sectioned CFRP part.at 0 degree (fibre in white in the insert).

Material properties in and out of fiber directions are assigned in MAT_58, including the Young's modulus of the fiber and the matrix, Poisson ratios, 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.

Within Mat_58, there are SLIM values built to account for one structural response, that is the residual of the residual strength of the materials after failure. Five SLIM values are introduced for the strength of fiber in tension, fiber in compression, matrix material in tension, matrix material in compression, as well as all in shear. In addition, the EROD parameters in Mat_58 is deactivated and three parameters are defined in Mat_add_erossion: threshold strains in compression, tension, and shear. The reason is that EROD, once activated, mandatorily delete the elements with Mat_58 when their strain exceeds 1. This is not working well with CFRP materials due to the ductility of matrix materials, especially when they are softened by the heat generated during the crush. Mat_add_erossion parameters allow the elements to stay existing after failure until totally losing functionality. Also, the friction between the crushing plate and the

Optimization

LS-OPT is utilized to look for the correct values of those defined parameters by optimizing the match between force-displacement curves from the tests and simulations. The baseline model for optimization is C channel 0 degree (straight down) crush. As shown in the flowchart in Fig. 4, design space is filled with sampling data point, each with a set of values that are implemented in the baseline model for computation. The force and displacement curves are derived from the simulation. A comparison with the test data is conducted using Dynamic Time Warping (DTW, as in the flowchart). DTW compares the similarity of two curve shapes rather than just the magnitude of the peak or simply the average like in other algorithms. Based on the first batch of sampling point after iteration 1, a metamodel is constructed so that the design domain is reduced but a second batch of points are picked for iteration 2. A maximum of ten iterations are possible.

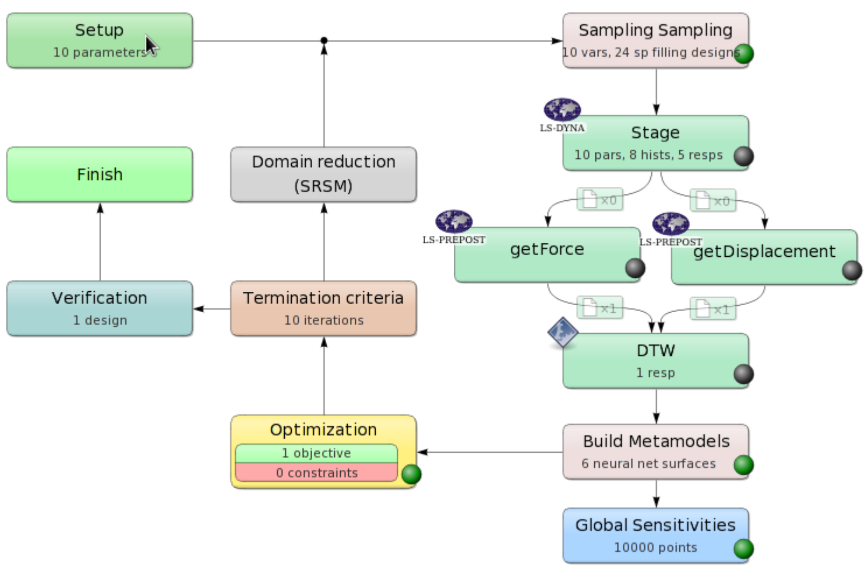

Figure 4: Optimization flowchart in LS-OPT using C channel 0 degree case.

It should be noted that the optimum results are not necessarily the best match between the test and the simulation. The force-displacement curves can be fairly like each other while the actual crush and failure modes can be very different. A manual check of the crush is required to pick out the best results.

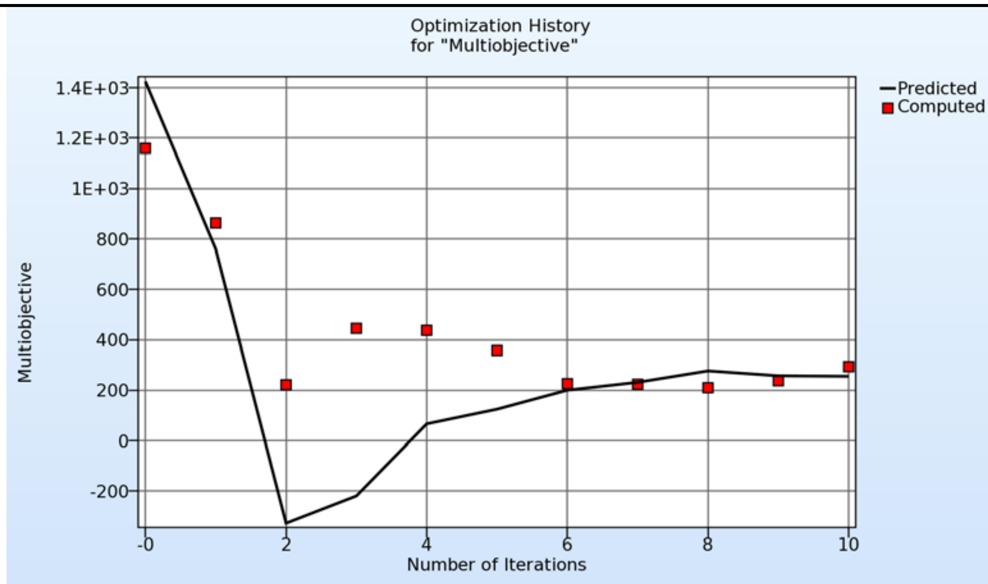

Figure 5: Convergence of the optimization.

Over the ten iterations, a lowest DTW value is found and a convergence is reached. However, when applying the obtained set of value to the next case C channel 30 degree. The match was not good. Therefore, the second case is put in to the flowchart as part of the optimization as shown in Fig. 6.

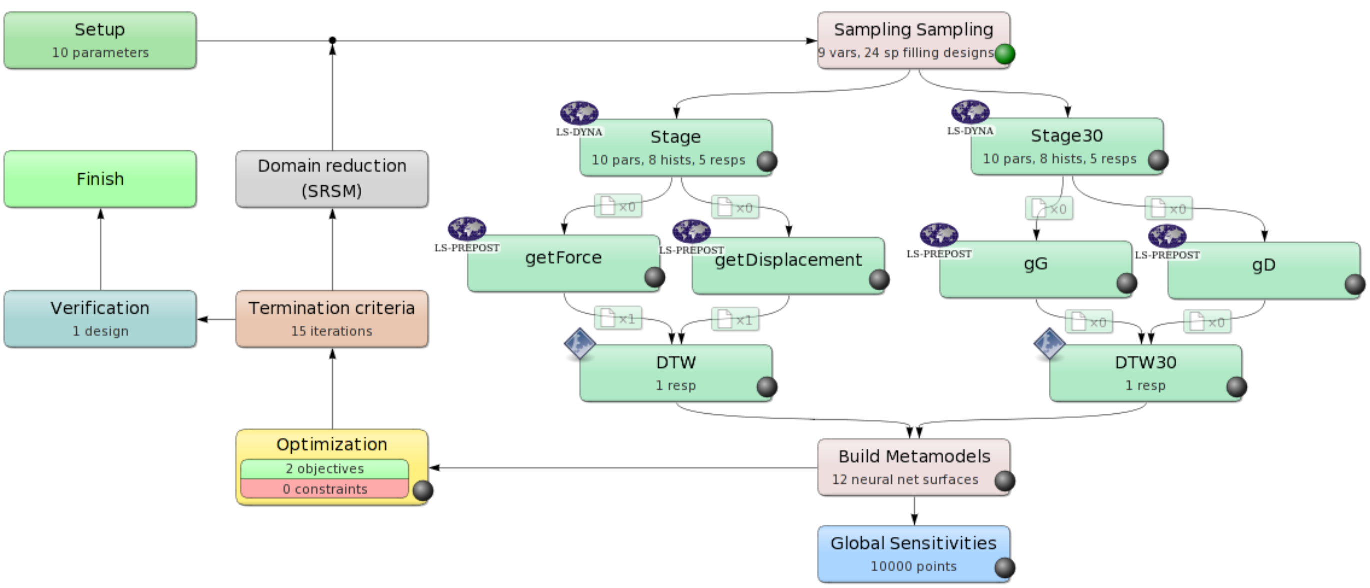

Figure 6: Parallel optimization flowchart in LS-OPT using C channel 0&30 degree case.

The DTW value of the optimum results from parallel optimization are compared with the ones from 0 degree only and 30 degree only, in Figure 7 . To the left, when optimum values are derived from 0 degree case only, the DTW is well kept under 300. However, that set of values does not work well directly to 30 degree only case, resulting in a DTW four times higher. To the right, when only 30 degree case is used for optimization, the DTW value is very small. However, when those values are applied to 0 degree case, DTW is ten times higher. Only when both 0 degree and 30 degree are combined for optimization, the DTW values for both case are both low and acceptable. Therefore, it is required to derive the parameters with respect to the objectives of both cases.

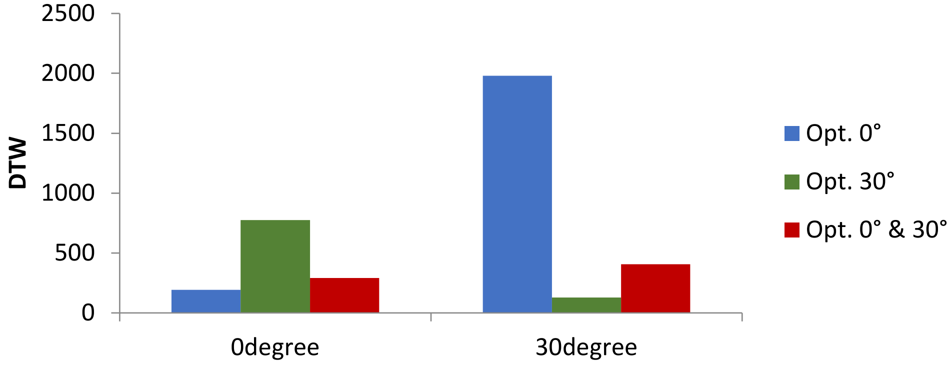

Figure 7: Comparison of the DTW results from the different optimization runs.

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 8, 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).

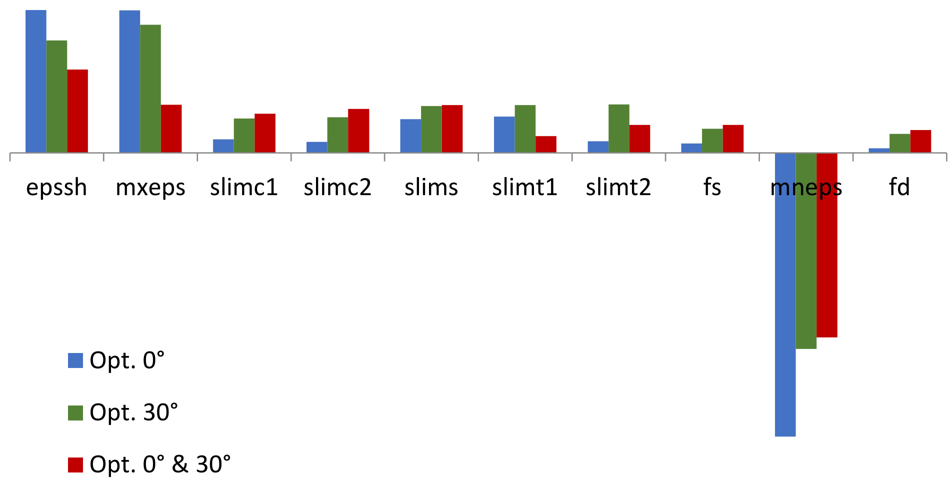

Figure 8: Comparison of normalized parameter values from the different optimization runs.

Results

The force and displacement curves are the main index to show the match between the simulation and tests. For the validation cases, the failure modes are also compared. Since CFRP materials are structures composed by two distinctly different materials, the tests results have significant variation due to the manufacturing tolerance, testing conditions, and misalignment and so on.

C channel 0 degree

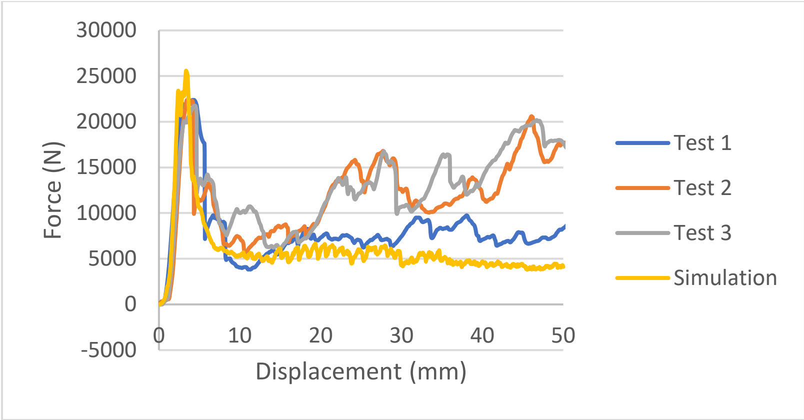

Figure 9: Comparison of simulation and tests for the C channel 0 degree crush.

Test results show that the parts buckle in the beginning of the tests, which gives uniform peak forces. However, the force level after the buckle varies depending on whether the failed pieces stay in the load path. The simulation correlates to the test curves well, especially in capturing the peak of the crush force.

C channel 30 degree

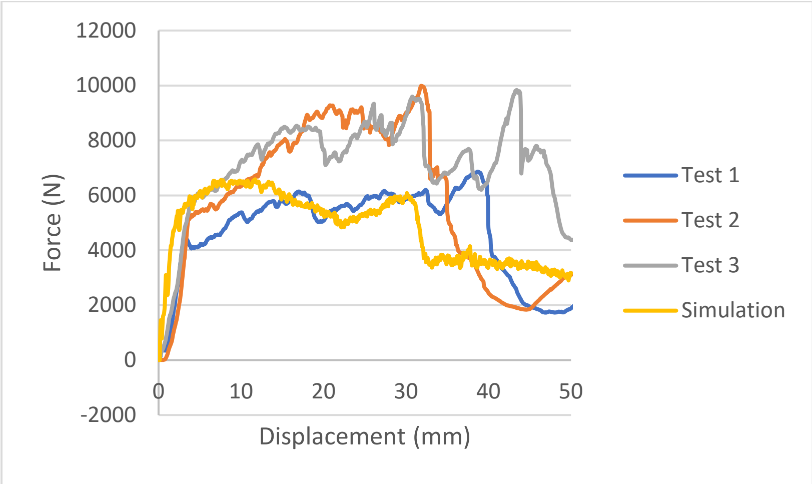

Figure 10: Comparison of simulation and tests for the C channel 30 degree crush.

For 30 degree crush, samples come into contact with the crushing plate and snap at around 30 or 40 mm displacement depending on the tests. The variation in the level of force may come from the manufacturing variation on the thickness of the samples, or the buckling fashion of the sample.

Corrugated single thickness 0 degree

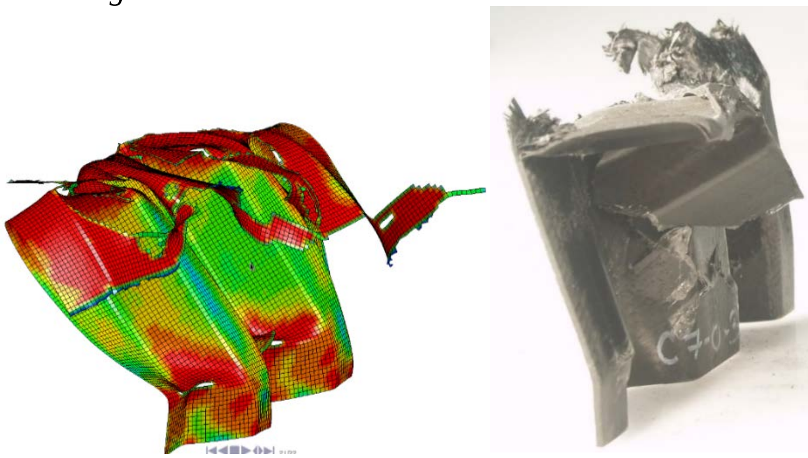

Figure 11: Comparison of simulation and tests for the corrugated single thickness 0 degree crush.

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.

Corrugated single thickness 30 degree

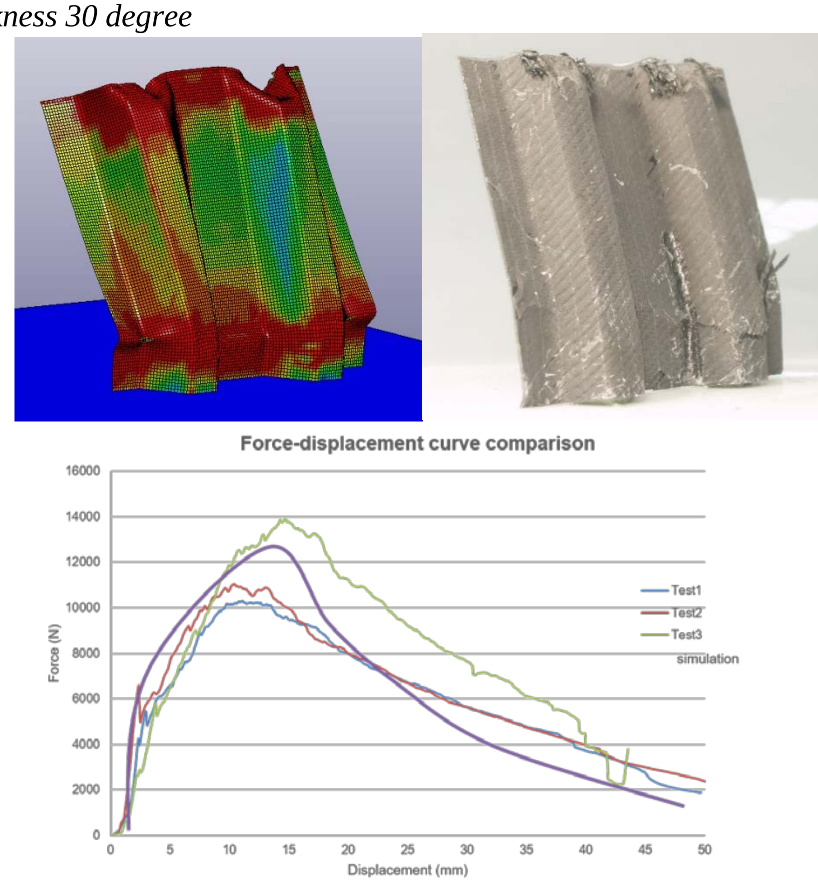

Figure 12: Comparison of simulation and tests for the corrugated single thickness 30 degree crush.

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.

Corrugated double thickness 0 degree

Figure 13: Comparison of simulation and tests for the corrugated double thickness 0 degree crush.

The delamination is modelled using two layers of thin shells with tiebreaker contact connecting two layers. Each layer then uses Mat_58 with the set of parameters obtained from optimization. The delamination modeling technique shows a close match with epxerimental restuls.

C channel 90 degree

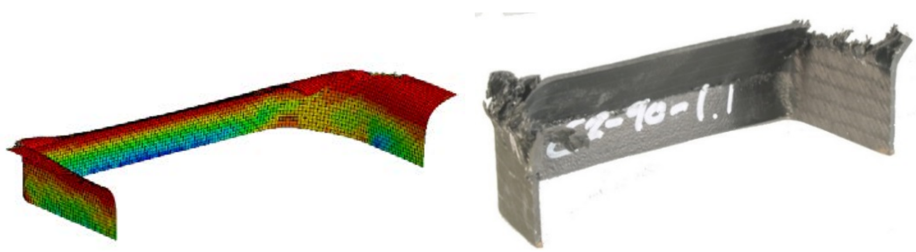

Figure 14: Comparison of simulation and tests for the c channel 90 degree crush.

Force-displacement curve are well matched between the simulation and the tests. The set of parameters that were derived from the parallel optimization of the c channel 0 and 30 degree crush load cases 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.

Conclusion

Carbon-fiber-reinforced polymer (CFRP) composite material can be challenging to model for CAE engineers due to the structural composition between the fiber and the matrix material. The modeling parameters obtained from coupon tests do not scale up well to larger components. This paper proposed a set of parameters that takes into consideration the structural response of CFRP parts, including the residual strength of the fiber and matrix in different loading directions as well as the deletion criteria for failed elements. CFRP materials are modeled using shell elements with Mat_58. Mat_add_erossion parameters are introduced for deletion criteria. An optimization in LS-OPT is conducted to search for the correct values for these parameters. A good set of values is derived from parallel optimization of the c channel 0 and 30 degree cases. Other testing cases are employed to validate. The results show good match between the simulation and test for all cases.

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References

Schweizerhof, K., Weimar, K., Munz, T., & Rottner, T. (1998, September). *Crashworthiness analysis with enhanced composite material models in LS-DYNA-Merits and Limits*. In LS-DYNA World Conference, Detroit, MI.

Matzenmiller, A., Lubliner, J., & Taylor, R. (1995). *A constitutive model for anisotropic damage in fiber-composites*. Mechanics of materials, 20(2), 125-152.

Dong, S., Sheldon, A., Pydimarry, K, & Dapino, M. (2016). *Friction in LS-DYNA: Experimental Characterization and Modeling Application.* 14th International LS-DYNA Users Conference, Detroit, MI, USA.

Dong, S., A. Smith, A. Sheldon. "Modeling of Curing Adhesives between Jointed Steel and Aluminum Plates using MAT_277 in LS-DYNA." 11th European LS-DYNA Conference, Salzburg, Austria, May, 2017.

Dong, S., A. Sheldon. "Characterization and Modeling of Engineering Friction and Wear with LS-DYNA." 11th European LS-DYNA Conference, Salzburg, Austria, May, 2017.

Dong, S., L. Gräning, K. Carney, A. Sheldon. "Parametric Optimization of CAE Material Models for Carbon-Fiber-Reinforced Polymer (CFRP) Composites." NAFEMS World Congress 2017, Stockholm, Sweden, June, 2017.

Dong, S., and A. Sheldon. "Engineering Friction Measurements and Applications in CAE Models." NAFEMS World Congress 2017, Stockholm, Sweden, June, 2017.

Dong, S., A. Sheldon, A. Smith, E. Boettcher, B. Meaige. "Thermomechanical Analysis of Dissimilar-Material Joints Incorporating Modeling of Curing Adhesives." NAFEMS World Congress 2017, Stockholm, Sweden, June, 2017.

Gemini Composites, LLC (2014). Material property testing and structural element crush testing of several carbon fiber composite materials and shapes.

Sakoe, H., & Chiba, S. (1978). Dynamic programming algorithm optimization for spoken word recognition. *IEEE Trans. on Acoust., Speec, and Signal Process., ASSP 26*, (pp. 43-49).

Stander, N., & Craig, K. (2002). On the robustness of a simple domain reduction scheme for simulation-based optimization. *Engineering Computations, 19*(4), 431-450.

Ye, K., Li, W., & Sudjianto, A. (2000). A Algorithmic construction of optimal symmetric Latin hypercube designs. *Journal of Statistical Planning and Inferences*, 145-159.