High-dynamic Drop Test Simulation for Fiber Reinforced Plastics in Automotive Electronic Control Units

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Abstract

Short fiber reinforced plastics (SFRP) are widely utilized for electronic control units (ECU) in automotive fields. Failures in plastic parts often lead to re-tooling hence unpredicted increase in cost of manpower and time. Simulation indeed can offer the chance to virtual investigation without real samples therefore can deeply contribute in early development phase. As well known anisotropic material behavior induced by non-trivial fiber distribution of SFRP strongly influences local failure prediction. Moreover in high-dynamic drop problems viscoplasticity needs to be accounted to obtain the correct failure location. An oversimplified model or alternative isotropic approach in simulation can easily raise misleading results, while by being comprehensive in material model and tool chain one can respectively describe and include dominant influencing factors.

To serve this interest, specimen made of reinforced polybutylene terephthalate with 30 wt% short glass fiber (PBT-GF30) are used for material characterization tests, mainly including 3-point bending and puncture tests by static and dynamic means respectively. By using 4a IMPETUS® software an anisotropic LS-DYNA® material card including the failure (DIEM) was determined reversely to describe the anisotropic viscoplasticity along with failure criteria applied in commercial program LS-DYNA®. Integrative tool chain with considering fiber distribution from process simulation to explicit structural simulation is implemented for an ECU level drop simulation, with which consistent ECU level drop tests are performed. By means of comparing critical drop height acquired from test, the feasibility of this tool chain simulation is shown.

1 Introduction

With speedy development in technology and more demands in comfort, various ECUs are implemented in automobiles to serve different purposes, e.g. for active safety, adaptive cruise control, lane keeping support, parking assistant, etc. Starting from ECU manufacturing, then transportation to customer and finally mounting at the OEM plant, during this journey ECUs may be dropped leading to various possible failure modes. Among these, a crack in the plastic part, especially if not visible from outside, could induce a reduction of the ECU's life time, in case that the respective part is not discarded.

The trend of product design being miniaturization and lightweight, ECU's structure can be quite complex. In consequence also the SFRP made parts usually are geometrically complex and thus are very non-uniform in fiber distribution leading to strong anisotropism of mechanical behavior. Additional to the strain-rate dependency in high-dynamic drop test, the fiber orientation anisotropism increases the challenge to predict crack failure. In product development, to avoid re-design or re-tooling of the plastic part respectively injection tooling it requires robust design in an early phase, which simulation can contribute to achieve. Various simulation approaches can be applied to serve different objectives, e.g. an isotropic simulation model typically delivers a time-cost-effective solution suitable for first qualitative comparison of different concepts, while a more advanced simulation approach will be needed to quantitatively predict crack locations – essential in design for reliability.

To design for reliability with respect to drop test requires the simulation to be based on a proper material model and tool chain to describe the anisotropic strain rate dependent mechanical behavior. To demonstrate the effectiveness of a good material model and tool chain in this study a typical automotive ECU [Fig.1] is chosen as example. The applied material characterization process as well as the simulation tool chain and consistent experiment set up for validation together with the resulting comparison results will be described in the following.

The tool chain applied here is composed of the following commercial software: AUTODESK® MOLDFLOW® software [1] for process simulation, FIBERMAP® software [2] as mapping tool and LS-DYNA® software [3] as dynamic structural solver.

Fig.1: Automotive ECU used in this study, with plastic housing and connector and metal base.

2 Material model and characterization

2.1 Material model

In the LS-DYNA® software over 200 types of material models are provided. It is clear that none of these models can achieve 100% description for a material; rather, each model serves a certain objective and is specifically designed to cover the main influencing factors dominating specific mechanical behaviors – for example in drop test or impact test, **`*MAT_24`** (elastic-to-viscoplastic model) is widely used for unreinforced plastics.

As discussed for drop test where SFRP material is concerned it is important to utilize a material model that can include fiber orientation anisotropism and strain rate dependency. In LS-DYNA® software **`*MAT_54, _58, _157, _158`** [Table 1] are available for such cases. However in order to predict cracks occurring in the plasticity range, only **`*MAT_157`** (**`*MAT_ANISOTROPIC_ELASTIC_PLASTIC`**) is capable of doing so.

*MAT_	Elastic	Plastic	Strain rate	Failure
54	Orthotropic	No	Yes	Yes
58	Orthotropic	No	Yes	Yes
157	Anisotropic	Yes	Yes	Yes
158	Orthotropic	No	Yes	Yes

Table 1: Overview of LS-DYNA® software material models with strain rate dependency and anisotropism.

Moreover, LSTC [3] and 4a engineering GmbH [2] are cooperating on a new material model (**`*MAT_215`**) based on micro mechanics. Generally speaking:

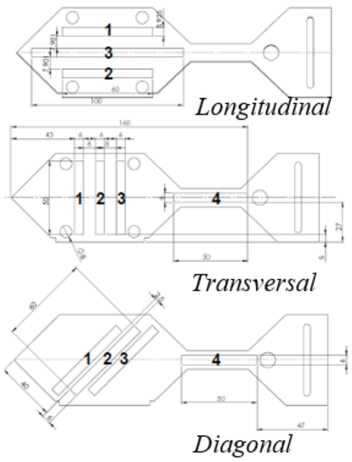
- **`*MAT_157`** is constituted based on elastic viscoplastic material law, Hill Plasticity is used to describe the failure (**`*MAT_ADD_EROSION,`** DIEM), anisotropism is represented by mapping material properties (stiffness matrix) based on process simulation fiber orientation tensor (FOT) result onto the structural simulation model.
- **`*MAT_215`** uses mean field homogenization approach based on Mori Tanaka model, therefore fiber and matrix will be separately modeled (fiber as elastic & matrix as elastic-to-viscoplastic), which of course also needs input from process simulation.

Both **`*MAT_157`** and **`*MAT_215`** are suitable to describe strain rate dependent anisotropism characteristics of a SFRP material.

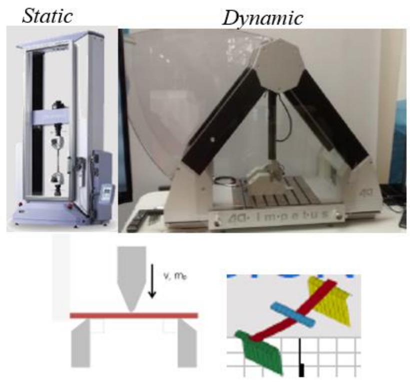
2.2 Material characterization

Different from calibration, material characterization is a method to describe a certain material behavior independent of geometry, fixed purpose or usage scenario. To support mechanical design concerning drop test requirement, usually different design concepts need to be evaluated. Therefore a geometry-independent material card is required for the simulation, which in turn makes the material characterization necessary.

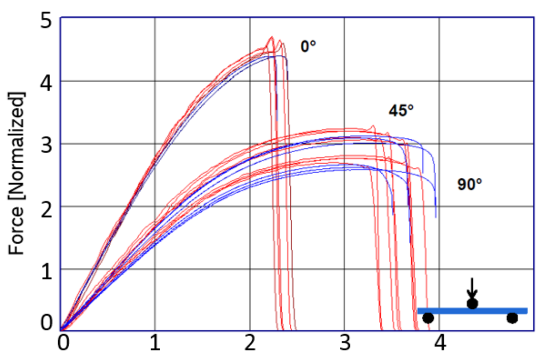
Bending is a typical cause of the failure mechanism of SFRP made parts in the drop test. In the frame of the material characterization to get the strain rate dependency and biaxial stress states 4a engineering GmbH conducted 3 point bending and puncture tests respectively in static and dynamic measurements, for which different fiber-oriented specimen were used [Fig.2, Fig.3]. Specimen were manufactured in year 2012 and 3 point bending tests were also conducted then. To check the influence of aging 3 point bending tests conducted in year 2016 were compared to the former results [Fig.2 (c), (d)] and it is shown that the aging influence can be neglected in this case (samples were well-conditioned stored, tests are done at room temperature).



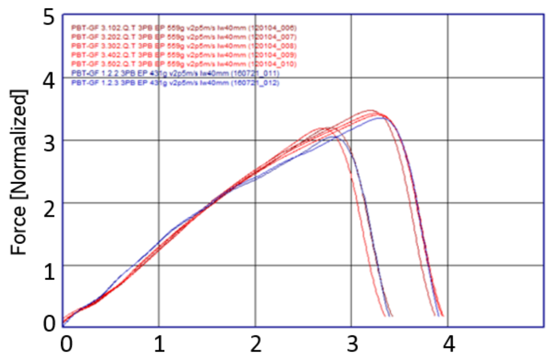
(a) Samples from fish-specimen



(b) 3 point bending set up

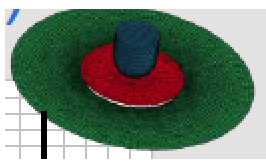


(c) Static tests results

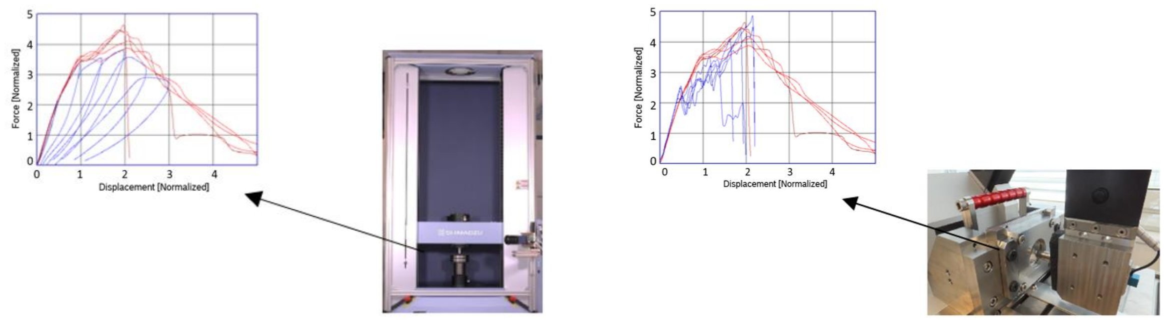


(d) Dynamic tests results

Fig.2: 3 point bending test with specimen (a), set up (b) and results overview (c), (d) [4]; each test is repeated 5 times; dynamic test results are of diagonal specimen; test results in red are from samples tested in 2016, test results in blue are from samples tested in 2012 – only approximately 5% scattering/difference is obeserved.



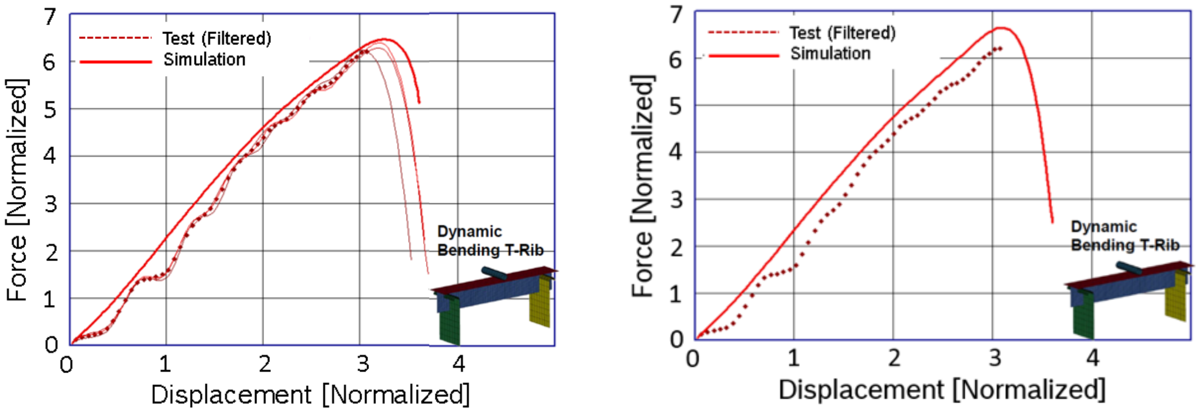
(a) Component simulation model for puncture test



(b) Static tests *(c) Dynamic test: 4a impetus® test system [2]*

Fig.3: Puncture test with simulation model (a) and test set up and measurement results (b), (c) [4]; each test is repeated 5 times; static results shown in different colors are of different loads; dynamic results shown in different colors are of different puncture velocities.

Both ***MAT_157** and ***MAT_215** material cards are generated by reverse engineering from above test results. 4a engineering GmbH did validation on T-rib shaped specimen for ***MAT_157**, using tetrahedron elements with EFLORM 4 & 10 respectively [Fig. 4] which both show very good agreement between simulation and test. With a request of LS-DYNA® R10 solver, simulation validation for ***MAT_215** couldn't be finished in time (until Mar. 2017) but is subject to ongoing studies.



(a) T-rib validation using ELFORM4 & 5 layers in thickness *(b) T-rib validation using ELFORM10 & 5 layers in thickness*

Fig.4: Validation on specimen level simulation and test, using different element formulations: ELFORM4 (a), ELFORM10 (b).

The reason to use EFLORM 4 as well as 10 for the "T-rib" validation simulation is as follows:
The Geometry complexness makes shell or hexahedron elements not possible for ECU level simulation; thus, tetrahedron elements are generated. Various element formulations are provided for tetrahedron elements, e.g. ELFORM 4, 10, 16, respectively leading to different mechanical response and also different calculation cost [5]. Out of time-cost-efficiency reasons here EFLORM 4 and 10 with multiple element layers in thickness are preferred in our ECU level simulation. To be consistent the "T-rib" simulation also uses EFLORM 4 and 10.

Both EFLORM 4 and 10 can deliver good correlation with experiment, EFLORM 4 is preferred as it is slightly better in correlation with experiment.

3 Finite element model

To take fiber anisotropism into account an integrative simulation toolchain needs to be implemented. Fig.5 shows the general workflow of such a chain – a fiber orientation tensor (FOT) related file is produced via process simulation and then mapped onto the structural simulation model through a mapping tool. Multiple types of software can be chosen to fulfill this purpose, in our study the AUTODESK® MOLDFLOW® software - FIBERMAP® software - LSDYNA® software toolchain is utilized.

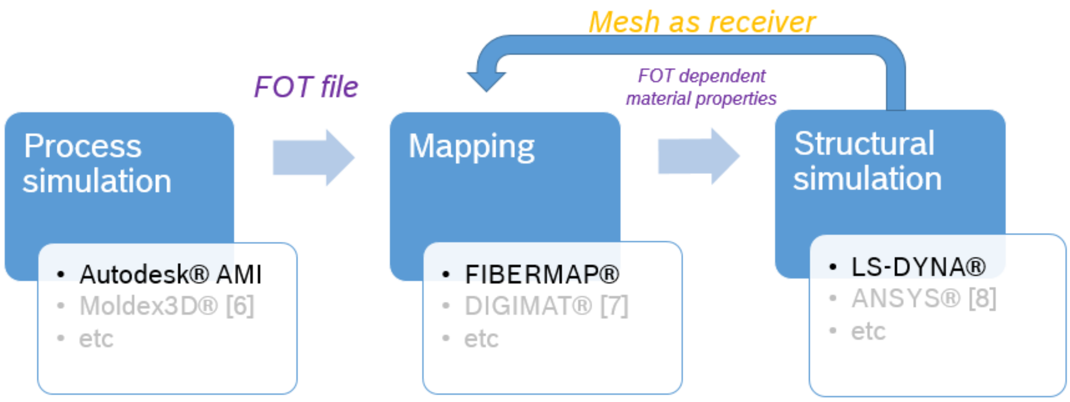


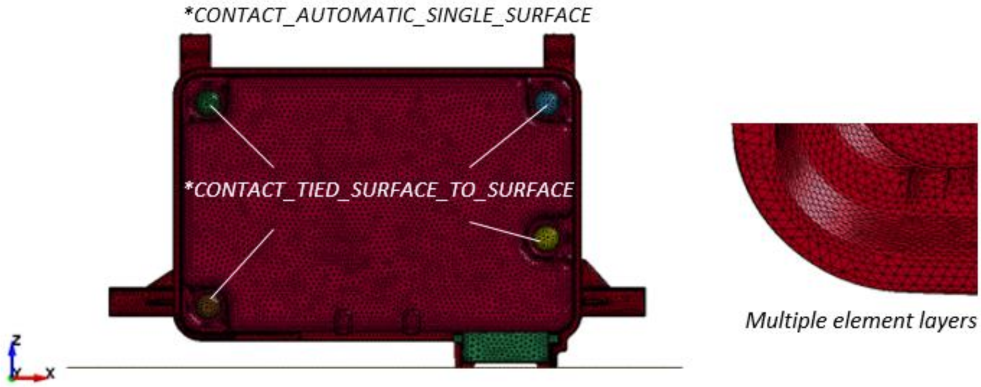
Fig.5: General workflow for the integrative simulation toolchain.

Process simulation with focus on fiber orientation result for use in structural simulation requires special attention on sensitive parameters which strongly influence the accuracy of the resulting fiber orientation – this as well as the mapping procedure is not the focus in this paper, for further reference see e.g. [9]. Here, the focus is on the effectiveness of the material card in combination with structural simulation part of the toolchain. In the following details of the structural simulation model set up are given.

As mentioned in the previous chapter for the SFRP part of interest, the housing, **`*MAT_157`** is used as material model with failure defined by **`*MAT_ADD_EROSION`**. Other parts of the ECU are modeled in **`*MAT_001`** (**`*MAT_ELASTIC`**). Depending on the specific objective and time-cost-efficiency demand one can use more sophisticated material models for the other parts in case they too need to be evaluated with a higher accuracy.

In what regards the contact settings, **`*AUTOMATIC_SINGLE_SURFACE`** contact is defined overall and **`*TIED_SURFACE_TO_SURFACE`** contacts are defined for screws [Fig. 6(a)].

As mentioned in chapter 2, being consistent with “T-rib” specimen simulation validation tetrahedron elements with ELFORM 4 is used in this ECU simulation with minimum 4 element layers [Fig. 6(b)]. In case of many design concepts to be optimized ELFORM 10 might be chosen as this will reduce the calculation cost – attention needs to be paid on the suitability of ELFORM 10: a first comparison with ELFORM 4 results for one concept should be done and should show only small differences – otherwise it is recommended to use ELFORM 4.



(a) Contact definitions *(b) Meshing of ECU*

Fig.6: Finite element model of the ECU (a) tied contacts for screws and automatic single surface contact overall; (b) in thickness direction multiple layers of tetrahedron elements, ELFORM 4.

Before impacting onto the concrete surface the ECU is free falling with no external load induced (air influence is neglected) therefore for the sake of less calculation time, in the simulation the actual drop is reduced to the phase when the ECU hits the ground. To this end

***INITIAL_VELOCITY_GENERATION** are defined for the ECU parts with the velocity v calculated based on energy conservation law, formula (1):

$$v = \sqrt{2gh} \quad (1)$$

With g being the gravity acceleration and h the initial dropping height of the ECU.

By doing this in the simulation the ECU hits the ground ideally in vertical direction (Z-direction, see Fig. 6(a)) while in reality the ECU may rotate resulting into an inclined impact. Therefore in the experiment the impact angles are recorded by high speed cameras to cross-check this simulation boundary condition.

4 Brief experiment set up description

Under different dropping heights not pre-treated ECU samples are free-fall-dropped in –Z direction [Fig. 6(a), Fig.7] onto a plane concrete surface. The drop test is set up as a guided free fall, where the ECU is – fastened by tape – freely hanging from a perpendicular supported beam which once released will glide down a vertical support thus resulting in a guided free fall of the ECU. As mentioned above the impact angles are recorded by high speed cameras for later evaluation and validation of the simulation model set up. After each drop the ECU is visually inspected and scanned by microscope to check if a crack has occurred.

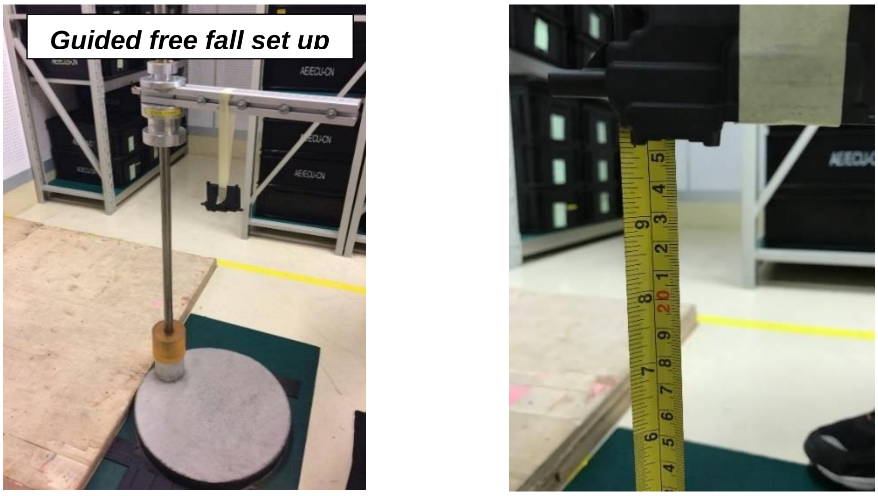


Fig.7: Guided free fall test set up.

In total 20 samples were used for two different drop heights. The results concerning crack location and crack initiation height and their comparison to the simulation prediction will be discussed in the next chapter.

5 Comparison of experiment and simulation

Simulations are conducted iteratively until the critical drop height is captured. The first element deletion is seen as crack failure, element deletion propagation is not considered here because of following reasons:

- Element failure initiation indicates already initial crack;
- Accurate element deletion propagation demands definition of crack evolution law;
- Crack propagation direction is difficult to ensure to be mesh independent.

The first step in comparison of simulation prediction with experiment result is the comparison of the crack location. As can be seen in Fig.8 a crack at the housing corner is predicted by the simulation and well observed in the same location after the free fall test.

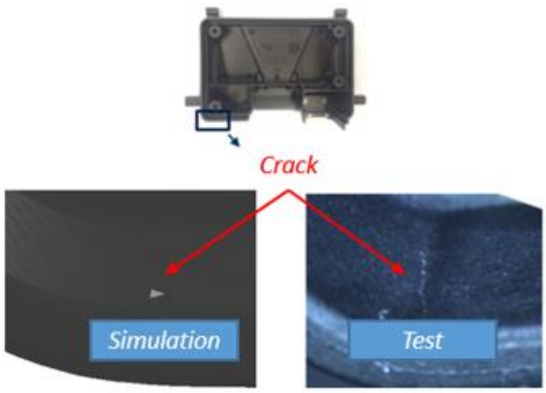


Fig.8: Crack detected at housing corner, same location in simulation as in guided free fall experiment.

Based on the iterative simulations, at drop height H1 crack initiation is predicted at that housing corner while at H2=90% H1 no element deletion occurs.

Similar to simulation, experiments are conducted iteratively to get the critical drop height. Table 2 shows the results of these experiments.

A- drop height H1						**B-drop height 110% H1**	
Sample	**Result**	**Sample**	**Result**	**Sample**	**Result**	**Sample**	**Result**
# A-1	Pass	# A-6	Pass	# A-11	Pass	# B-1	Fail
# A-2	Pass	# A-7	Pass	# A-12	Pass	# B-2	Fail
# A-3	Pass	# A-8	Pass	# A-13	Pass	# B-3	Fail
# A-4	Pass	# A-9	Pass	# A-14	Pass	# B-4	Pass
# A-5	Pass	# A-10	Pass	# A-15	Pass	# B-5	Fail

Table 2: Experiment results for two drop heights in the guided free fall test.

One drop height was chosen identical to the one predicted by simulation and 15 samples were tested. All of them showed no crack. The second drop height corresponds to 110% H1 and 4 of 5 tested samples showed a crack in the predicted housing corner. For reference, the results of the visual inspection by microscope of these 5 samples are shown in Fig.9.

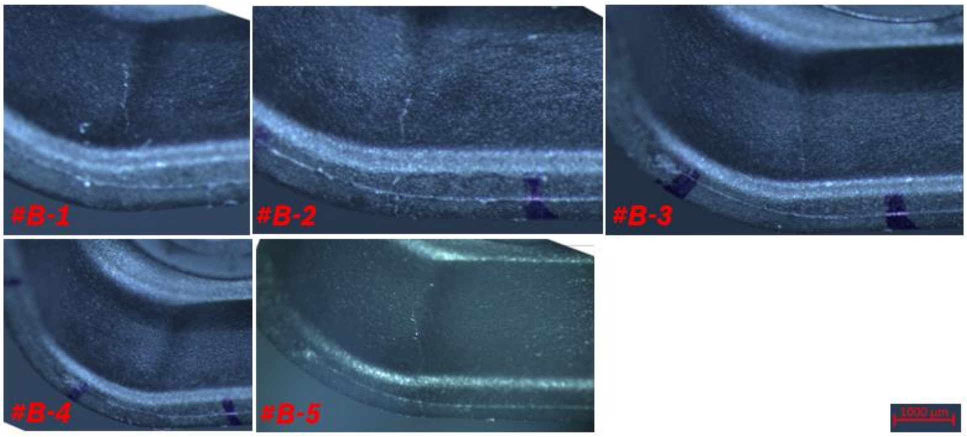


Fig.9: Result of visual inspection under microscope of test series B samples after drop.

A representative result of impacting angles recorded by high speed camera is shown in Fig.10 which shows that the ECU is not much inclined. Generally a sensitivity study with respect to the impacting angle could be considered in view of simulation for different products or different set ups; with only a very small inclined angle that investigation has not been done for the presented ECU case.

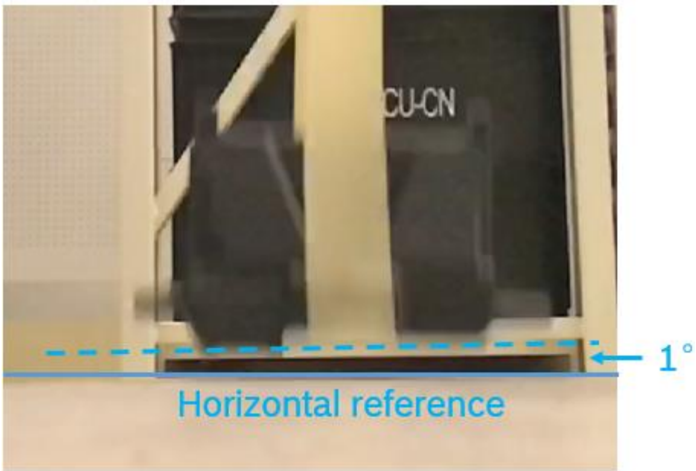


Fig.10: Representative example of impacting angle recorded by high speed camera.

When looking at the test result of series A [Table 2], according to Larson nomogram (based on diagram from [10]) [Fig.11, yellow line] one can deduce a reliability of 90% with a confidence level of 80% – seen as "certain" pass. For test series B [Table 2] on the other hand, 4 out of 5 samples failed and according to Larson nomogram [Fig.11, purple line] this gives a poor reliability with low confidence – seen as "certain" failure.

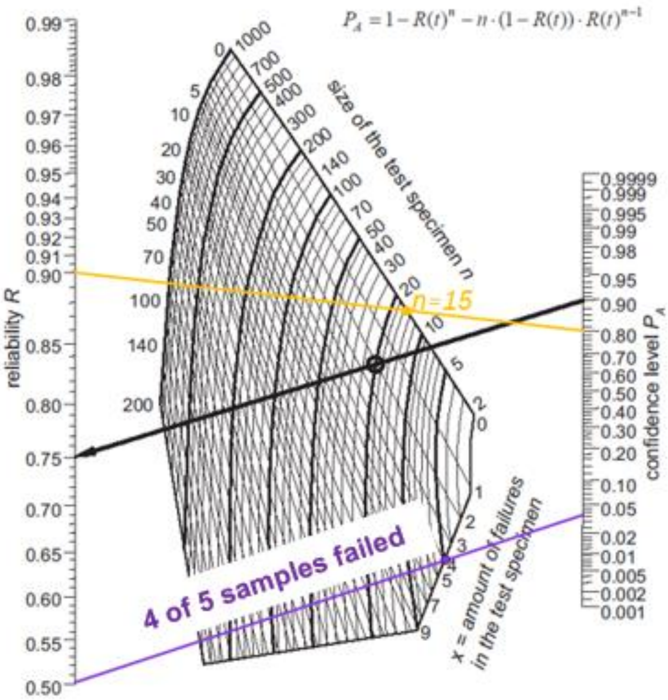


Fig.11: Larson nomogram (based on diagram from [10]), relationship between number of total samples, number of passing samples, reliability and confidence level.

The comparison of simulation and experiment can be summarized as follows:

- The simulation correctly predicts the crack location;
- The simulation is approximately 10% more conservative than the test (see summary Table 3), which can give a good quantitative judgement and thus contribute in the early development phase to the design of reliability with respect to the mechanical design.

	Simulation	Test
Pass height (m)	90% H1	H1
Fail height (m)	H1	110% H1

Table 3: Critical drop heights from simulations and tests.

It should be noted that the critical drop height was evaluated here only for two defined values due to limited capacity and limited number of available samples. More efforts could be made to get a more detailed distribution of the critical drop height but for this first validation case the above presented results were judged to be already conclusive.

6 Conclusion

To achieve quantitative prediction of the behavior of SFRP made parts in a high-dynamic drop test, an investigation of the effectiveness of proper material model, material characterization and integrative tool chain was performed and presented. The evaluation is based on ECU level simulation and corresponding experiments are also conducted and presented. The outcome shows that the use of material model **`*MAT_157`** in combination with the AUTODESK® MOLDFLOW® software - FIBERMAP® software - LS-DYNA® software integrative tool chain can not only predict the crack location correctly but, moreover the critical drop height obtained from simulation shows very good agreement with the experiment results, which proves this workflow being suitable for quantitative judgement.

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