Simplified Finite Element Model of a Prismatic Cell under different Crash Loadings

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Abstract. The inclusion of a battery system in an electric vehicle presents significant challenges due to various requirements, such as low weight, integration into the load-bearing structure, and safety concerns. Allowing for deformation of the battery system necessitates an understanding of its criticality in the event of a short circuit and the potential subsequent thermal runaway. The failure of separator foils can trigger such events, making it essential to assess their deformation. In this study, a simplified finite element (FE) model, comprising three components—the can, a homogenized inner part, and shell layers for the separator foils—is utilized. The model was calibrated using experimental data from a planar pressure test and material parameters sourced from the literature. The transferability of the modeling approach will be analyzed under various load cases, such as crush tests and three-point bending tests. Additionally, the validity of the short circuit criterion, based on representative separator layers, will be examined.

Keywords: Crash Safety, Cell Internal Structure, Abuse Testing, Finite Element Modeling, Electromobility.

1 Introduction

This research focuses on a prismatic Li-Ion cell, commonly found in automotive applications. The literature presents various methods to model the deformation behavior of Li-Ion battery cells. Homogenized models (e.g., [1-3]) characterize the internal structure of the cell as a singular material, which allows their application in vehicle crash simulations. However, these models do not accurately reflect local failure behavior, leading to ongoing research regarding their effectiveness in predicting short circuits, such as separator failures [4]. Meanwhile, advanced macroscopic material models capable of identifying short circuits are in development (e.g., [5-7]). In contrast, detailed models (e.g., [4-5] and [8-10]) that take the cell's internal architecture into account offer valuable insights into the deformation behavior of components, yet they are computationally intensive and unsuitable for crash simulations. Our objective is to create a partially homogenized model that effectively simulates cell deformation while minimizing the number of individual component properties included. This study is based on the work presented in [11]. The same approach of a partly homogenized model is used and the transferability for further load cases and the validity of the representative short-circuit criterion will be examined.

2 Description of the Experimental Setting and the Numerical Model

A typical automotive prismatic battery cell is investigated (see also the illustration in Fig. 1). This cell was experimental characterized with different loading cases. From plate compression, crush and bending, to punch indentation tests with two different geometries. All tests were performed with a SOC of 10% and a velocity of v = 1 mm/min. The experimental settings and the recorded force-displacement and voltage-displacement curves are illustrated in the following sections.

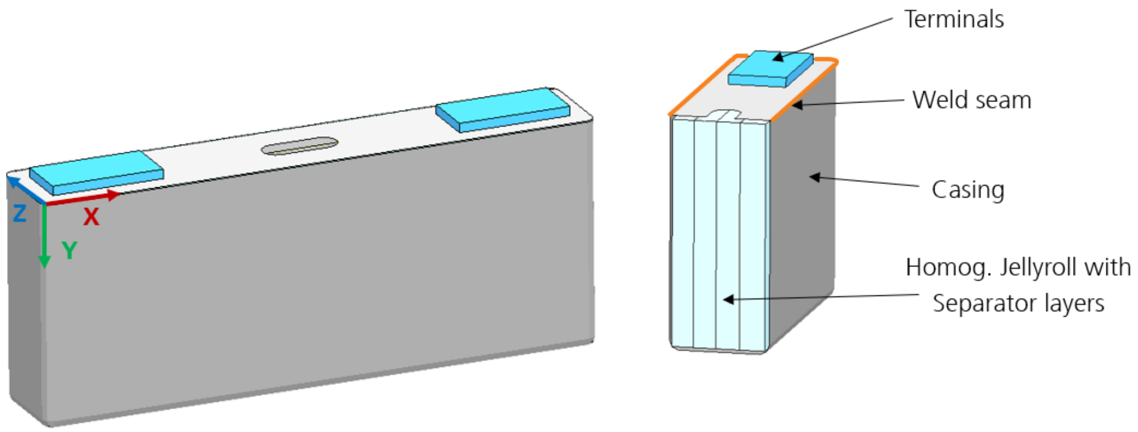


Fig.1: Illustration of the simulation model of the prismatic cell.

For simulating the mechanical deformation behavior at the different loading cases a LS-DYNA simulation model was developed. As shown in Fig.1 the cell consists of three main parts: the casing, the terminals and the homogenized jellyroll. The casing is modeled with fully integrated shell elements (ELFORM - 16) and is made up of a body, a lid (where the terminals are placed) and a connecting row of small elements, which represents the connecting weld seam. The terminals are modeled with fully integrated solid elements (ELFORM 2) and are merged with neighboring elements of the casing. The jellyroll, which usually consists of a big number of thin layers, is homogenized to a block of solid elements (ELFORM 2) with three layers of membrane shell elements (ELFORM 5). These layers are merged with the elements of the jellyroll block. A contact algorithm is used to model the interaction between the cell interior and the casing. A typical element size of 2 mm was chosen. For the aluminum casing and the terminals, a plastic-kinematic material model is used. In accordance with the literature values, the Young's modulus is 70 GPa, the yield stress is 170 MPa and the tangent modulus is 560 MPa. A plastic strain of 0.35 is taken as erosion criterion to model failure of the aluminum. The homogenized cell interior is modeled with the crushable foam model. For compression, the model needs a stress-strain curve as input, the curve was calibrated based on the plate compression test (see section 3.1). In tension, a yield stress of 30 kPa is applied. Simulations were calculated using LS-DYNA R13.1.

3 Validation of the Simulation Model

The following sections show the results and the analysis of the simulations of the different loading cases. For calibrating the crushable foam model of the cell internal, the plate compression test is used (section 3.1). The material parameter set was not further modified or adapted for the other scenarios. This ensures the comparability and validity of this model approach.

3.1 Plate Compression

In Fig. 2, the test setup and the resulting force-displacement curve of the experiments and simulations is shown. By assuming one-dimensional stress and strain state the input curve for the crushable-foam model was determined from the experimental curves (black and gray). Applying this material parameter curve to a model of the cell interior only (no casing or separator layers) results in a satisfying agreement with the experiment (green curve compared to black and gray).

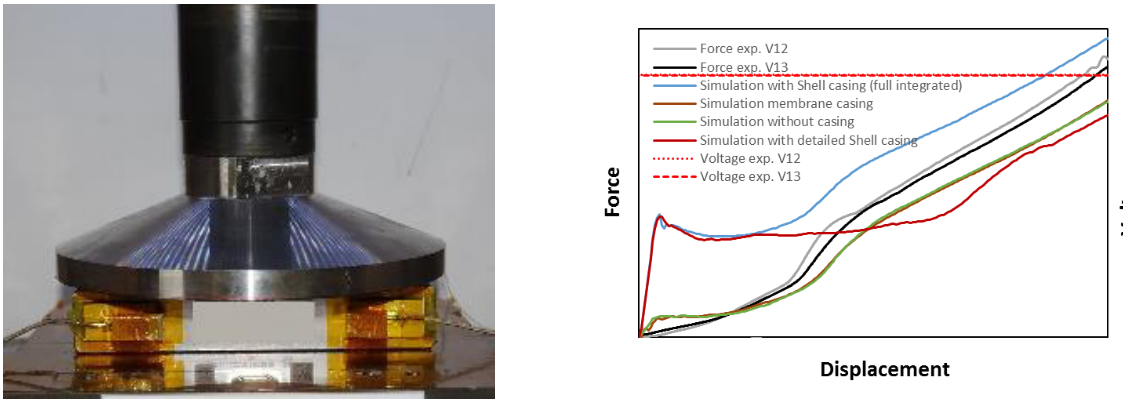


Fig.2: Setup of the plate compression test (left) [11]; force-displacement and voltage-displacement curves (right).

However, adding a casing to the previous model, leads to different results of the force curve. In Fig. 2 the blue and the red curve belong both to a casing of fully integrated shell-elements which both lead to a strong overestimation of the initial stiffness. For larger displacements, both show the characteristic change of the slope and are similar to the origin curve. These casings differ in the level of details. The red one belongs to the described structure above, while the blue one has a casing without the represented weld seam and no vent. However, this structure had the disadvantage in the shown deformation behavior during the test. Adding more details the observed characteristics are also seen in the simulation. In Fig. 2 only the case »membrane casing « (ELFORM 5) the force-displacement curve is quasi-identical to the simulation without casing. This difference between models with shell-casing and the experiment needs further investigation.

3.2 Crush Test

In the crush test, the cell is positioned on the short side and held with a small support (see Fig. 3 left) to avoid tipping of the cell. Applying the outlined simulation model (detailed casing with ELFORM -16) shows a very good agreement between experiment and simulation: The force increase at the beginning is slightly overestimated by the simulation due to the higher initial stiffness. However, the force level is well kept by the model. It should also be noted that no short circuit was detected in the experiment, despite the strong deformation.

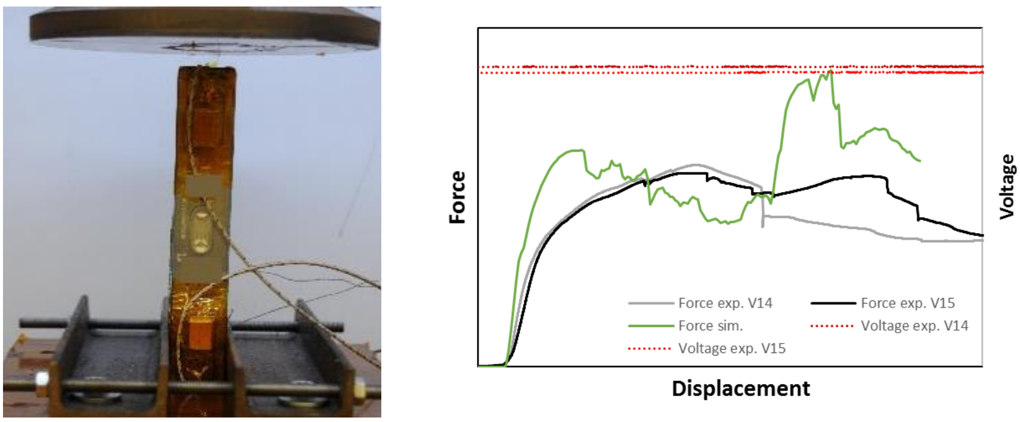


Fig.3: Setup of the crush test (left) [11]; force-displacement and voltage-displacement curves (right).

3.3 Three-Point Bending Test

The three-point bending test is the loading case with the highest displacement of all performed tests. As seen in Fig. 4 (on the right) the simulation model reaches a good agreement to the experimental force curve, even there is more oscillation in the numerical force signal. This load case also shows no short circuit in the experiment.

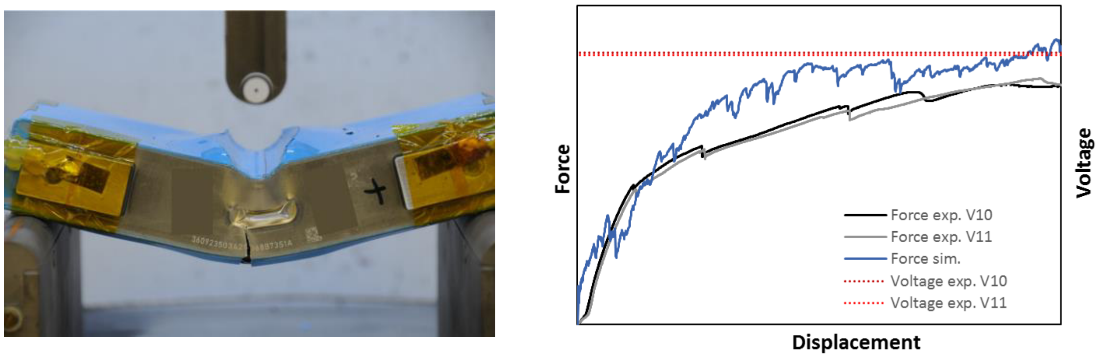


Fig.4: Setup of the three-point bending test (left) [11]; force-displacement and voltage-displacement curves (right).

3.4 Hemispherical Punch Indentation

Indentation with two different punches is conducted. In this section the result of a hemispherical punch is shown. Fig.5 shows the experimental setup on the left and the voltage-displacement and force-displacement curves on the right.

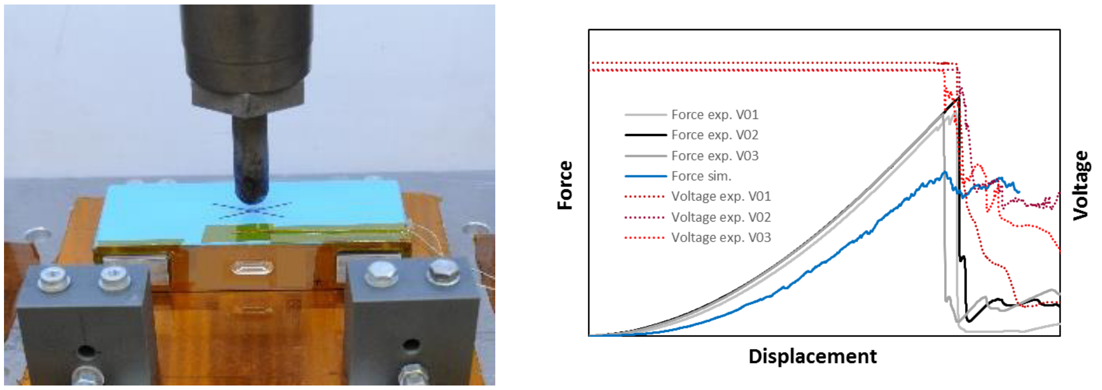


Fig.5: Setup of the hemispherical punch indentation test (left) [11]; force-displacement and voltage-displacement curves (right).

Experimental and numerical force-displacement curves show a good agreement of the slope, even that the numerical result reaches a slightly lower force level. The experiments show short circuits, which coincide with the respective force maximums and a strong force drop afterwards. The simulation shows the force maximum, and a following force drop at a slightly lower displacement and force level. Noticeable is also that the force-drop in the simulation is not as pronounced as in the experiment. It is assumed that not considering failure of the interior structure is the main reason for this difference. However, the critical displacements of the force drops show a good agreement between experiment and simulation.

3.5 Flat Punch Indentation

This section deals with the indentation of a flat punch. Fig. 6 shows the experimental setup on the left and on the right, the resulting the force-displacement curves with the respective voltage-displacement curves.

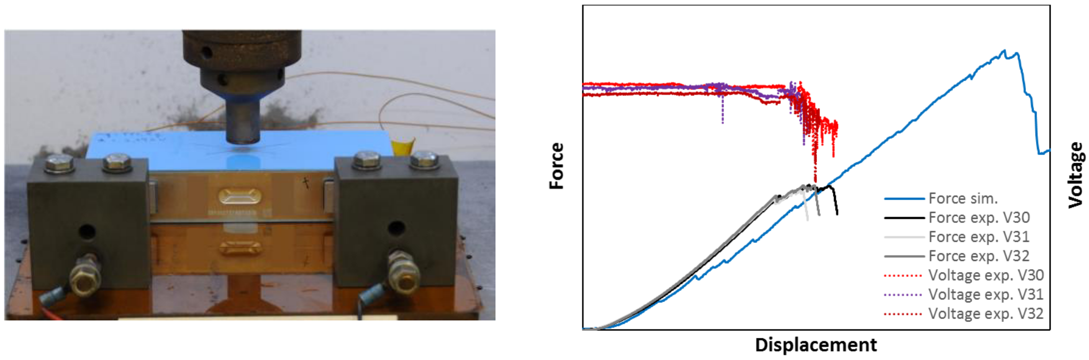


Fig.6: Setup of the hemispherical punch indentation test (left) [11]; force-displacement and voltage-displacement curves (right).

All voltage curves in the experiment show a decline, indicating that a short circuit occurs. The decrease of the voltage starts before the maximum force is reached. Also, the slope of the force curve changes as soon as the slight voltage drop starts. The simulated force curve has a good agreement of the initial slope but overestimates the maximum force level strongly. The force drop correlates with the failure of elements of the casing.

4 On the way to Evaluate the Criticality of Deformations

Besides the prediction of the mechanical deformation of the cell in different loading cases, a big aim of the simulation of battery cells is to make a statement about the possible occurrence of a short circuit. Out of literature it is known that a short circuit often depends on the failure of the separator. This criterion is hardly to address in completely homogenized models. Therefore, the described modelling approach consists of a homogenized jellyroll with inner layers of membrane shell-element as already outlined in [11]. For modelling its material behaviour, the piecewise linear plasticity model is used, the parameters were determined based on tensile tests of a typical separator material illustrated in [4]. These shall mimic the separator in the real cell (Fig. 7).

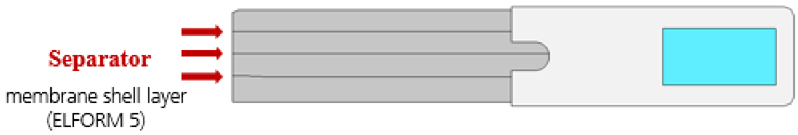


Fig.7: Positioning of the membrane- shell-layers in the cell inner.

The outlined experiments just show a short circuit in the two indentation tests, therefore these two are analysed in the following. In Fig 8 and Fig. 9 the principal strain of the three separator layers is shown at the moment of force drop. The choice to use this material parameter as a criterion for a short circuit is based on the results in [4] and [9], where the analysis of a detailed cell model show that the active material is in a pressure state as the electrodes are in tension. Due to that it is assumed, that the here considered separator-layers are also in a tension state and the in-plane deformation might be the critical one. Therefore, principal strain is preferred over plastic strain for the analysis.

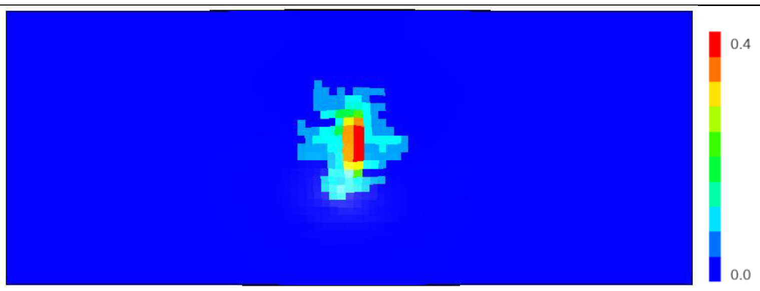
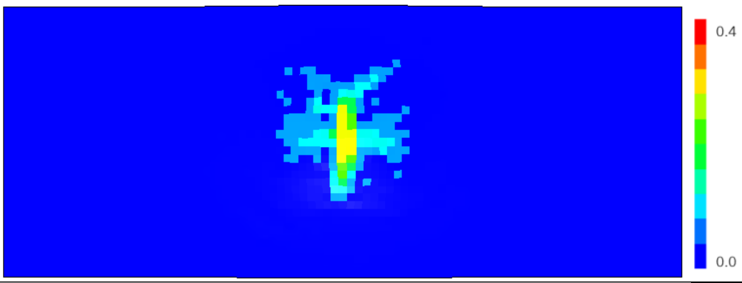
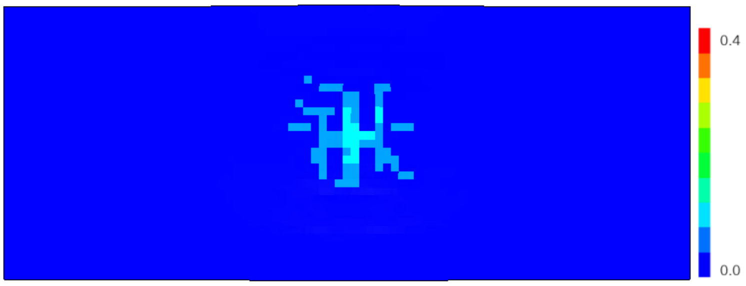
Top layer	
Middle layer	
Bottom layer	

Fig.8: Hemispherical Punch Indentation: Principal Strain of Separator layers at moment of force drop: Blue = 0; Red =0.4.

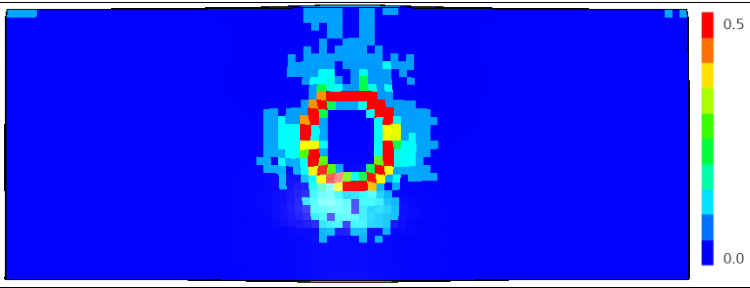
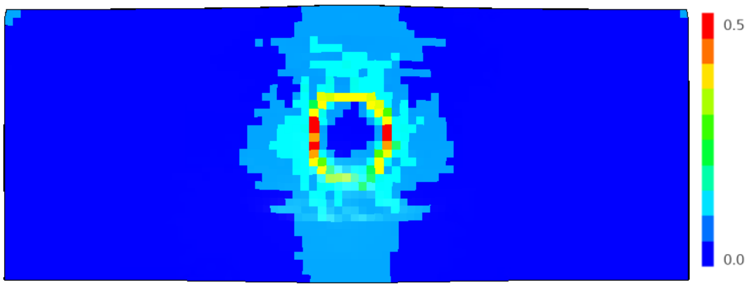
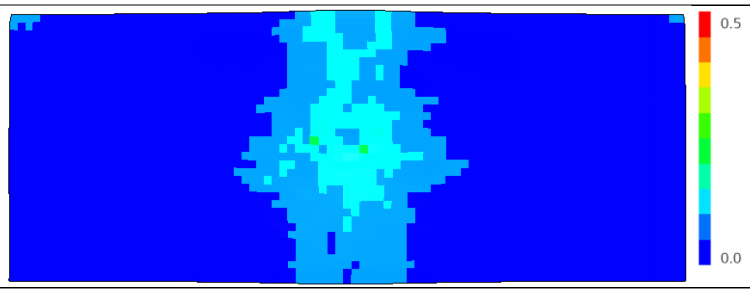
Top layer	
Middle layer	
Bottom layer	

Fig.9: Flat Punch Indentation: Principal Strain of Separator layers at moment of force drop: Blue = 0; Red =0.5.

In both cases the top layer shows the highest strain values, and the pattern is for the hemispherical punch at force drop like a crack which is initiated beneath the tip of the punch. For the flat punch in the moment of force drop the strain pattern shows a full circle around the punch edge, which suits the observation of the overall punching behaviour.
For comparison with the two loading cases which do not show a short circuit, Fig. 10 shows the principal strain of the layer with the maximum value. In these cases, the maximum values of 0.26 and 0.28 were determined. So, it seems, that a value of 0.4 and higher correlates to a critical state of the cell. For proofing this, further analysis of loading cases with the occurrence of a short circuit are necessary.

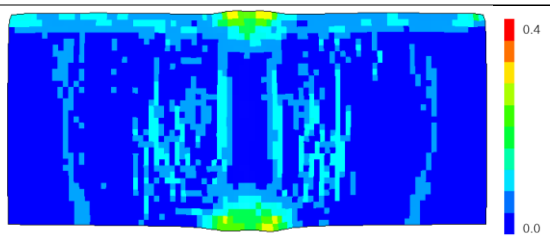
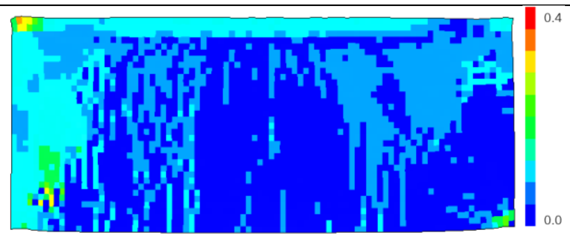
Three-Point Bending	Crush
	

Fig.10: Separator layer with the highest occurring principal strain of the two experiments without a short circuit. Contour plot from Blue=0 to Red=0.4. Maximum value at the bending test is 0.26 and in the crush test 0.28.

5 Summary

We demonstrate a homogenized cell model of a prismatic cell, considering the casing with a small number of details, and the homogenized cell interior with additional membrane layers, that can be calibrated on a single plate compression test. Without further specific knowledge of the cell (except the outer dimensions), the material parameters are either taken from literature or adapted to one cell test (plate compression). The prediction of the of the force is surprisingly good. This is especially true for hemispherical punch, crush and bending. One exception is the compression test, where an unattended dependence on the modelling of the casing has become apparent. For flat punch loading, the simulation overpredicts the force peak including of membrane layers into a homogenized jellyroll shows a promising approach for a simple short-circuit criterion. The principal strain seems to be a meaningful parameter to give an information about the critical state of a cell. The criterion, calibrated on hemispherical punch, correctly predicts no short-circuit for bending, crush and plate compression. For the flat-punch an evaluation is not yet meaningful, due to the not-sufficient simulation of the force-displacement curve.

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6 Literature

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