Constitutive model parameter identification via full-field calibration

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Abstract. The main goal of constitutive model calibration in the field of sheet metal forming is to describe the stress and strain relationship for numerical simulation of the production process as accurate as possible. This may be achieved through enlarged reverse-engineering strategies which are based on available classical or even modified experimental investigations. Therefore, coupon tests have to be discretised and the corresponding test setup is simulated by using the desired spatial and temporal discretisation by finite elements. In this respect the most common characterisation procedure for the identification of constitutive properties of sheet metal is the tensile test acc. to DIN EN ISO 6892-1. In this test, the measurement data such as the tension force and the specimen elongation serve as the basis for classical parameter identification. It particularly aims at identifying the yield behaviour, i.e. the yield locus and the hardening curve of the targeted sheet metal material. The goal of the present research is to investigate how the massive amount of data obtained from state-of-the-art full-field measurement via Digital Image Correlation (DIC) can be used to not only simplify the approach in constitutive parameter identification but also to automate and speed up the process in general. Furthermore, the authors believe that a more accurate description of the yield locus should be possible since the transient development of the deformation gradient is known for every measured local material point. For this purpose a concept to compare transient but scalar data from the DIC measurement with the respective data from virtual tests was developed. These so-called hyper-curves represent response curves in an optimization procedure which are evaluated at multiple locations and are extracted from simulation and experimental data. In a first step, the validation of the method which is based on synthetic (i.e. simulated) data generated with the finite element solver LS-DYNA was accomplished. The generated virtual data consists of hyper-curves with the global force as ordinate value and the local true strain in transversal and longitudinal direction as abscissa value. The results of the validation show that the target hyper-curves can be mapped almost identically and thus the parameter identification using the full-field information from simulated data has proven its applicability. Furthermore, the method was applied to data gained from an experimental tensile test of high strength steel CR210IF. To digitise the transient deformation field on the surface of the specimen a gom/aramis optical measurement system (DIC) has been used. Based on the findings of the present work, it can be stated that the proposed full-field calibration (FFC) method delivers an excellent and efficient approach for the identification of the yield curve parameters. However, the identification of yield curve parameters only shows a small range of the many possibilities that the method could provide in the future. Further constitutive parameters such as those describing the anisotropy of the yield locus, i.e. values for the exponents, Lankford parameters and such, can be identified.
1. Introduction

For the simulation of forming processes for sheet metal components of cars and trucks using the finite element method (FEM) and for predicting the passive safety of vehicles in crash load cases, calibrated constitutive models of sheet metal materials are required. These constitutive models are capable of describing their mechanical deformation and failure behaviour in a predictive manner. With a more exact knowledge of this material behaviour and also with an improved parameter identification of the material models, design deficits are recognised already in early development phases of the body structure. Hence, the component production and the design may be optimised as well as the production costs lowered.

Due to the use of poorly or inaccurately identified material parameters or unsuitable material and structural models in the forming and crash simulation, the prediction quality of the simulation models does not achieve the desired quality [1]. The effort required to correct inaccurate forecasts ranges from reengineering the tools for component manufacture to revising the entire load path in crashworthiness. Experience shows that the correlating costs increase exponentially as the project progresses.

For material characterisation and calibration of existing material models, quasi-static tensile tests are usually performed at three angles (0, 45 and 90°) to the rolling direction of sheet materials. The classical method for parameter identification of yield curves is based on stress-strain curves determined in these tensile tests according to DIN EN ISO 6892-1. The state of the art procedure includes the recording and evaluation of elastic and plastic deformation in the area of uniform elongation by means of tactile or optical strain measurement. Following the classical procedure, a fixed reference length (see figure 1), which is located within a zone of the homogeneous, uniaxial stress state in the specimen loading direction, is defined for the evaluation of the digitised distortion images. Furthermore, this reference length is used to determine the technical stress-strain curve. In figure 1 it can be seen that the choice of the reference length provides different engineering stress-strain curves. Clearly this reference length can be reduced to the smallest optically detectable sample size in the strain measurement. Yield curve extrapolation is typically done by using established extrapolation approaches (e.g. according to Gosh, Swift, Voce or Hockett-Sherby etc.)[2][3][4][5]. The accuracy of parameterised extrapolation approaches may be further improved with the help of numerical optimisation.

![Figure 1. Influence of the reference length on engineering strains.](image)

At present the use of DIC merely imitates the classical method of yield curve identification. Hence, a large part of the recorded data remains unused. However, the transient strain information required for material characterisation is actually available within the entire evaluation area of the camera image and could as well be used for a comprehensive new calibration strategy (figure 2).

The identification of the yield curve parameters w.r.t. the experimentally determined technical (engineering) stress-strain curve which, after further transformation assuming isochoric yield, is
typically carried out by means of optimisation methods [6][7]. However, only the technical strain curve is included in the associated metric, which, as already shown, depends decisively on the choice of the specific reference length of the tensile test. The local deformation behaviour of the material into the unstable range, which is especially relevant for the production of complex components, e.g. with sharp radii, design edges, in multiple curved component areas, or also in crashworthiness simulation, is typically approximated. This inaccuracy in modelling the material deformation behaviour, which is unavoidable at present also due to the procedures defined in the ISO standard, may be significantly reduced by the proposed use of optical deformation measurement systems to identify yield curve and yield location parameters. Alternative approaches which allow the parameter identification of yield curves on DIC’s base are, for example, known from [8].

2. An overview of the methodology

In figure 2 an overview of the methodology is given. As described in the previous section, it is based on the experimental tensile tests and its optical evaluation by the DIC system and also on the simulation of the tensile test strain field which is computed and evaluated with a finite element solver.

The optimisation procedure was carried out using the software LS-OPT, which is enhanced to enable the handling of so-called hyper-curves which are extracted from simulation runs on the one hand and the optical measurement data of the experiments on the other hand. Both, in the validation of the method and in the optimisation using experimental tests, the target data consists of hyper-curves, that represent the global force on the ordinate and the local true strain in transversal and longitudinal direction on the abscissae. As optimisation variables the parameters of a Hockett-Sherby yield curve extrapolation are selected. The variables of the Hockett-Sherby extrapolation are iterated until the optimisation objective, a similar strain field w.r.t. spatial and transient evolution, is achieved [9].

![Figure 2. Overview of the methodology.](image)

2.1. Yield curve extrapolation

The numerical simulation is based on an anisotropic constitutive model with a Barlat yield criterion (MAT_3-PARAMETER_BARLAT or MAT_36 in LS-DYNA). For the calculation of the yield curve, the elastic part of the technical stress vs. strain curve is subtracted. Thus, the technical stresses and strains can be converted directly into the true (Cauchy) stress and plastic (logarithmic) strain up to the point of uniform elongation due to the homogeneous uniaxial stress state:

$$\sigma_y = \sigma_{y\text{text}} \left(1 + \varepsilon_{y\text{text}}\right) \quad \text{and} \quad \varepsilon_{pl} = \ln \left(1 + \varepsilon_{y\text{text}}\right) - \frac{\sigma_{y\text{text}}}{E}$$

(1)
Beyond the point of uniform elongation the extrapolation of the yield curve follows the approach of Hockett and Sherby:

\[ \sigma_y(\varepsilon_{pl}) = A - B \exp^{-c \varepsilon_{pl}} \]  

(2)

Due to the requirement of C1-continuity in the transition from uniform to non-uniform elongation, the Hockett-Sherby equation is being reduced by two parameters, namely \( A \) and \( B \) [5].

The remaining parameters \( c \) and \( n \) furthermore serve as optimisation variables in the numerical procedure controlled via LS-OPT [9]. The creation of the yield curve is shown schematically in figure 3. The blue curve is an example of a typical engineering stress vs. strain curve from an experimental tensile test. The black curves above show the resulting yield curve with various shapes of the extrapolation. The figure illustrates the removal of the elastic portion (1), the conversion of the stresses below uniform elongation and then, the extrapolation with the aid of the Hockett-Sherby approach [9].

![Figure 3. Relationship between the engineering stress-strain curve and the yield curve with an enhanced extrapolation approach.](image)

By following this approach, the shape of the yield surface and the flow rule are regarded as sufficiently close approximated w.r.t. the real constitutive behaviour. Hence, only the two remaining Hockett-Sherby parameters \( c \) and \( n \) are regarded as free parameters to be found. In a broader sense this leads to the conclusion that the model which is set up shall contain enough degrees of freedom within its spatial and physical representation of the problem to find a suitable set of parameters that allows correlation with the experiment. In turn, one could conclude that, for example, an approach with an isotropic constitutive model may be insufficient for a material with orthotropic behaviour. And it is obvious that an optimisation procedure may not necessarily deliver a convergent result in this case. Consequently, one has to make sure that the applied model (spatial discretisation and constitutive representation) incorporates the correct dimensions and size of the design space in order to enable a successful optimisation [9].

3. Validation of the method

For the validation of the full-field calibration method a problem based on synthetic test data was constructed. The curves are generated by using a fixed value of 0.5 for the parameter \( n \) and 0.0575 for the parameter \( c \) in the Hockett-Sherby extrapolation approach mentioned above. With this fixed value, three simulations with different angles w.r.t. the rolling direction are performed. The validation of the method is done with a subset of the specimen (figure 4-b).

For the optimisation procedure, the parameters \( c \) and \( n \) of the Hockett-Sherby extrapolation served as optimisation variables. The optimisation goal is chosen to recover the target curves from a different starting point to get the minimal distance of the similarity measure named Partial Curve Mapping (PCM) which describes the correspondence of the calculated nodes and the measured points in each evaluated deformation state [11]. The optimization is conducted using the metamodel-based optimization algorithm of LS-OPT with a Feedforward Neural Network (FFNN). The multi-layer FFNN is one of the
most common neural architectures used for approximating functions. It has a layered topology in the sense that its processing units (‘neurons’) are divided into several groups (‘layers’), the outputs of each layer of neurons being the inputs to the next layer. In a Feedforward network, each neuron performs a biased weighted sum of their inputs and passes this value through a transfer (activation) function to produce the output. Activation function of intermediate (‘hidden’) layers is generally a sigmoidal function. The Generalised Cross Validation (GCV) is used as selection criterion to estimate the appropriateness of the model [10].

In figure 4-a, the results of the optimisation are shown for zero degree to rolling direction. In the diagram on the left the global force on the ordinate and the local true strain in transversal and longitudinal direction are displayed. The black and orange curves, consisting of individual points, are the target curves. The blue curves show the results of the simulation after the initial run with random starting values for the parameters $c$ and $n$ of the Hockett-Sherby extrapolation. The final run, after 20 iterations, is represented in red. Since this problem consists of only two variables, the corresponding distance function can be displayed in three dimensions as illustrated in figure 4-c. The 3D view shows how well the individual combinations of the parameters $c$ and $n$ approach the optimization target. A lower value represents a better correlation. The meta-model in figure 4-c demonstrates that the example is significantly unstable, depicted by a deep, but relatively flat valley roughly connecting $[c, n] = [0.01, 0.5]$ with $[0.75, 1.0]$. The orange cross marks the combination of the parameters $c$ and $n$ with which the target curves were generated. The red cross shows the resulting combination of the parameters after the optimisation with the FFNN. The results indicate that all factor combinations within this valley lead to a good representation of the target curves and that there is no unique solution with these optimisation settings. To obtain the exact solution and to escape local minima, the convergence criteria can be adjusted. For this purpose, either the number of iterations (15 in this example) can be increased or the target residuum can be minimised. The results of the optimisation coincide with the results of a validation of the FFC method based on simple J2-plasticity [12].

![Figure 4. a) Hyper-curves of the synthetic data (black/orange) and the optimisation results after the initial run (blue) and the final run (red) along the rolling direction. b) FE mesh and subset of synthetic data. c) Meta-model after the optimisation with the FFNN.](image)

4. Application of the method on full-field measurement data

The FFC method, based on optical measurements from tensile tests with different angles to the rolling direction, is now applied in the context of this work. The optimisation is performed within a similar framework as shown in the validation above. Hence, six parameters, $c$ and $n$ for each yield curve per angle to the rolling direction, are used as optimisation variables. In addition, the parameter $m$, which represents the exponent of the yield locus, was included in the optimisation.

The principle optimisation task that has to be solved needs to focus on the correlation between the measured strain field and the numerically predicted strain field gained from a finite element simulation. A big challenge is seen in the fact that both strain fields may be based on different characteristic lengths.
While the measured field is computed from the characteristic length of the facet-point field, the numerical simulation delivers strains from the spatial finite element discretisation. Clearly, if both length scales are comparable only basic spatial interpolation is necessary.

4.1. Experimental setup
Tensile tests of high-strength steel CR210IF are carried out with an electromechanical testing machine. The displacement fields on the surface of the specimen are measured by means of non-contacting, optical grey scale correlation. For this purpose a stochastic speckle pattern is applied to the targeted domain of the specimen, photographed by two high resolution camera systems and eventually the applied deformations identified through correlation of local points in the pictures adjacent in time. Based on the identified deformation fields, subsequently, the corresponding deformation gradient and eventually local strain tensors are computed. To identify the sought parameters in a next step, local smoothing depending on the used software package is applied. However, while these technological aspects might influence the calibration procedure to some extent, its features are not the focus of this paper. For the calibration of the extended anisotropic constitutive model MAT_3-PARAMETER_BARLAT (MAT_36 in LS-DYNA) six tensile specimen of the CR210IF sheet metal at three angles (0, 45 and 90°) in the rolling direction were tested. The number of six tensile tests only serve to comply with the statistical design of experiments to identify deviations or outliers [9].

The measured r-values of the different test directions are used in the material model in order to take the anisotropy of the material into account. This approach also offers the possibility to parametrise these r-values in order to use them as optimisation variables and thereby the yield locus may also be included in future optimisation runs. The selection of the yield function parameters, i.e. r-values as well as the exponent m, is not automated and must be defined by the user. To compare the strain fields, the measured hyper-curves are imported into LS-OPT. The facet points from the optical measurement are mapped via the FE mesh to allow the comparison at identical locations. The time required for the optimisation depends on the used material model as well as the optimisation parameters and lasts between 6 and 8 hours.

4.2. Results of the optimisation
In Figure 5 the hyper-curves of the experimental target curves (black/orange) and the curves extracted from the initial run (blue) and the optimisation result (red) in the rolling direction are shown on the left. The final run reaches the force level of the target curves. However, higher strains are calculated in the simulation. This can also be observed by comparing the strain fields in longitudinal and transversal direction of the experiment and simulation (figure 5 right). Especially in the necking area the simulation reaches higher strains.

![Figure 5. Hyper-curves of the experimental target curves (black/orange) and the optimisation results after the initial run (blue) and the final run (red) on the left. Comparison of the strain field in longitudinal and transversal direction of the experiment and the simulation on the right.](image-url)
5. Investigations on a hole tensile test
Within the scope of this work, investigations are also carried out on another sample – a tensile test with a hole (Figure 6-b). Due to the shape of the specimen, compressive stresses occur around the hole in the specimen in contrast to the stresses that are typical for standard tensile tests. In the first step, the optimisation is based simply on individual points located directly at the hole in a zone with continuous plastic deformation (Figure 6-c). In this case, the force-strain curves in the x-direction served as target curves.

Figure 6. Hyper-curves of the target curves (black/orange) and the optimisation results after the initial run (blue), seven iterations (green) and 12 iterations (red).

First investigations with a constitutive model based on J2-plasticity in which the yield curve for tension according to paragraph 2.1 was used, showed that the target curves (see Figure 6-a) cannot be reproduced. Therefore, a non-symmetric elasto-plastic constitutive model is used in the further course of the investigation in which both tension and compression behaviour may be defined with separate yield curves (MAT_124 in LS-DYNA). In addition, the Hockett-Sherby yield curve extrapolation approach without modification of the stress-strain curve is used to compute the complete yield curve. The yield curve for the compressive regime is generated using a scalar factor on the tension yield curve. This factor serves as an optimisation variable also.

Figure 6-a shows the force-strain curves in longitudinal and transversal direction of the target curves and the simulations after one (blue), seven (green) and 12 (red) iterations of the optimisation. The target curves can be approximated after 12 iterations. The stress-strain curve generated with an optical extensometer with a reference length of 30 mm is also reproduced with the simulation after optimisation.

6. Conclusion
Based on the findings of the present work, it can be stated that the present FFC method is a suitable alternative for the identification of yield curve parameters. The method was validated by synthetic data from an anisotropic constitutive model based on the Barlat yield criterion. The optimisation did not provide the same parameters with which the data was generated, but the target curves could still be replicated with a sufficient accuracy.

After that, an optimisation procedure based on data from a tensile test with the sheet material CR210IF was performed. The test curves could be approximately reproduced using the FFC method. Only in the localisation area the simulation overestimates the actually occurring strains. Possible reasons...
for this deviation in the localisation area are on the one hand the discretisation of the FE model with classical 5 parameter shell elements. Hence straight fibres are assumed which deviates especially in the case of necking from the experimental measurement. Therefore a straight forward solution might be the application of a full 3D model. Another possible reason for the deviation is conspicuous when looking at the test curves. While the synthetic data are all smooth, the experimental data from the optical measurement show a large amount of noise. For the further development of the method, various filters or similarity measurements will therefore be used in upcoming test runs to smooth the noisy curves.

The optimisation example based on the holed tensile specimen gives an insight into the various application areas in which the FFC method can be used. In particular, data from areas that show non-proportional strain paths may serve as basis for such optimisation approaches.

However, limitations of the method may be found in the fact that the measurement is taken on the surface of the specimen, but the data obtained are mapped to the shell midplane. This might result in small deviations, depending on the thickness of the specimen and the ductility of the material, since the strain state at the surface differs from the strain state at the middle of the measured specimen.

7. References
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