Parameter Identification for Transmission Housings

FE Analysis of a Diecast Aluminum Alloy

In order to meet the increasing requirements in terms of the reliability of component simulations using the Finite Element Method, it is necessary to identify the material parameters of the material routine applied using several experiments with multi-axial stress states. This article describes a method for the identification of material parameters for the simulation of elasto-plastic material behaviour in the FEM for transmission housings. The method was developed further together with GM Powertrain Germany GmbH at the Chair for Applied Mechanics at the Technische Universität Kaiserslautern (Germany).

1 Introduction

In lightweight designs, diecast aluminum components are increasingly being used. The diecast process leads, however, to a comparatively high number of microstructural imperfections. This has to be considered for the design of complex components as, for instance, transmission housings. Due to the high manufacturing costs for the experimental testing of several geometry variations, component simulations are increasingly being used to secure the design.

The Finite Element Method (FEM) as a widely used simulation technique in automotive engineering, however, is only capable of predicting the mechanical behaviour sufficiently accurately if an optimal set of associated material parameters is applied. A usual process is to calculate material parameters directly from tensile tests with homogeneous stress states on standard specimens. The parameters calculated in this way are, however, often not sufficient for simulating the deformation behaviour of complex component geometries. In order to be able to simulate multi-axial stress states precisely, it is necessary to identify the parameters for inhomogeneous displacement fields [2, 3]. Therefore, a process, developed further by GM Powertrain Germany GmbH at the Chair for Applied Mechanics at the Technische Universität Kaiserslautern (Germany), is used.

Using image correlation photogrammetry, specimens with defined inhomogeneous distributions of strains are measured contactlessly. The process presented in this article for generalised parameter identification [1] allows for the consideration of the occurring scattering in repeat tests and the simultaneous consideration of many different measurement points for inhomogeneous displacement fields. The optimal set of material parameters of an elastoplastic material law in the FEM is calculated by minimising the sum of squared differences which compares the experimentally measured displacement data with simulated displacement data. The verification and validation show the very good applicability of the presented process for the diecast aluminum considered.

2 Experiment Preparation

The parameter identification is an optimisation problem with which sufficiently accurate material parameters can only be identified if both the test program in combination with a suitable specimen geometry and the measurement method provide useful experimental data for the tested material.

For the considered diecast aluminum, a specimen geometry must be chosen which is as application oriented as possible to the components to be simulated in the following and which at the same time excludes as many production-related differences in the material quality as possible. The occurrence of inclusions such as cavities, pores and micro-cracks, appearing generally in cast aluminum parts, depend strongly on the cooling rate and thus also on the wall thickness of the component. Therefore a specimen thickness similar to that of transmission housings was chosen. The slugs were produced by die-casting and have been reworked, **Figure 1**.

Since tensile stresses occur primarily in the component ‚transmission housing' and since it is known that cast materials bear considerably higher stresses under pressure than under tension, tensile tests are conducted for the following parameter identification. As mentioned above, the informational value of measured data of inhomogeneous displacement fields is generally much higher than that of homogeneous displacement fields, as they are measured on standard specimens. The inhomogeneity of the state of stress in the applied specimens is induced specifically by a hole with a diameter of 3 mm. Thereby, the location of the necking is defined as well. For the given requirements, the measurement system has to measure the very small displacements with sufficient accuracy on the one hand. On the other hand, the measurement should be conducted with an sufficient number of measurement points in the vicinity of the hole. Thereby, it can be assured that the localized and inhomogeneously distributed deformations in this area can be measured as fully as possible. A measurement system which is very suitable for these requirements is the image correlation photogrammetry, in which a black and white

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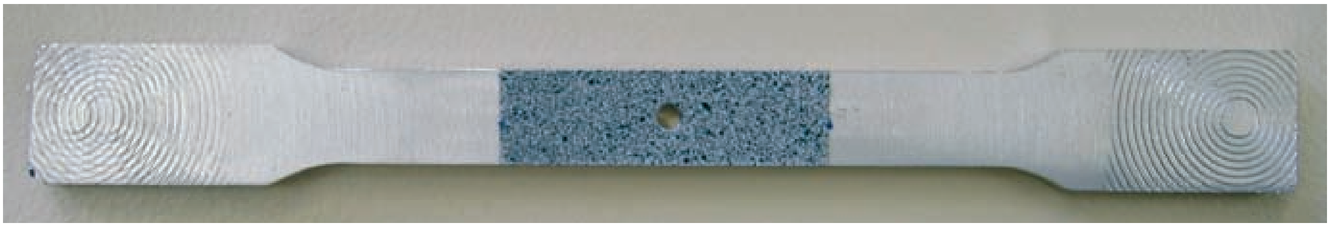

Figure 1: Specimen with stochastic pattern

stochastic pattern is applied onto the considered area on the specimen surface, Figure 1. For the measurement of the two-dimensional displacement data, a CCD camera tracks the pattern during the test, whereby images of the pattern are recorded at different load stages. After the test, the displacement fields are calculated using a photogrammetric evaluation procedure (for a detailed description of this measurement method, see for example [4]).

3 Constitutive Law

The mechanical behaviour of the considered cast aluminum alloy is simulated with ‚von Mises plasticity' with isotropic hardening and associated flow rule. For a detailed description of the constitutive law, see for example [5]. In this formulation, plastic flowing occurs if the second invariant $J_2^{dev} = \frac{1}{2}\|\sigma^{dev}\|^2$ of the deviatoric part σ^{dev} of the Cauchy stress tensor reaches the value $\frac{1}{3}\,h^2$, thus the flow function yields $\Phi = \|\sigma^{dev}\| - \sqrt{2/3h}$. The hardening law is defined by $h = y_0 + H\,\alpha + [y_\infty - y_0]\,[1 - \exp(-\,\omega\alpha)]$ with the strain-like internal variable α. The set of material parameters for the employed material law is given by $\kappa = [E, v, y_0, y_\infty, \omega, H]$. Thereby, E is the elasticity modulus, v the Poisson's ratio, H the linear hardening modulus, ω the exponential hardening modulus, y_0 the initial yield limit and y_∞ the saturated yield limit.

In 'von Mises plasticity', the three-dimensional stress state is compared with the one-dimensional yield stress h on the basis of the one-dimensional equivalent stress $\sigma_e = \sqrt{3/2}\,\|\sigma^{dev}\|$. Since measurement data of inhomogeneous displacement fields and therefore multiaxial states of stress is employed for the following parameter identification, the applicability of the 'von Mises plasticity' is checked for the simulation of the considered cast material.

4 Experiments

The experiments were conducted at room temperature. In order to avoid temperature effects due to the lighting of the specimens, two cold lights (Dedocool, 250 W Quartz Halogen ELC Type) were used. The CCD camera (Vosskühler 1300, resolution 1024 x 1280 pixels) with 50 mm lens (Schneider Kreuznach) is positioned vertically to the direction of movement in front of the specimen. The two-dimensional displacement fields are computed using the photogrammetric software Aramis.

Measured data from several experiments are used for the parameter identification of the cast aluminum alloy. For example, the procedure is represented using three specimens P83, P84, and P85 in three different tests: A (P83), B (P84) and C (P85).

In order to differentiate between the purely elastic and elasto-plastic parts of the deformation for the following identification, a test program with an (elastic) unloading is chosen for all tests. The tests are conducted in force control with a rate of 45 N/s up to a maximum force of 9000 N (maximum tensile stress per square unit of original cross section: 200 MPa). Then the specimens are unloaded with a rate of −45 N/s to 0 N. Every 5 s an image of the specimen is taken with the CCD for the displacement measurement (total number of 80 pictures per specimen). The total time for each test is 320 s. The experimental results are the force-time curves, whereby F represents the total force in the loading direction and the two-dimensional displacements of the measurement points in longitudinal (x) and transverse direction (y) on the area of the specimen's surface considered. It must be noted that the displacement data of the measurement points are relatively imprecise directly on the edge of the hole. These measurement points are discarded for the following parameter identification. Furthermore, significant measurement noise occurs in the experiments, which results from the

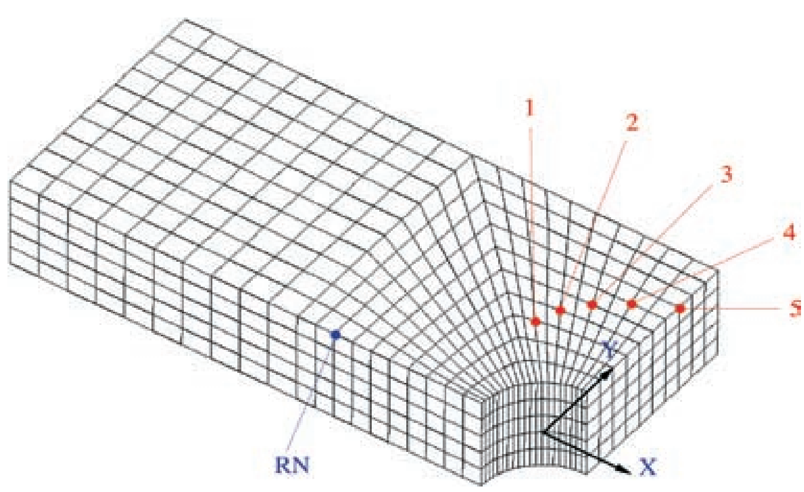

Figure 2: FEM model

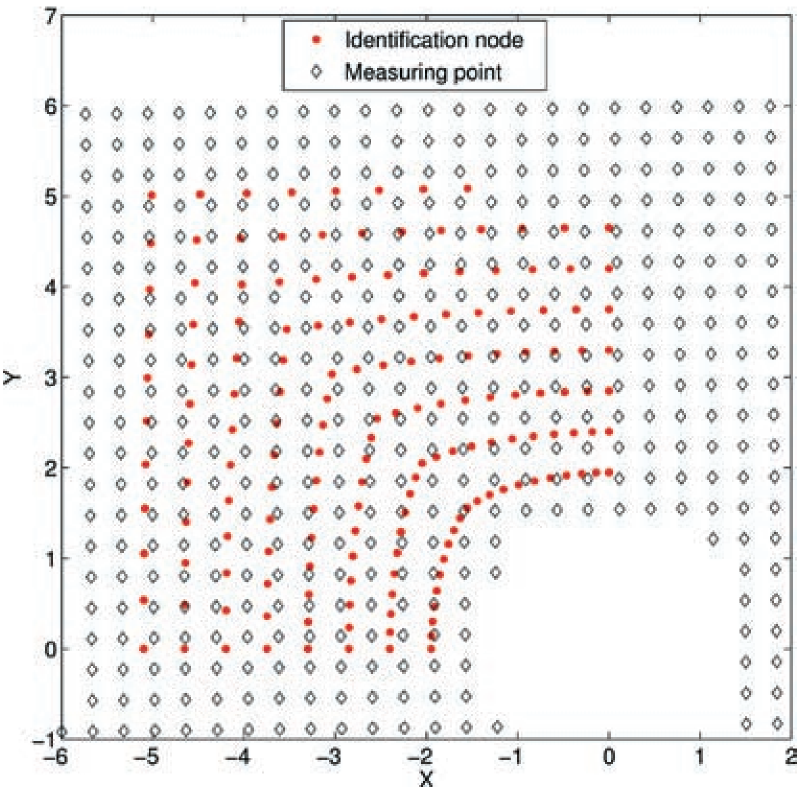

Figure 3: Interpolation of the measures displacements on the selected identification nodes for the specimen P83

very small displacements in conjunction with unavoidable uncertainties in the force control and the optic measurement technique.

The experimental data were calculated by M. Bosseler at the Institute of Resource centred Product Development under the supervision of Prof. Dr.-Ing. R. Renz, Technische Universität Kaiserslautern.

5 Parameter Identification

In the following interpolation of the experimental data, parameter identification for relative displacements and parameter identification for the combination of three tests are described in detail.

5.1 Interpolation of the Experimental Data

For the parameter identification, effects such as the slipping in the clamping and the influence of the stiffness of the testing machine have to be excluded. Therefore, the measured and simulated displacements are calculated relative to an identification node within the identification algorithm. Hereby, the measurement of the displacement field can be restricted to a section of the specimen. Furthermore, the FE model has to be discretised lengthways only until an approximately homogeneous stress state can be assumed at a sufficient distance to the hole. This procedure allows an equivalent force transmission in the FE simulation in analogy to the experiment. For the simulation of the tests, an FE discretisation of the specimen with 1500 eight-node enhanced elements (Q1E9) is used. Because of the symmetry of the geometry of the specimens, only half the width, half the length and half the thickness is discretised, **Figure 2**. In addition to the symmetry conditions, the boundary conditions for both ending planes normal to the longitudinal direction are chosen in correspondence with the experiments.

Since the coordinates of the measurement points generally do not coincide with the coordinates of the identification nodes, the measured displacements are interpolated on the identification nodes. In order to make tests A (P83), B (P84) and C (P85) comparable, identical identification nodes are chosen for all three tests. Taking specimen P83 as an example, **Figure 3** shows the interpolation of the measured displacements to the selected identification nodes.

5.2 Parameter Identification for Relative Displacements

In order to minimise the discrepancies between the measured and simulated data, an objective function, the least squares problem, is defined. For each load step j and for all identification nodes i, the differences of the displacements to the identification node l_{rel} are formed (for I_{rel} let $i = i_r$). Therefore, at load step j the relative displacements for the FE calculation are $\bar{u}_{i_r j}(\kappa) - \bar{u}_{ij}(\kappa)$, and for the interpolated measured displacement they are $\bar{u}^{exp}_{i_r j} - \bar{u}^{exp}_{ij}$. Thus the following least-squares approach is applied for parameter identification for a single test:

$$f(\kappa) = \frac{1}{2}\sum_{i=1}^{T}\sum_{j=1}^{N}\left[\left[\bar{u}_{i_r j}(\kappa) - \bar{u}_{ij}(\kappa)\right] - \left[\bar{u}^{exp}_{i_r j} - \bar{u}^{exp}_{ij}\right]\right]^2 \quad \text{Eq. (1)}$$

5.3 Parameter Identification for the Combination of Three Tests

As described above, the casting process leads to inevitable material inhomogeneities and thus to scattering of experimental data which has to be considered. The following approach allows identification with which a non-linear averaging of the single parameter set κ is determined using measurement data of three experiments: Analogously to equation (1), the objective function with displacements relative to the identification node I_{rel} is formed, Figure 2 (RN). Tests A (P83), B (P84) and C (P85) are considered simultaneously within the iteration algorithm:

$$f^{ABC}(\kappa) = \quad \text{Eq. (2)}$$

$$\frac{1}{2}\sum_{i=1}^{N_g}\Bigg(\underbrace{\sum_{j=1}^{T_A}\left[\left[\bar{u}_{i_r j}(\kappa) - \bar{u}_{ij}(\kappa)\right] - \left[\bar{u}^{exp}_{i_r j} - \bar{u}^{exp}_{ij}\right]\right]^2}_{A(P83)}$$

$$+ \underbrace{\sum_{k=1}^{T_B}\left[\left[\bar{u}_{i_r k}(\kappa) - \bar{u}_{ik}(\kappa)\right] - \left[\bar{u}^{exp}_{i_r k} - \bar{u}^{exp}_{ik}\right]\right]^2}_{B(P84)}$$

$$+ \underbrace{\sum_{l=1}^{T_C}\left[\left[\bar{u}_{i_r l}(\kappa) - \bar{u}_{il}(\kappa)\right] - \left[\bar{u}^{exp}_{i_r l} - \bar{u}^{exp}_{il}\right]\right]^2}_{C(P85)}\Bigg).$$

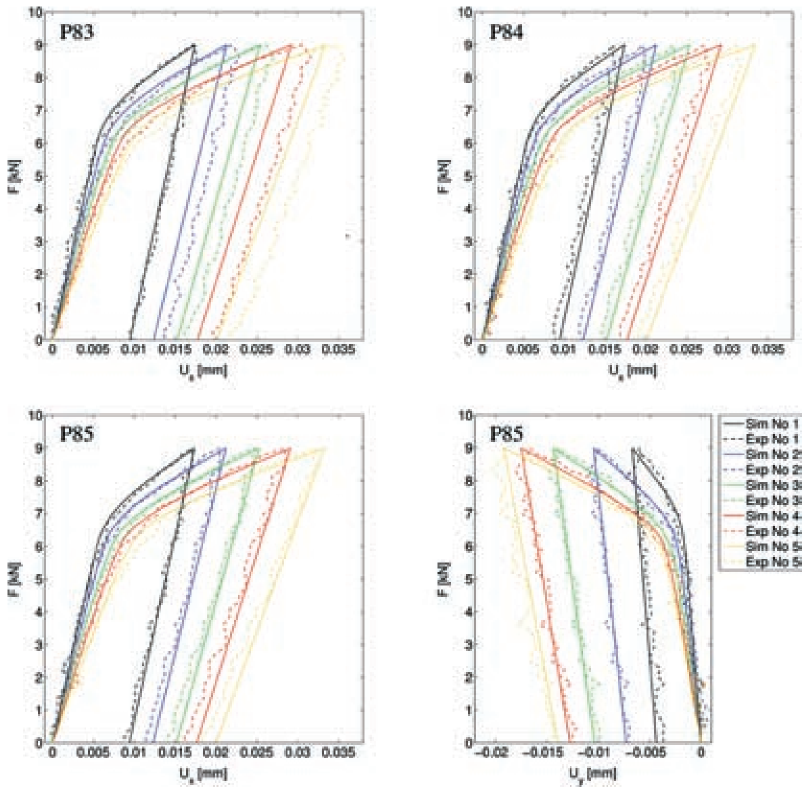

Figure 4: Verification

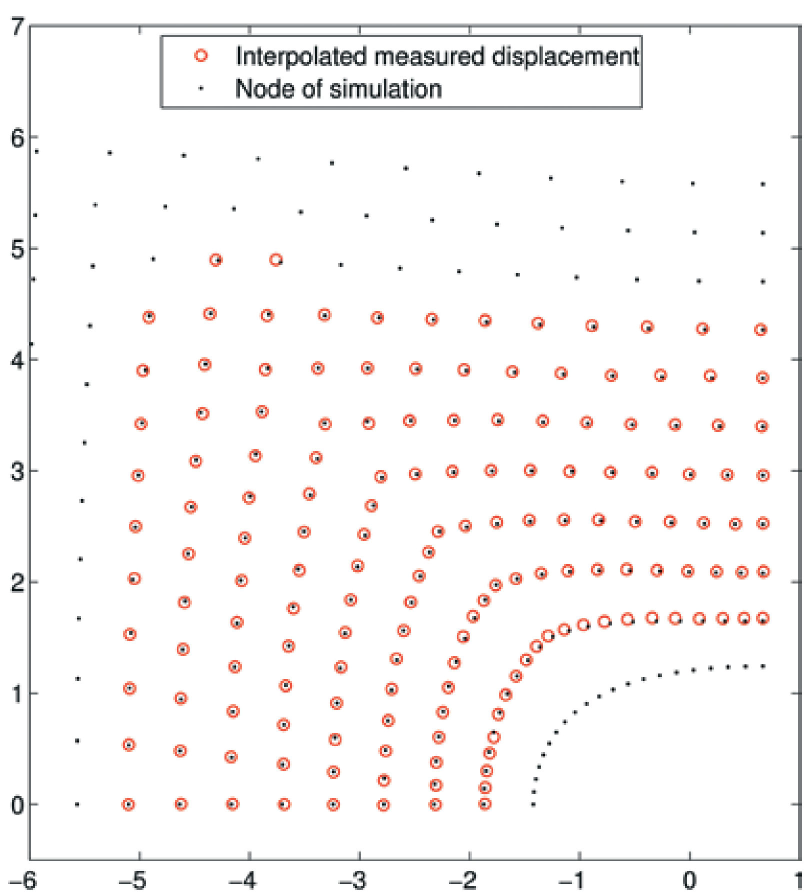

Figure 5: Verification for test C (P85) for load step 40; the displacements have been scaled by a factor of 20 for this representation

All three tests have an equal number of load steps $T_A = T_B = T_C = 80$ and equal numbers of identification nodes $N_g = 159$. The simulation of the displacement fields $\bar{u}_{ij}(\kappa)$,$\bar{u}_{ik}(\kappa)$ and $\bar{u}_{il}(\kappa)$ of the three tests the FEM simulation is force controlled with the measured forces of the associated real experiments (see section 4). The aforementioned least squares problem is solved using the Levenberg-Marquardt optimisation algorithm, whereby a (local) minimum of the objective function is sought for different start parameter sets. The smallest of all tested (local) minima is $\kappa = \kappa_{\mathrm{Im}_{ABC}}$.

It must be noted that the number of terms in the least squares sum totals 76,320 per iteration step of the optimisation algorithm: In the objective function, for 159 identification nodes for three tests each with 80 load steps, the measured and simulated displacements go in two directions.

6 Verification and Validation

In the following the topics verification and validation, as a final step, are discussed more in detail.

6.1 Verification

In the verification, the simulated data – calculated as based on the identified parameter set $\kappa = \kappa_{\mathrm{Im}_{ABC}}$ – are compared with the experimental data. In diagrams in **Figure 4**, the force is represented versus the relative displacements for the tests A (P83), B (P84) and C (P85), whereby the curves shown each refer to the identification nodes 1 - 5 marked in Figure 2. U_x and U_y are the relative displacements in longitudinal and transverse direction. **Figure 5** shows the verification for all identification nodes for test C at load step 40. For a clearer representation, the interpolated experimental and simulated displacements have been scaled here by a factor of 20.

The verifications show that the material law is suitable for simulating the mechanical behaviour of the considered cast material sufficiently precisely in terms of quality and quantity. The calculated inhomogeneous displacements in the vicinity of the hole, which result from the multi-axial stress state, are in good agreement with the respective ex-

Table: Comparison of the sum of squared differences f for the solutions of the individual identifications (κ_{Im_A}, κ_{Im_B}, κ_{Im_C}) and the combined identification ($\kappa_{Im_{ABC}}$)

$f^{ABC}(\kappa_{Im_{ABC}})$ [mm²]	$f^{A}(\kappa_{Im_A})$ [mm²]	$f^{B}(\kappa_{Im_B})$ [mm²]	$f^{C}(\kappa_{Im_C})$ [mm²]
0.0530473	0.0121345	0.0154719	0.00753172

perimentally determined displacements. Furthermore, it can be observed that the local minimisation of the least squares functional provides a parameter set which enables to fit the simulations to the respective experiments in an average way. Thus this procedure is suitable for considering the scattering of experimental data.

For the three tests A, B and C, individual parameter identifications were performed which yield the parameter sets $\kappa = \kappa_{Im_A}$, $\kappa = \kappa_{Im_B}$ and $\kappa = \kappa_{Im_C}$, respectively. As expected, since the parameters did not have to be averaged for three tests, a better agreement between experimentally determined and simulated displacements can be observed here. The **Table** shows the comparison of the sum of squared differences for the respective identifications. The parameter set $\kappa = \kappa_{Im_{ABC}}$ calculated for all three tests results in an average sum of squared differences of $ø^{comb}_{ABC} = f^{ABC}(\kappa_{Im_{ABC}})/3 = 0.0176824$ mm² per test. The average sum of squared differences for the individual identifications yields $ø^{ind}_{ABC} = [f^{A}(\kappa_{Im_A}) + f^{B}(\kappa_{Im_B}) + f^{C}(\kappa_{Im_C})]/3 = 0.0117127$ mm². Thus there is an average reduction in the sum of squared differences between the individual and combined parameter identification of $\Delta f = 100\ [ø^{comb}_{ABC} - ø^{ind}_{ABC}]/ ø^{comb}_{ABC} = 66,24\ \%$.

6.2 Validation

As a final step, the identified parameter set $\kappa = \kappa_{Im_{ABC}}$ is validated. The experimental data applied for validation and for parameter identification must be independent from each other. In order to fulfil this requirement, additional tensile tests are conducted on specimens, which differ in terms of geometry from the specimens used for parameter identification. Therefore specimens without a hole are employed, Figure 1. In an idealised homogeneous material, this geometry under tensile load would induce an almost homogeneous stress state in the area of the measured field. The scattering of strains in the longitudinal direction ε_{xx} for different measurement points as a result of the material inhomogeneities of the examined cast aluminum are averaged for the validation, **Figure 6**. A good agreement can be found between the stress-stretch curves measured and simulated using the parameter set $\kappa = \kappa_{Im_{ABC}}$.

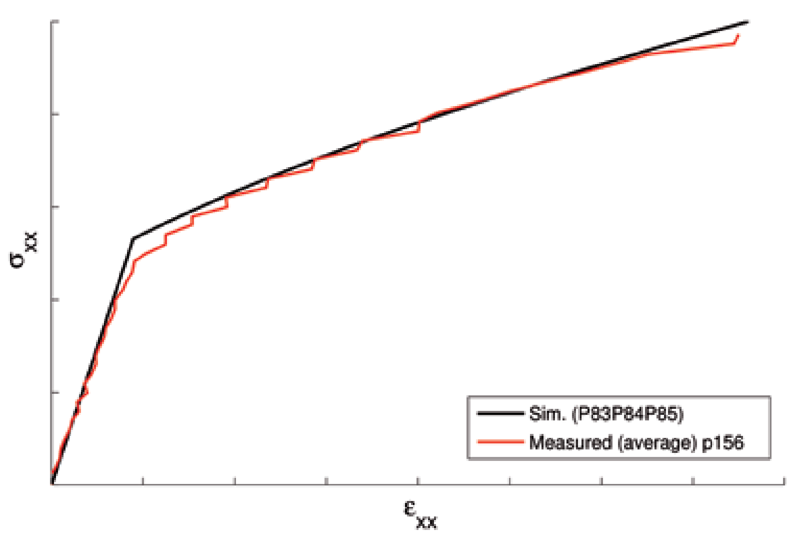

Figure 6: Validation

7 Summary

The Finite Element Method can only predict the mechanical behaviour of components accurately if a suitable constitutive law is applied and the associated material parameters are known for the considered material. In this work by GM Powertrain Germany GmbH and Chair for Applied Mechanics at the Technische Universität Kaiserslautern (Germany), the material parameters of 'von Mises plasticity' have been identified for a cast aluminium using inhomogeneous displacement fields, whereby the data from several tests were applied. By means of verification and validation, a very good agreement of tests and simulation could be proven for the transmission housing.

As a result, various current uncertainties could be resolved: On the one hand, it has been shown that the 'von Mises plasticity' can simulate multi-axial stress states for this material sufficiently precisely despite using the one-dimensional equivalent stress and hardening within the flow rule. On the other hand it became obvious that the method used can average the material parameters non-linearly for several tests. Both aspects lead to a considerable improvement of the reliability of the parameter set and therefore also of the simulation of complex components made of this cast aluminium alloy.

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