MECHANICS AND CONTROL
Vol. 30 No. 1 2011

Mariusz WARZECHA*, Andrzej MŁYNIEC*, Tadeusz UHL*

PREDICTION OF THE PLASTIC COMPONENT PARTS DURABILITY WITH USE OF A DROP TEST SIMULATION

SUMMARY

This paper describes the method of performance of a drop test simulation for elements made of polymeric materials. Possible to use material models were described and material model choices were shown. Material tests needed to obtain material model parameters were presented and the results of analysis and measurement data were shown. As an example a drop test of the housing of a car electrical box made of Polypropylene with 20% Talc filler (PPTD20), have been simulated in ABAQUS/Explicit and results have been compared with data registered by a video camera system during the real drop test of this housing.

***Keywords**: drop test, nonlinear rate dependent elastic-plastic material model, FEA*

PRZEWIDYWANIE TRWAŁOŚCI PRODUKTÓW Z TWORZYW SZTUCZNYCH Z UŻYCIEM SYMULACJI TESTU ZRZUCANIA

W poniższej publikacji opisana jest metoda wykonywania symulacji testu zrzucania dla elementów wykonanych z materiałów polimerowych. Przedstawione zostały możliwe do użycia modele materiałowe wraz z modelem użytym w symulacji. Ukazane zostały także testy materiałowe konieczne do uzyskania parametrów modelu wraz z wynikami pomiarów. Jako przykład, zamodelowany został test zrzucania obudowy skrzynki bezpiecznikowej samochodu, wykonanej z Polipropylenu z 20% dodatkiem talku. Wyniki symulacji zostały porównane ze zdjęciami wykonanymi za pomocą systemu wizyjnego, podczas rzeczywistej próby zrzucania obudowy skrzynki bezpiecznikowej.

***Słowa kluczowe**: test zrzucania, nieliniowy zależny od prędkości sprężysto-plastyczny model materiałowy, MES*

1. INTRODUCTION

A drop-test is often performed for products used in the automotive industry, especially for those made of polymeric materials, which are vulnerable to drop during the assembly process. They are used in cockpit modules, engine parts, bumpers, electrical housings etc. Using numerical simulations for analysing the effects of a drop-test can reduce the number of prototypes and development time. Thus, time and development cost can be reduced and products can be more competitive on the market.

2. PROPERTIES OF POLYMER MATERIALS

Generally engineering plastic materials can be extensively deformed and yielding and plastic flow occurs before failure. At small strains observed behaviour is predominantly linear elastic. Where more precise results are demanded, viscoelastic behaviour, which implies curvature in stress/strain relationship, have to be included. Plastic materials exhibit stress/strain rate dependent behaviour also. Thus, stress/strain curves are different for different deformation rates. Depending on simulation specifics, appropriate material properties sets have to be created. Those that are possible to use in a drop test simulation engineering plastics properties are described below.

2.1. Elastic properties

Elastic behaviour assumes linear stress/strain dependency. It can be used to calculate stress and strain distributions at low strains. It is usually described by two values: tensile modulus E and the elastic Poisson's ratio υ_e. It is generally more accurate to measure properties using tensile tests (Dean and Crocker 2005).

2.2. Plastic properties

The effect of strain hardening, which causes subsequent increases in stress with strain, is described by plastic behaviour. It occurs when the stress level called the first yield stress is exceeded. Plastic behaviour is not described by a set of parameters but most commonly by a relation between tensile yield stress σ_T and plastic strain ε_T^p (Ward and Sweeney 2004). The plot showing the dependence is called tensile hardening curve.

2.3 Viscoelastic properties

The viscoelsastic theory was developed to describe polymer behaviour, when subjected to a history of stress and strain, at modest strains (less than 0.5%). It can be used for example to model energy dissipation, which occurs during cyclic loading of vibration dumper made of polymer material. The shear relaxation modulus $G(t, T_1)$ measured at some reference temperature T_1 is most commonly used to characterise viscoelastic response. Spring-damper models for example Maxwell (Fig. 1) or Kelvin-Voigt (Fig. 2) are often used to approximate the viscoelastic behaviour. Generally the idea is simple: force applied to the spring – dashpot system represents shear stress and the extension represents shear strain (Bower 2010).

* AGH University of Science and Technology, Faculty of Mechanical Engineering and Robotics, Department of Robotics and Mechatronics, al. A. Mickiewicza 30, 30-059 Krakow, Poland

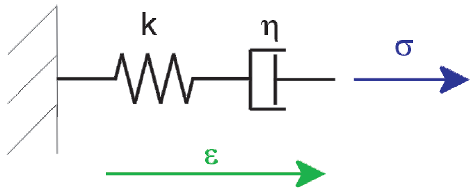

Fig. 1. Maxwell spring-damper model

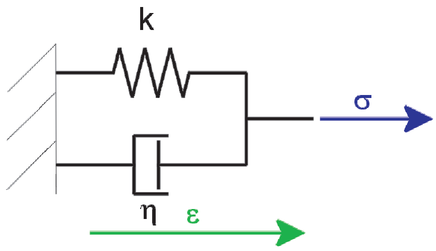

Fig. 2. Kelvin-Voigt spring-damper model

2.4. Rate dependent elastic-plastic

Elastic-plastic models combine elastic and plastic behaviour of material. In small strains the material behaviour is described by liner stress/strain relation and after exceeding the first yield stress the plastic behaviour is taken into account. Thus, in non-linear region total strain ε can be presented as a sum of a plastic component ε^p and elastic component ε^e.

Because plastic materials exhibit strain-rate dependent behaviour hardening curve for a set of different strain-rates have to be measured and elastic-plastic stress-strain curve for each strain-rate have to be created. Strain-rate dependent behaviour has to be calculated in simulations where the goal is to simulate dynamic situations such as a drop test (Dean and Crocker 2005).

2.5. Linear Drucker-Prager

The most popular and simple yield criterion is that created by Huber and von Misses. It assumes that effective shear stress σ_e is related to yield stress in tension σ_T by equation (1). Measurement data obtained during compression and shear of plastics specimens reveal that yielding is sensitive to the hydrostatic component of stress in addition to the shear component and thus equation (1) is not true for plastics (Dean and Crocker 2005).

$$\sigma_e = \sigma_T \tag{1}$$

where:
- σ_e – effective shear stress,
- σ_T – yield stress in tension.

Because equation (1) cannot predict behaviour of plastics it has to be extended to include hydrostatic stress sensitivity. It was done as follows:

$$\sigma_e + \mu\sigma_m = \frac{\mu+3}{3}\sigma_T = \sqrt{3}\sigma_S \tag{2}$$

where:
- σ_e – effective shear stress,
- σ_T – yield stress in tension,
- σ_m – hydrostatic component of stress,
- σ_S – effective shear yield stress,
- μ – hydrostatic stress sensitivity parameter.

Equation (2) is the basic equation of linear “Drucker-Prager model”. The hydrostatic component of stress σ_m can be derived from equation 4. Parameter μ can be determined from test under two different stress states. In this paper yield stress from tensile and shear test was used. Equation (3) was used to calculate a value of μ parameter.

$$\mu = 3\left(\frac{\sqrt{3}\sigma_s}{\sigma_T} - 1\right) \tag{3}$$

where:
- σ_T – yield stress in tension,
- σ_S – yield stress in shear.

$$\sigma_m = \frac{1}{3}(\sigma_1 + \sigma_2 + \sigma_3) \tag{4}$$

where: σ_1, σ_2, σ_3 – components of principal stress.

To define material model in Abaqus FEA system, the flow parameter μ' is also needed. A value for this parameter can be derived using equation (5).

$$\mu' = \frac{3\left(1 - 2\upsilon^p\right)}{2\left(1 + \upsilon^p\right)} \tag{5}$$

where:
- μ' – flow parameter,
- υ^p – plastic component of Poisson’s ratio.

The plastic component of Poisson’s ratio can be determined using equation (6).

$$\upsilon^p = -\frac{\varepsilon_t^p}{\varepsilon_T^p} \tag{6}$$

where:
- ε_t^p – true plastic transverse strain,
- ε_T^p – true plastic tensile strain.

Material model described above, can be implemented directly into Abaqus FEA system using special parameters shown in the case study (chapter 5). To capture rate dependent behaviour during simulation, it is necessary to define material data for different strain rates. Abaqus system interpolates the model for higher speeds, matching interpolation function to the data received.

3. EXPERIMENTAL EXAMINATION

The choice of the material model determines the experimental tests that have to be performed. For defining rate dependent elastic-plastic model with linear Drucker-Prager yield criterion tensile and shear test with different strain-rates are needed. Three specimen shapes were used for these tests. First shape, according to the EN-ISO 527 standard (EN-ISO 527), presented in the Figure 3 was used for determining data necessary for calculating tensile modulus E and the elastic Poisson's ratio υ_e. Figure 4 presents specimen used for tensile test with different strain rates (Dean and Crocker 2005). Geometry of specimen presented in the Figure 5, according to the ASTM D 732-02 standard (ASTM D 732-02), was used for shear test. Specimens were tested for three different strain rates: 0.001, 0.01 and 0.1 s^{-1}. a Universal material testing machine Zwick-Z20, with a video camera system was used. For the shear test a punch tool according to ASTM D 732-02 standard was used. On each specimen for tensile test white ink marks for the video camera were made. The material used in the experiments was PP TD20.

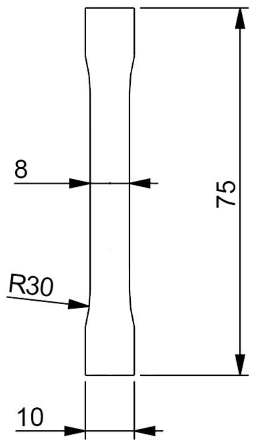

Fig. 3. Tensile specimen geometry according to EN-ISO 527

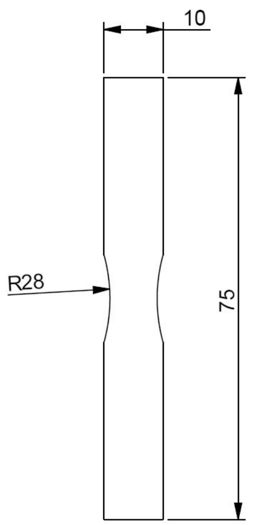

Fig. 4. Tensile specimen geometry used for test with different strain rates

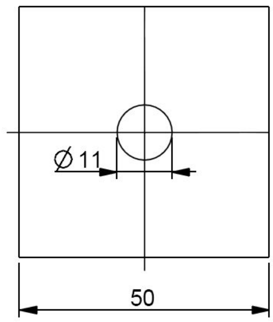

Fig. 5. Shear specimen geometry according to ASTM D 732-02

4. MATERIAL MODELLING

The choice of an appropriate material model for simulation is an important decision in which many factors have to be accounted for. Generally a material model should precisely describe material behaviour and at the same time be of simple form. For industrial needs these two factors have to be balanced. For the simulation of a drop test presented in this paper rate dependent elastic-plastic model with linear Drucker-Prager yield criterion was used. This choice was reasoned by sufficient accuracy of this model and simplicity of use due to implementation available in Abaqus FEA system.

Data registered during material testing has been analysed and values needed to define material model in Abaqus have been obtained. Using pictures created by a vision system and data from standard test machine stress-strain plots were made for each specimen. Figure 6 presents measuring points and approximation curves obtained for three test specimens with three different strain rates. Measuring points have been fitted using function:

$$\sigma_T(\varepsilon_T) = \sigma_1 e^{\varepsilon_1 \varepsilon_T} + \sigma_2 e^{\varepsilon_2 \varepsilon_T} \tag{6}$$

where:

σ_T – true tensile stress,
ε_T – true tensile strain,
$\varepsilon_1, \varepsilon_2, \sigma_1, \sigma_2$ – function parameters.

Fitted functions have been used to approximate material behaviour under bigger strain-rates. The least square method was used to curve fitting. All hardening curves have been presented in the Figure 7. It is characteristic for polymer materials that yield strength increases with strain rate. This behaviour is pictured in the Figure 7, which allow the assumption that material tests and approximations are correct. Tensile data has been used for calculating tensile modulus E and the elastic Poisson's ratio υ_e. Hydrostatic stress sensitivity parameter μ have been calculated using shear and tensile data (equation (3) has been used). Flow parameter μ' have been calculated using the plastic component of Poisson's ratio (equation (5) has been used).

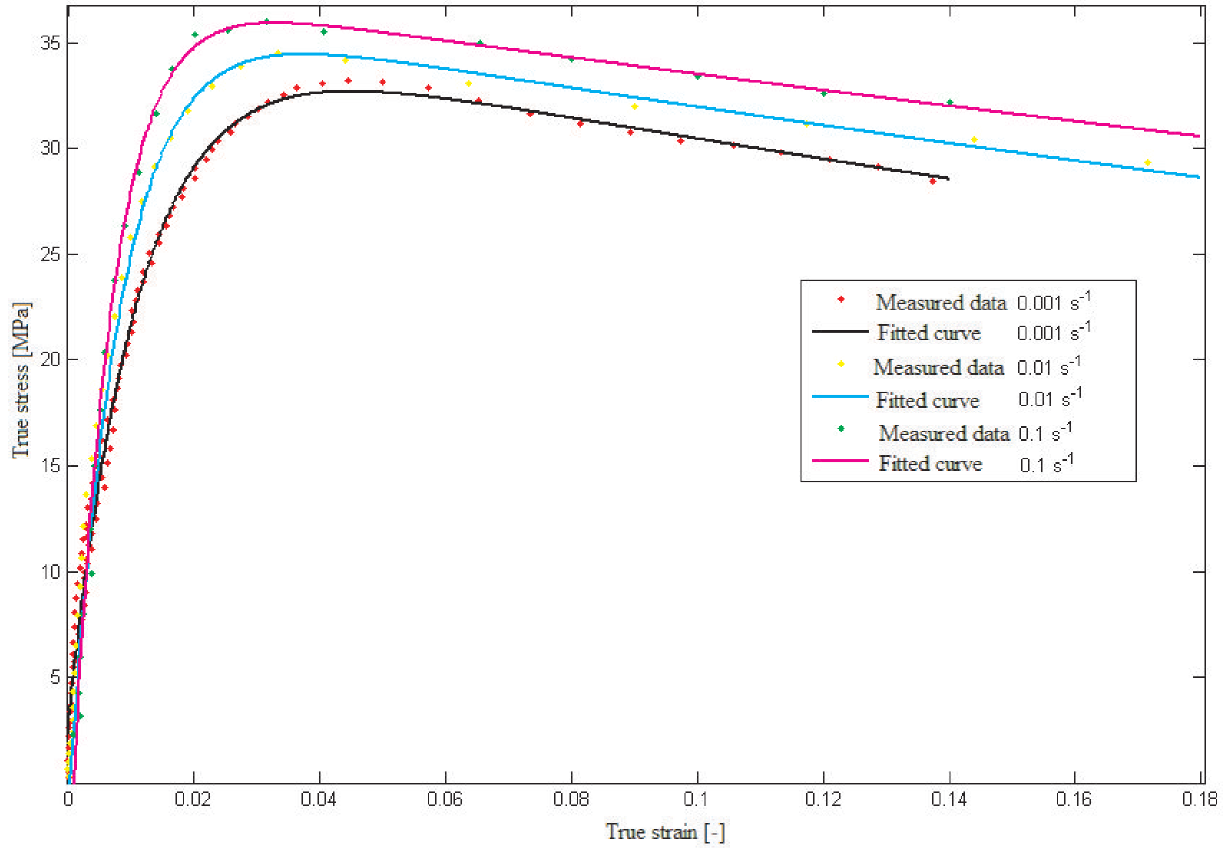

Fig. 6. Tensile measure data with fitted hardening curves

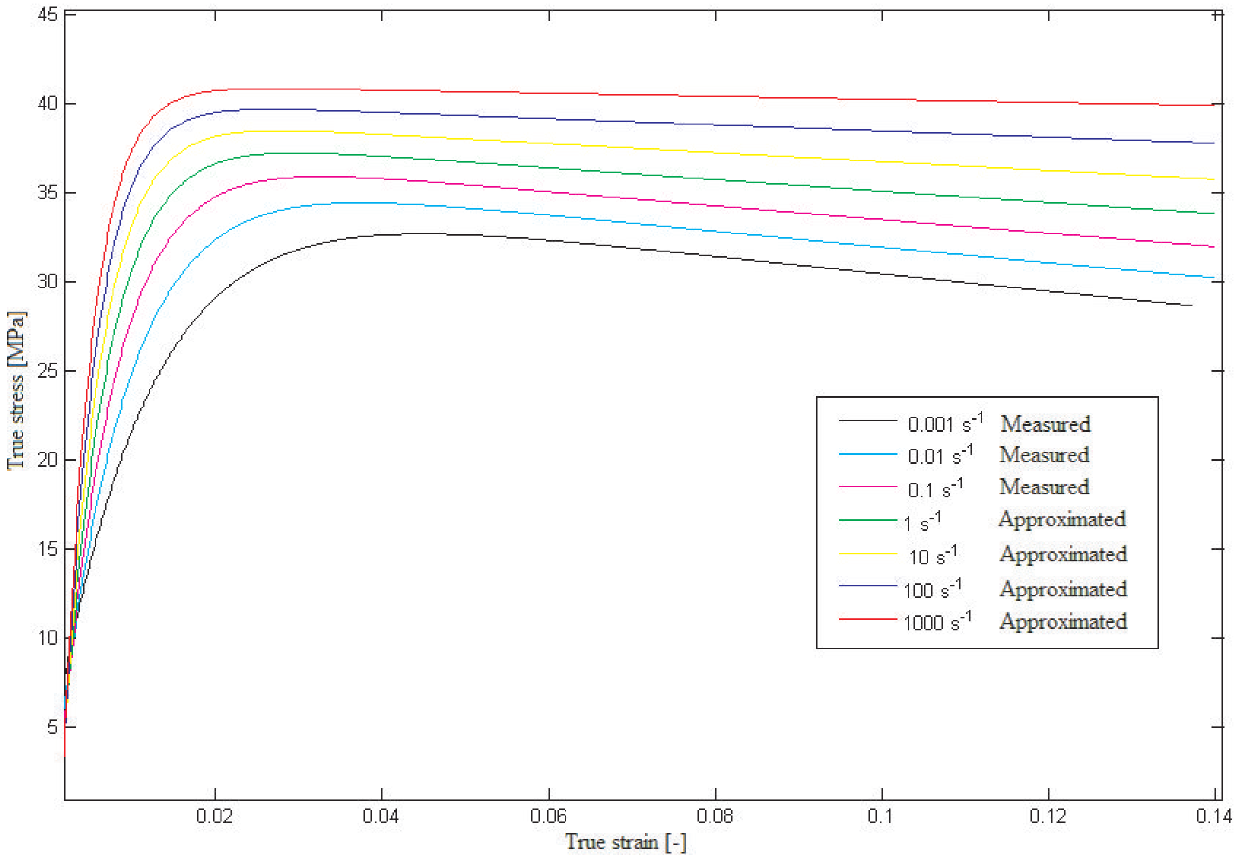

Fig. 7. Approximated hardening curves

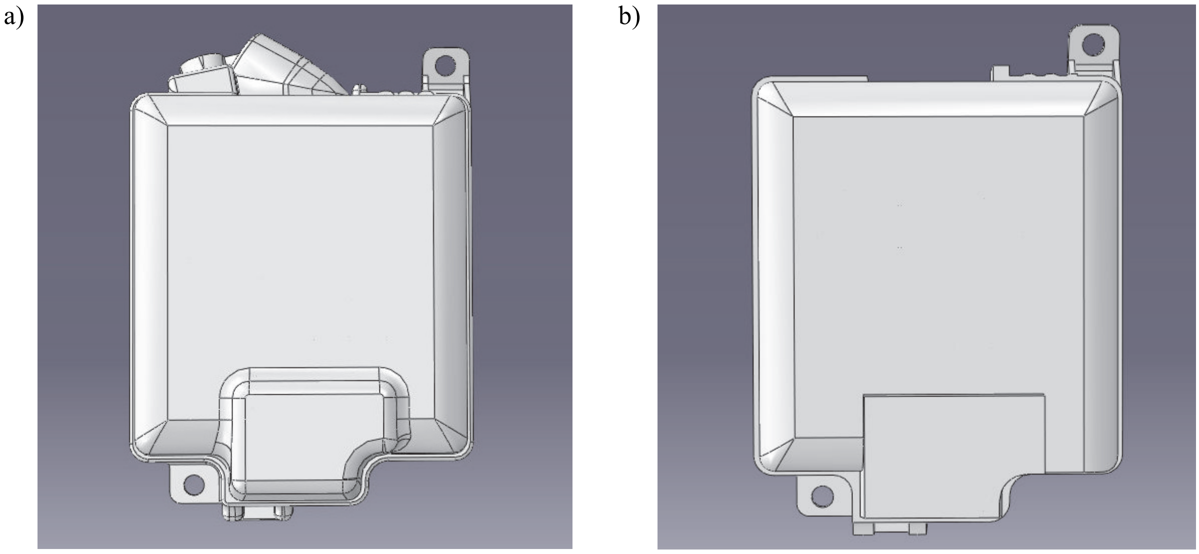

Fig. 8. 3D model of housing of car electrical elements: a) original and b) simplified geometry

5. CASE STUDY

The 3D model of the housing of car electrical elements used for simulation was presented in the Figure 8a. Because not all features of the geometry have an impact into analysis results, the 3D model was simplified and then imported to Abaqus/CAE. Geometry after importing was presented in the Figure 8b.

Parameters determined from test data were used to create a material model within the FE system. In Abaqus system, Drucker-Prager material model is defined using the angle of friction β, dilatation angle ψ, flow stress ratio K and hardening curves for different strain rates. The angle of friction can be derived using equation (7).

$$\beta = \arctan \mu \tag{7}$$

where:
- β – angle of friction,
- μ – hydrostatic stress sensitivity parameter.

Dilatation angle can be derived using equation (8).

$$\psi = \arctan \mu' \tag{8}$$

where:
- ψ – dilatation angle,
- μ' – flow parameter.

The third parameter required by Abaqus is Flow stress ratio which describes differences in material behaviour under tension and compression. This parameter used for the material model has been set to 1 which implicates comparable behaviour under tension and compression. Points coordinates describing hardening curves were exported to a text file and then used in a created material model. Abaqus uses these curves to approximate material behaviour under all strain rates, which occur in simulation. Other simulation parts including rigid contact surface, boundary conditions and meshing were defined, and simulations at different falling directions were performed. The strike surface has been modelled as a rigid surface with all degrees of freedom set to zero. The model of the housing has been positioned with regard to created rigid surface so, that the distance between this surface and the nearest point of housing was 0.01 mm. Initial velocity has been specified for the housing. This velocity has been calculated using the measured mass of housing and the initial distance to the strike surface. Figures 9 and 10 present the results of simulation and a real drop test in which the housing drops at one of the handles. Because the failure model was not implemented in simulation, the handle is not snapped off. Plastic strain analysis showed that the handle should break at places pointed to by the arrows. Comparison with real test results has shown that the simulation gives acceptable results.

Figures 11 and 12 present results of a simulation and a real drop test at one of the housings corners. In this situation in a real test only elastic deformation occurs. Characteristic shape deformations were pointed out by arrows in each of the presented figures. Comparison of this region shows that the simulation described clearly the component deformation under impact loading.

Fast FEA result achievement allows us to calculate several iterations to optimize part geometry without expensive mould changes. A presented comparison yields the conclusion that the Drucker-Prager material model, previously created for metal parts analysis, is good for fast and effective drop test modelling, although it should be complemented by the influence of void formation and failure which play preponderant roles in the plastic parts destruction.

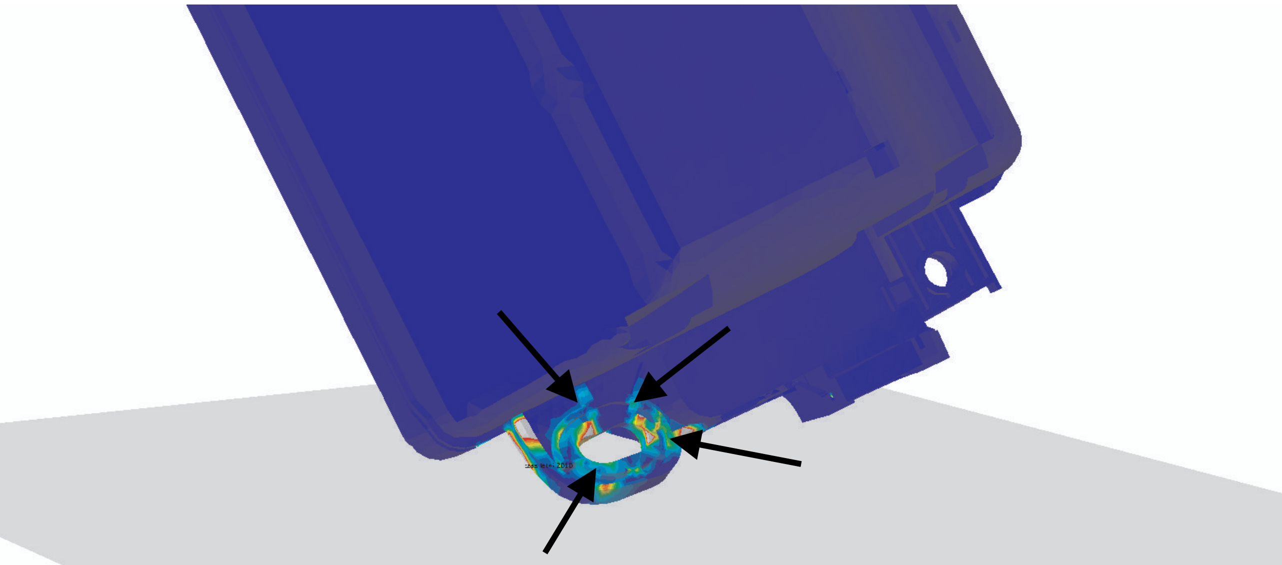

Fig. 9. Simulation results – strike of the housing handle

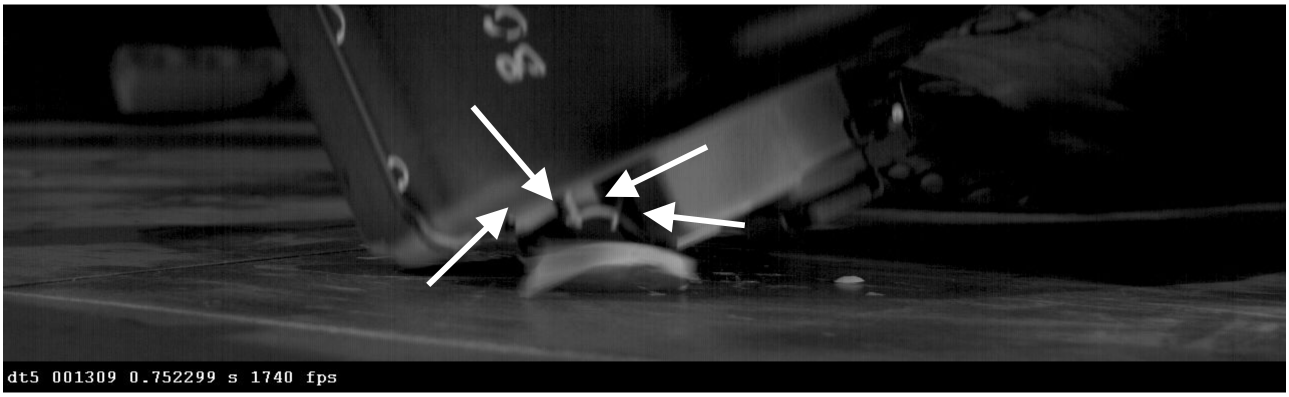

Fig. 10. Real test results – snapping off of the housing handle

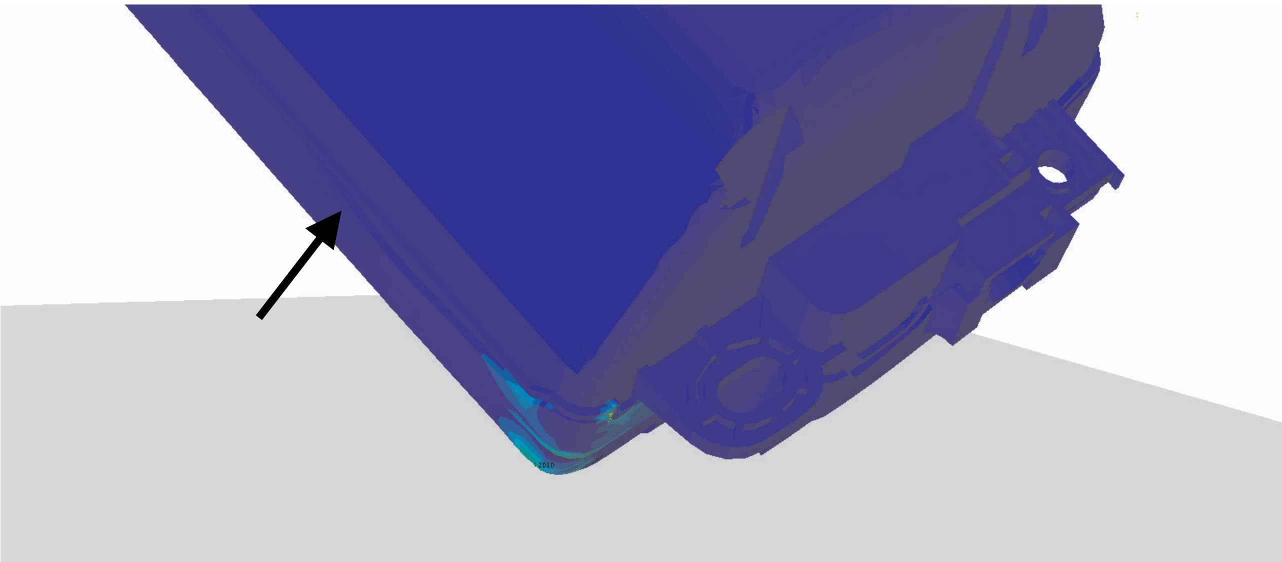

Fig. 11. Simulation results – corner drop

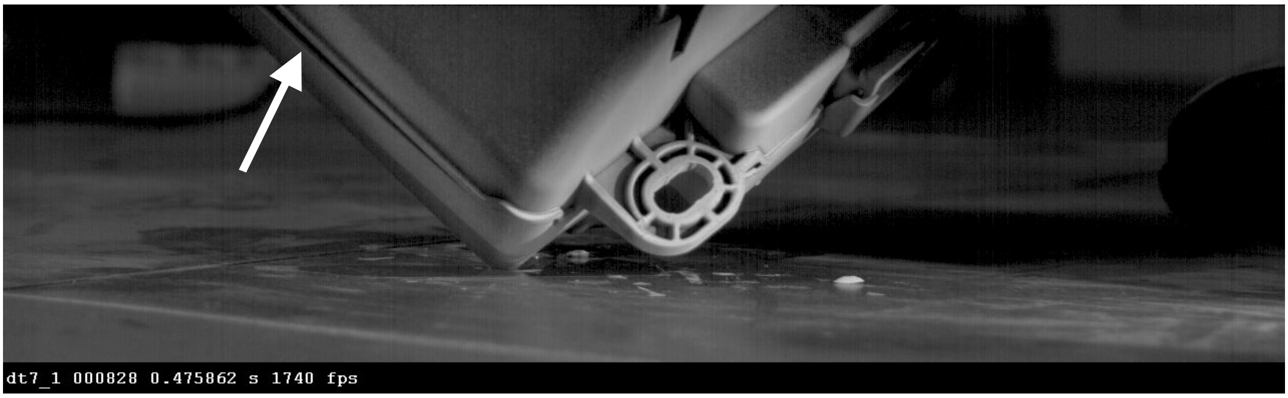

Fig. 12. Real test results – corner drop

6. CONCLUSIONS

Performed simulations have shown, that a real drop test of plastic parts can be easily replaced with a numerical simulation. A presented computation method can be performed without problems in industrial conditions and can be used in a relatively short time. Simple tensile tests with different strain rates and shear tests are sufficient to create a rate dependent elastic-plastic material model, which can be used in the modelling process of arbitrary shape impact analysis. The presented material model can be complemented by failure criteria, which should further increase the accuracy at calculations.

Acknowledgments

Authors would like to acknowledge the Delphi TCK E/EA team for sample providing and all their technical assistance.

References

Abaqus user's manual ver. 6.9, Dessault Systems, Simulia 2009.

ASTM D 732-02, Standard Tests Method for Shear Strength of Plastics by Punch Tool.

Belayachi N., Benseddiq N., Nait-Abdelaziz M., Hamdi A. 2008, *On cavitation and macroscopic behavior of amorphous polymer-ruber blends*. Science and Technology of Advanced Materials 9.

Dean G., Crocker L. 2005, *Prediction of the impact performance of plastics using Finite Element Methods*. NLP Laboratory.

EN-ISO 527 1993, *Plastics – Determination of Tensile Properties*

Gholami T., Lescheticky J., Paβmann 2003, *Crashworthiness simulati on of Automobiles with ABAQUS/Explicit*. ABAQUS User's Conference.

Ward I.M., Sweeney. J. 2004, *An introduction to the mechanical properties of solid polymers*. John Wiley&Sons Ltd., West Sussex.

Yeo Tae-Young, Park J. 2003, *A unified FE modeling approach to an automobile cocpit module*. ABAQUS User's Conference.

Bower F.A. 2010, *Applied Mechanics of Solids*. CRC Press.