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DEVELOPING OF PHENOMENOLOGICAL DAMAGE MODEL FOR AUTOMOTIVE LOW-CARBON STRUCTURAL STEEL FOR USING IN VALIDATION OF EURONCAP FRONTAL IMPACT

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Abstract. Results presented in this paper demonstrate the process of material models development for automotive structural steels in order to implement it into the SUV digital twin. Developed digital twin is capable to simulate vehicle crash impact in the same way as full-scale test but among of many parameters it needs correctly defined material models. One of the most difficult things to develop is failure models which simulate the behavior of real material correctly. Usually standard approach considers using only stress-strain curves for several strain rates that does not follow the requirements of advanced model of digital twin. Implementing of damage theory based GISSMO failure description into the vehicle model, especially for high strain rates, leads to achieving good correlation with full-scale crash tests. Also it helps to improve digital twin's quality and speed up overall process of vehicle developing. As a result of research this paper demonstrated the difference of simulations between usual and improved material models

Keywords: damage, GISSMO, digital twin, vehicle, crash test, triaxiality

1. Introduction. Computer simulation of car collisions with different barriers (so-called crash tests) became standard procedure in set of activities to improve passive safety of vehicle structure. Increasing requirements to complex technical systems on the one hand, and increasing computing power, on the other hand led to a "digital twin" concept in modeling based on high quality mathematical model included thousands of input parameters [1]. Digital twins can provide an opportunity of obtaining accurate information about related real objects and their behavior. Consequently, mathematical model that digital twin is based on should represent behavior of real object with acceptable accuracy, and one of the basic components of this concept is correctly defined mathematical model of material which related part is made of.

Vehicle collision is a process which includes large high-speed deformations that often leads to failure of vehicle parts. Failure changes stress-strain state of vehicle body elements and their location after impact. These facts explain that fracture should be taken into account, but modeling it according to classical mechanics approach leads to significant increase of computational efforts.

Alternative approach consists of using phenomenological damage-based failure criteria, one of which called GISSMO (acronym of **G**eneralized **I**ncremental **S**tress-**S**tate damage **Mo**del) was proposed and developed by Neukamm et al. [2,3,4], and recently implemented into commercial finite-element code LS-DYNA. This model is based on incremental damage accumulation that depends on a failure curve which is a function of the current stress state.

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Furthermore, GISSMO includes the evolution of instability measures based on a critical strain, and this feature helps to take into account behavior of steel with better accuracy.
Brief description of fracture curve obtaining was provided by F. Andrade et al. [4]. Description of GISSMO development for dual-phase sheet steel was presented by J. Effelsberg et al. [5] and by Andrade et al. [6]. Herein presented a process of GISSMO developing for low-carbon automotive structural steel.

2. Description of GISSMO model. Detailed description of the model was provided by Andrade et al. [6]. Therefore, only brief description and most important equations are provided herein.

In the late 1960's and 1970's several authors provided contributions showing dependency of the fracture strain of notched sample upon notch radius [7]. As a result, the new stress-state indicator called triaxiality was proposed, defined as:

$$\eta = \frac{\sigma_m}{\sigma_{eq}} = -\frac{p}{\sigma_{eq}}, \tag{1}$$

where σ_m means stress and σ_{eq} – equivalent stress defined as:

$$\sigma_{eq} = \sqrt{\frac{1}{2}[(\sigma_1-\sigma_2)^2(\sigma_1-\sigma_3)^2(\sigma_2-\sigma_3)^2]}. \tag{2}$$

A phenomenological scalar quantities D called damage measure and F called instability measure are introduced as:

$$\dot{D} = \frac{n}{\Lambda(L_e,\eta)\varepsilon_f(\eta)} D^{(1-1/n)}\dot{\varepsilon}^p, \tag{3}$$

$$\dot{F} = \frac{n}{\varepsilon_{crit}(\eta)} F^{(1-1/n)}\dot{\varepsilon}^p, \tag{4}$$

where n – damage exponent, ε^p- accumulated plastic strain, $\varepsilon_{crit}(\eta)$ and $\varepsilon_f(\eta)$ – critical strain curve and failure curve, respectively, both are functions of triaxiality η. $\Lambda(L_e,\eta)$ – regularization function for spurious mesh dependence compensation:

$$\Lambda(L_e,\eta) = \begin{cases} \beta_{shear} \; if \; \eta \le 0 \\ \left\{\frac{\alpha(L_e)-\beta_{shear}}{1/3}\right\}\eta + \beta_{shear} \; if \; 0 < \eta \le 1/3 \\ \left\{\frac{\alpha(L_e)-\beta_{biaxial}}{1/3}\right\}\eta + \beta_{biaxial} \\ \beta_{biaxial} \end{cases}. \tag{5}$$

Herein $\alpha(L_e)$ – monotonically decreasing function of finite element size, factors β_{shear} and $\beta_{biaxial}$ defined as:

$$\beta_{shear} = 1 - [1-\alpha(L_e)](1-k_{shear}), \tag{6}$$

$$\beta_{biaxial} = 1 - [1-\alpha(L_e)](1-k_{biaxial}), \tag{7}$$

where k_{shear} and $k_{biaxial}$ vary from 0 to 1. Coupling of damage and stress is considered as [8]:

$$\sigma = (1-\widetilde{D})\tilde{\sigma}, \tag{8}$$

where $\tilde{\sigma}$ – undamaged stress tensor, $\widetilde{D}$ – damage that take place when strain localization arise and given by:

$$\widetilde{D} = \begin{cases} 0, & if \; F < 1 \\ \left(\frac{D-D_{crit}}{1-D_{crit}}\right)^m & if \; F = 1 \end{cases}. \tag{9}$$

Herein D_{crit} is accumulated damage when F = 1 and m is so called fading exponent.

Finally, GISSMO model assumes defining several parameters: curves $\varepsilon_{crit}(\eta)$, $\varepsilon_f(\eta)$ and $\alpha(L_e)$, factors k_{shear} and $k_{biaxial}$, and exponents m and n. This provides more flexibility during calibration procedure, but, on the other hand, this procedure becomes more complex and difficult.

3. Experimental testing. The purpose of experiments is to determine failure curve. At first, force-extension curves for specimens of several types were obtained as a basis for calibration of material model. Four types of specimens were manufactured, each types corresponds to certain triaxiality value. Also, standard proportional specimen for obtaining hardening curve and basic material data (yield stress, elongation, etc.) was made. Specimens and their dimensions are schematically presented on Fig. 1. Thickness of steel sheets is 1.5 mm.

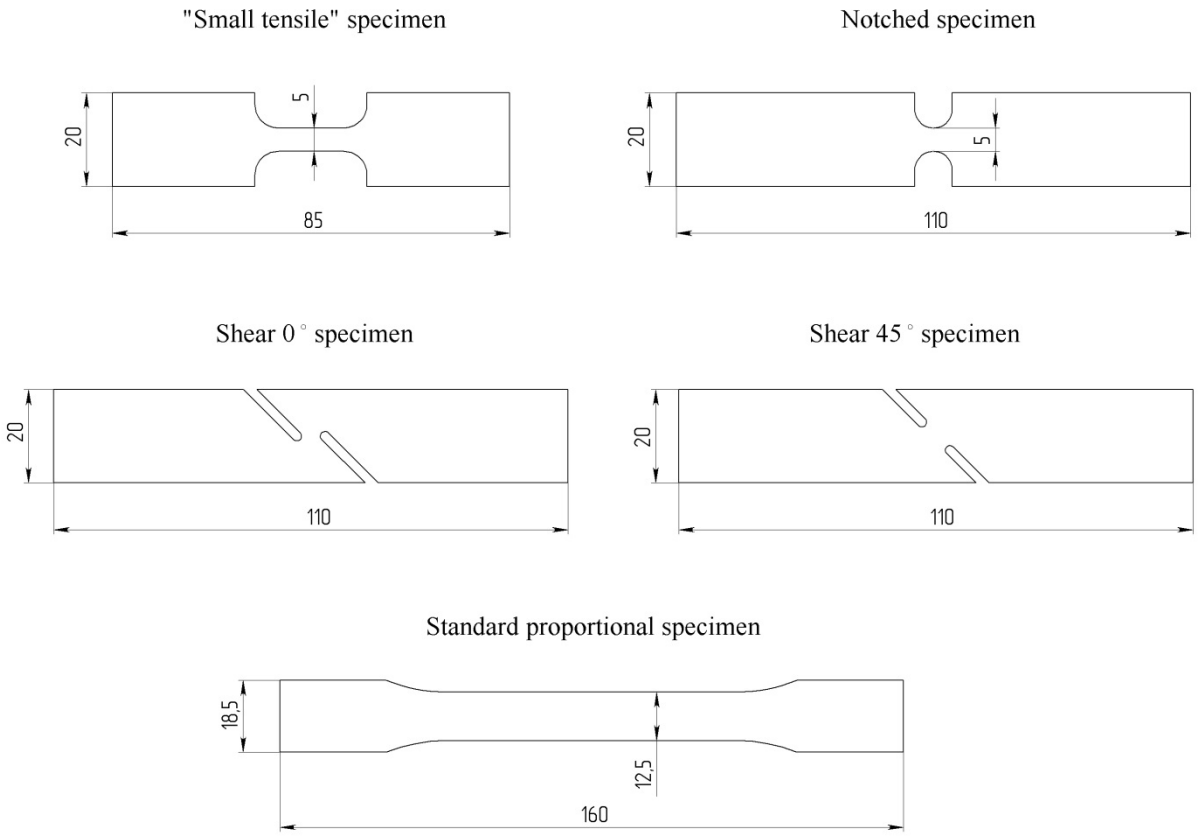

Fig. 1. Testing specimens sketches

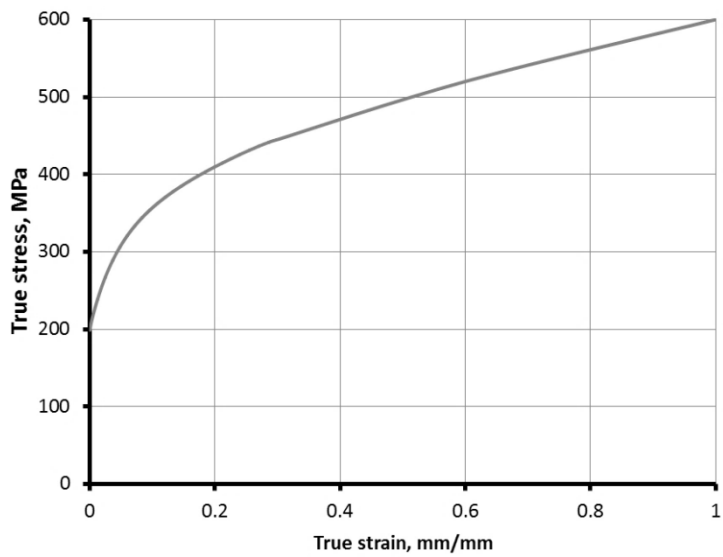

Fig. 2. Hardening curve of tested steel

Tensile testing performed by universal testing machine Zwick/Roell Z100 with extensometer mounted on sample to minimize measurement error. All tests were performed at room indoor temperature, with nearly quasistatic conditions (strain rate was about $10^{-3}s^{-1}$). Testing of standard proportional specimen resulted in obtaining basic material parameters: Young's modulus, yield stress, tensile strength and elongation. Hardening curve is presented on Fig. 2. Force-extension curves for failure curve samples presented on Fig. 3.

Usually, five types of specimens are processed, including biaxial tension. In this research we used four types and developed an approximation for boundary triaxiality value of 0.667. It saved resources spent on experimental testing and kept appropriate accuracy level.

4. Finite element modeling of tests. Calibration of model parameters. Full-scale tests presented in previous section were simulated with finite element modeling technique using commercial code LS-DYNA. Geometry of the sample repeats the shape of real samples. Sample is modeled with shell finite elements, the same as in the case of vehicle crash test modeling. Firstly, tests were performed with finite element size 1.5 mm in the central part of sample, and then regularization carried out that allowed using 5 mm finite element mesh. Elastic-plastic behavior of material defined using *MAT_024 card, GISSMO parameters defined with *MAT_ADD_EROSION card. Sample is fixed at one side by setting translational and rotational degrees of freedom equal to zero. At the other side, slightly increasing velocity applied which allows minimizing inertia effects and guaranteeing quasi-static conditions. Calibration parameters m and n for GISSMO input curves were also identified. Failure curve identified using iterative technique of comparing simulation results with corresponding experimental results. Obtained failure curve is presented on Fig. 3.

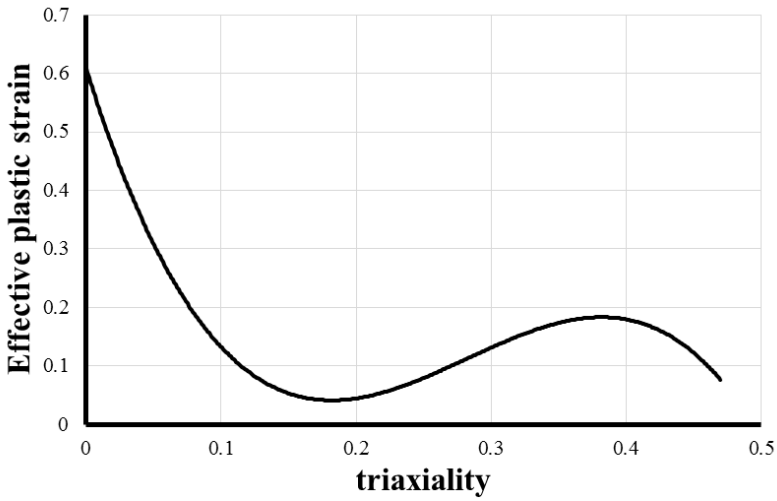

Fig. 3. Obtained failure curve for GISSMO input

Obtained force-extension curves for both experimental and virtual tensile tests are presented on Fig. 4.

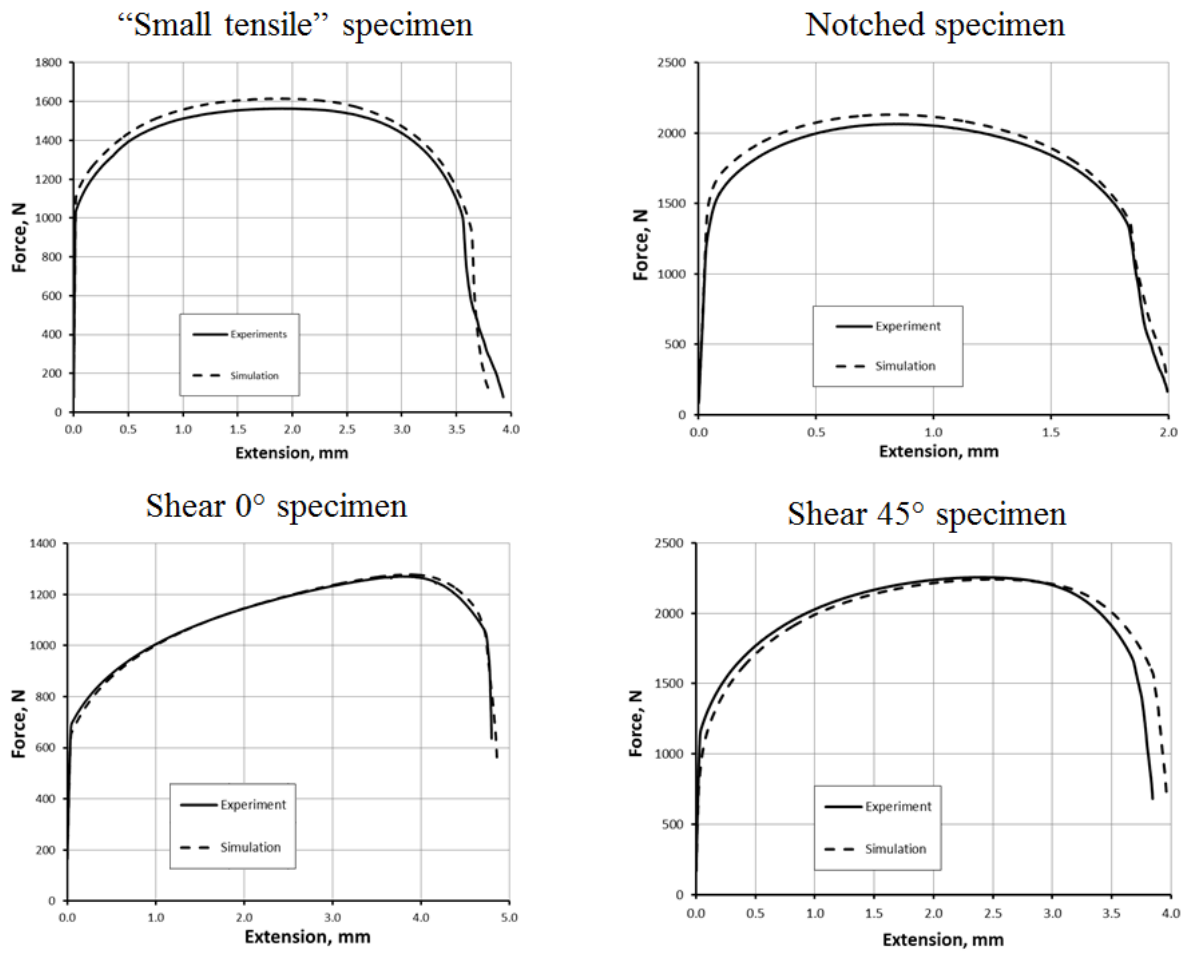

Fig. 4. Force-Displacement curves for four sample types

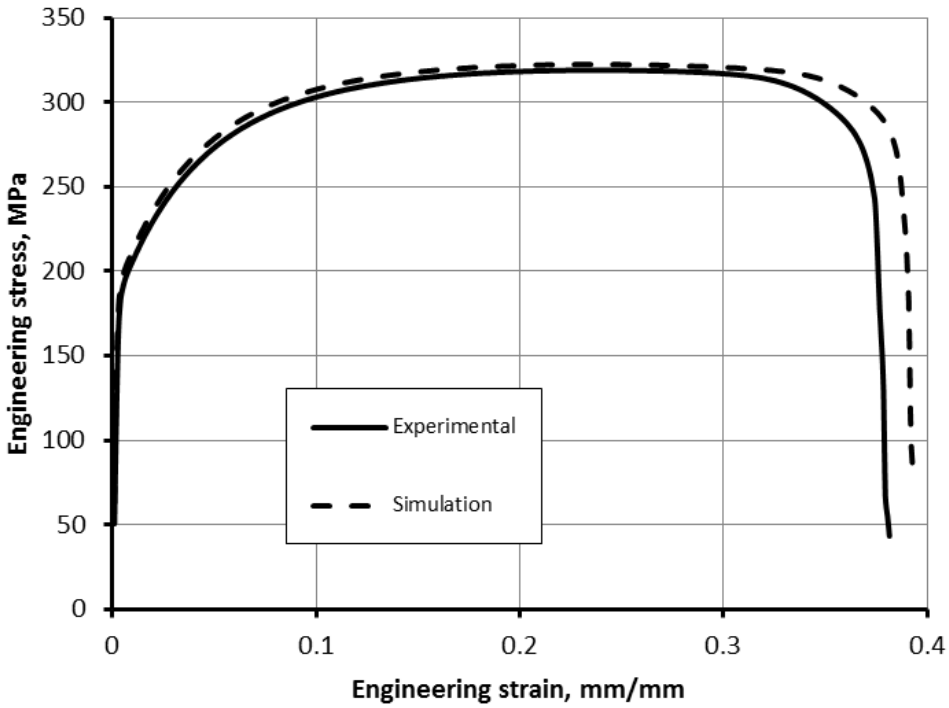

Fig. 5. Comparison of tensile testing results for standard proportional sample

5. Model validation. Validation of calibrated GISSMO model is conducted using sample model that did not take part in calibration process (see Fig. 1, standard proportional sample). Results are represented on Fig. 5. Comparing results of experimental and virtual testing one can see that GISSMO provide acceptable representation of sample failure. Little divergence between two curves shows that some additional calibration may be done, and this is a question for further investigation.

It should be mentioned that the localization occurs in two stages: firstly, when localization begins, one can see a decrease of sample width, and, secondly, the thickness become to decrease. Thus, second stage of localization can be modeled only concerning fully three-dimensional formulation. But in the case of vehicle collisions modeling this couldn't be done at the moment, because of high computational efforts requirements. So, keeping in mind restrictions of shell elements, material with defined GISSMO provided good results.

Validated GISSMO damage model was implemented into a detailed FE model of 2016 four-door passenger SUV that includes the full functional capabilities of a suspension, a driveline and steering subsystems. The "digital twin" includes all the necessary parameters for prediction of object behavior during any physical interaction of the related real vehicle [9]. Deformed SUV body with standard material models that do not include difficult damage behavior is presented on figure 5, deformed SUV body with GISSMO defined presented on Fig. 6. On the figure 6 one can see the frame taken from full-scale test at the same millisecond.

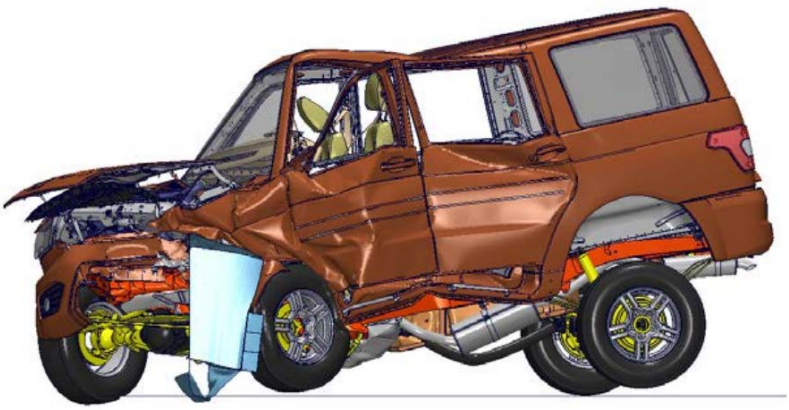

Fig. 6. Deformed SUV body FE model with standard material models

Fig. 7. Deformed SUV body FE model with calibrated GISSMO damage model defined

Fig. 8. Deformed SUV body, full-scale test

Results of simulation of detailed full-scale vehicle model shows that GISSMO model helped to achieve values of floor panel and motor shield deformation that have high correlation with real crash test.

6. Summary and conclusions. GISSMO model provides researcher with possibility to model failure of structure with acceptable accuracy level and without increasing of computing time for simulation. Input parameters set provides user with wide range of possibilities for model calibration. Typical automotive low-carbon structural steel was investigated in this research, failure and critical strain curves were received, calibration parameters such as damage exponent were defined.

Developed GISSMO model was validated using standard tensile sample and showed high level of correlation with experimental data. Calibrated GISSMO model was implemented into full-scale SUV FE model. Comparing experimental and simulation results showed that material model with defined GISSMO demonstrates acceptable representation of real object behavior, and, thus may be used for creating vehicles "digital twins".

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