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Gissmo Failure Modelling for Crashworthiness Analysis Using Different Test Specimens

M. Emin TAMER
Borçelik Çelik Sanayii Ticaret A.Ş.

Almila Gulfem OZGULTEKIN
Borçelik Çelik Sanayii Ticaret A.Ş.

Beyzanur AYDIN
Borçelik Çelik Sanayii Ticaret A.Ş.

Abstract: The demand for lightweight products to reduce CO2 emissions and high safety requirements is an increasing trend, especially in the vehicle and electrical appliance industry. The use of high-strength steels instead of conventional mild steels by using predictive modeling methods in finite element analysis plays a major role. Moreover, physical full-scale crash tests are time-consuming as well as expensive. Crash tolerance analysis in the finite element environment depends on the accuracy of the damage and the definition of the material model parameters. This study examines the damage model GISSMO-Generalized Increasing Stress State-induced damage model and the onset of fracture was calculated by sample optimization via finite element analysis in this study. This research presents the modeling of a specific region of the material fracture curve using the different geometric samples. The results of the numerical simulations are validated by comparing the experimental data of the optimized test samples with their measurements.

Keywords: Gissmo, Damage, Mechanical characterization, Crashworthiness

Introduction

Nowadays, the demand on advanced high strength steels (AHSS) is significantly raising due to its industrial applications especially in automotive and defence industry which includes lightweight design. Brilliant mechanical properties of dual-phase (DP) or multiphase steels with elevated strength as well as improved ductility are chosen rather than other steels. The complexity in microstructure design of AHSS has been an enhanced and superior method to develop the mechanical properties in various grades of steels, such as DP steels (Liu et al., 2019). According to safety legislation the crash avoidance, mitigation the severity of an accident, crash mitigation and reducing injury is significant to address the pedestrian health. Numerical analysis for crashworthiness improves the safety of the cars and hence it considers the human safety. The priority policy of safety legislation of European commission are reducing serious and fatal casualties identified by research are a standardized test method for car-to-car compatibility and truck to car compatibility and improved methods for front and side, improving frontal protection for vulnerable road users, and implementation of Intelligent Speed Adaptation systems, seat belt reminders in all seating positions, alcohol interlocks for fleet drivers, event and journey data recorders and identification of further systems with large potential for casualty savings (Road Safety Annual Report, 2018). Almost all the cars which have 73% CO2 emitted should lower its weight done by different safety components (Hörling, 2015). Crashworthiness simulations are used to develop safety

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components in the automotive industry (Roth et al., 2016). The simulations may also give valuable information and understanding about different phenomena in a car crash (Bao et al., 2004). Moreover, crash tests of the cars are significantly expensive, and it is not reproducible due to variations in manufacturing (Mohr et al., 2007). Since the development time to launch a new car has been shortened and the demand for better crashworthiness and passive safety the manufacturers must rely more on crashworthiness simulations than before (Gholami et al., 1970). The milestones of related studies in deformation and fracture mechanism of metals have been summarized in literature (Mohr et al., 2004). Different deformation states can be executed by conducting several combinations of loading to test specimens such as butterfly specimen under biaxial loading with a combination of tension/shear and compression/shear (Peirs et al., 2012). The desires stress state is not exactly acquired by these experimental methods, involving biaxial loading setup, separate driving systems (displacement or force controlled) for the horizontal and vertical axes, and complexity in the sample manufacturing process. Another study includes different specimen geometries for a tensile testing device positioned in-plane notches or the out-of-plane notches between two central holes to obtain the shear stress state (Driemeier et al., 2010). The specimen geometry gives better chance to obtain the stress states, but it doesn't give an opportunity to acquire the proportional loading condition at the critical deformation in other words at the onset of necking during the damage tests.

In this study, the mechanical characterization test data were evaluated and optimized with finite element analysis by a new geometrical design with finite element analysis environment. In this context, tensile and compression tests are performed in order to obtain flow curve using Swift and Hockett-Sherby combined material model. This study depends on quick data processing, generally when raw data obtained there several methods to process and prepare for simulations. In the first part of this study the raw data were measured form mechanical tests and the second part includes the optimization with finite element analysis program. The evaluation of finite element analysis is done at Ls-Dyna environment. The validation is done with the real measurement's force-displacement curve.

To obtain different stress states range, a set of damage specimens were produced according to the identical uniaxial tensile test setup. These specimens were investigated with different deformation states of sheet material. The specimen set similarly involves in literature such that shear, notched and sub size tensile specimens. The new design is based on a consistent to tensile specimen, to figure out mid part of material instability curve called smile shear test specimen. On the contrary, it should be noted that despite having the same test set up and specimen geometry, the deformation states may be affected by plastic deformation. The damage model GISSMO-Generalized Incremental Stress State dependent damage model has been investigated and the onset of fracture has been figured out with specimen optimization. According to the literature all the specimen dimensions are redesigned. At a certain region of the material failure curve is modelled using different geometric specimens. The results of the numerical simulations are verified through the comparison of the results with the measurements of experimental data of those optimized test specimens. For the future study, the onset of fracture will be investigated with fractographic experiments.

Method

Material

A DP steel of HDG CR330Y590T-DP with 1.09 mm thickness is considered for the experimental study of the specimen geometry. DP590 is commonly used in automotive industry especially in safety parts. The tests were performed with three repetitions in each direction (rolling, diagonal and transverse) with Euro norm testing speed. The average values with standard deviation of the test results in three directions are given in table 1.

Table 1. The average mechanical properties of CR330Y590T-DP.

t (mm)	Yield Stress(MPa)	Tensile Stress (MPa)	A80 (%)	n	r
1.09 ± 0.02	380 ± 4	694 ± 5	25.2 ± 0.2	0.22	1.02

To acquire the biaxial flow, curve the stack compression tests, which was first proposed by Pawelski (Pawelski, 1967), in which an alternative experiment for acquiring flow curve in a wide range of strain values due to its deformation state, were performed (Merklein et al., 2009). This method is not standardized, and different test investigations and researches are still being made (Hochholdinger et al., 2009).

GISSMO Model and Damage Parameters

The model GISSMO is peculiar to an incremental formulation for damage accumulation and based on a phenomenological background of crashworthiness and can be expressed as (Neukamm et al., 2009),

$$\Delta D = \frac{n}{\varepsilon_f} D^{(1-1/n)} \Delta\varepsilon_v \quad (1)$$

where n is the damage exponent which leads to nonlinear representation of damage accumulation which increases the accuracy of forming and crash analysis. Moreover, $\Delta\varepsilon_v$ and ε_f describe the notation for the incremental step in equivalent plastic strain and triaxiality dependent failure strain in other words equivalent plastic strain to failure, respectively. The triaxiality is a measure of stress state acquired in different deformation states and given as,

$$\eta = \frac{\sigma_H}{\sigma_V} \quad (2)$$

where σ_H and σ_V represent hydrostatic and equivalent von Mises stress, respectively. The damage threshold, D_{crit}, is defined either as a fixed value or as a function of the forming intensity at the actual

state of deformation. When the damage reaches this curve for the actual triaxiality the damage threshold will be stored for the actual element and the flow stress and the damage will be coupled and the effective stress tensor which is expressed as,

$$\sigma_r = \sigma_n \left[1 - \left(\frac{D - D_{crit}}{1 - D_{crit}}\right)^m\right] \quad (3)$$

where m is the fading exponent which alters the stress state and checks the energy dissipation depending on element size in the analysis.

In this study, the five different specimens convenient for testing on tensile testing device covering the triaxiality range between pure shear and biaxial strain are selected for the identification of damage model parameters. The flow curve of dual phase steel and the tensile & stack compression test specimens are shown in Figure 1 and Figure 2, respectively. The test specimens are cut on electric discharge machine in the rolling direction. Their force vs. displacement curves serve as experimental data for the inverse optimization process.

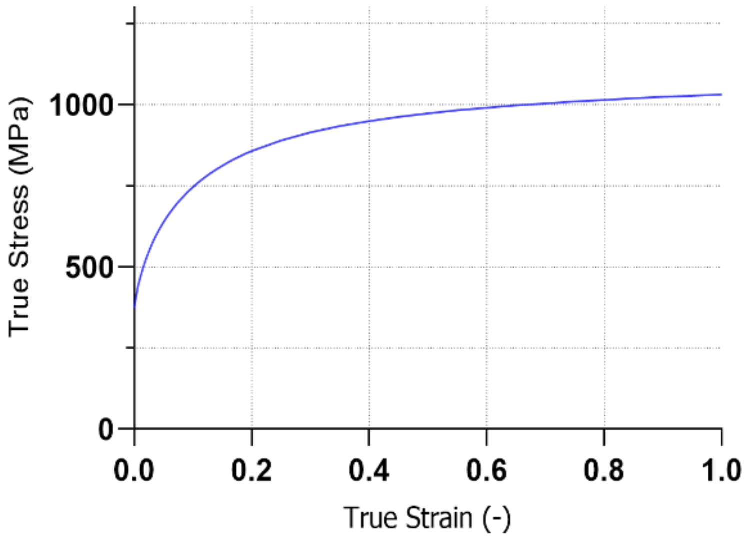


Figure 1. True stress-strain curve of CR330Y590T-DP with the thickness of 1.09 mm.

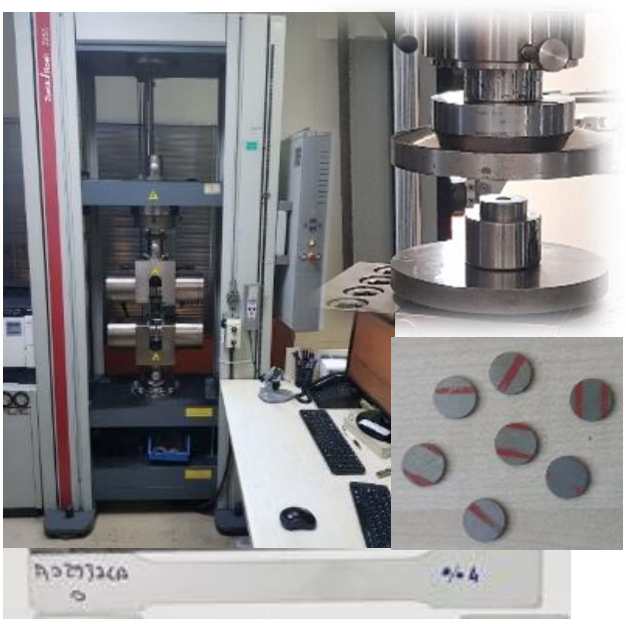


Figure 2. The test specimens for initial material characterization.

Numerical Analysis

Five different geometries are conducted to obtain different triaxiality paths. Numerical analysis of the test specimen is conducted to acquire insight into the deformation states details. Furthermore, the numerical analysis can also be used to reveal the effect of the design of the geometry on localization and distribution of strains at the beginning of necking. Regarding to this, Ls-Dyna is used as the simulation environment. The MAT-36 3 Parameter Barlat material model is used to model the test specimens. A mild steel is considered for optimizing the geometries, since it is found to be commonly used materials of its wide application range in automotive industry. The finite element analyses were conducted with Borcelik material cards. The initial mesh size was 0.5 mm, with 5 integration points. The triaxiality path are plotted using these geometries. In figure 3 and figure 4, the optimized geometries are illustrated both for FEA and experiments. In figure 5, the triaxiality paths are demonstrated and the critical points for determination of material failure and instability curves will be used according to this point.

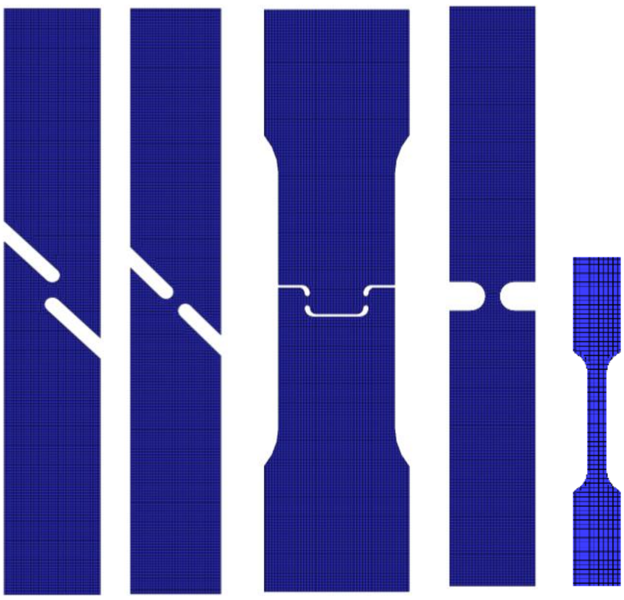


Figure 3. The undeformed test specimens used for modelling damage parameters

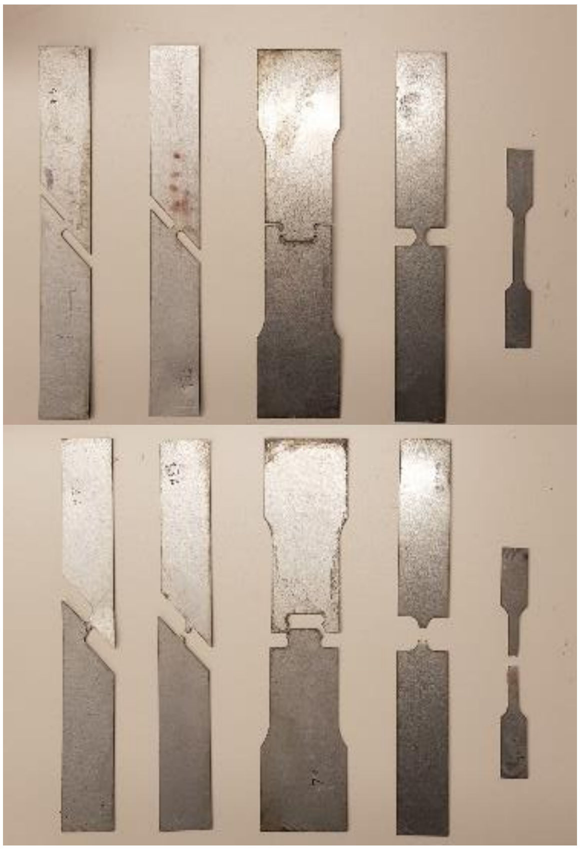


Figure 4. Deformed and undeformed test specimens for experimental study

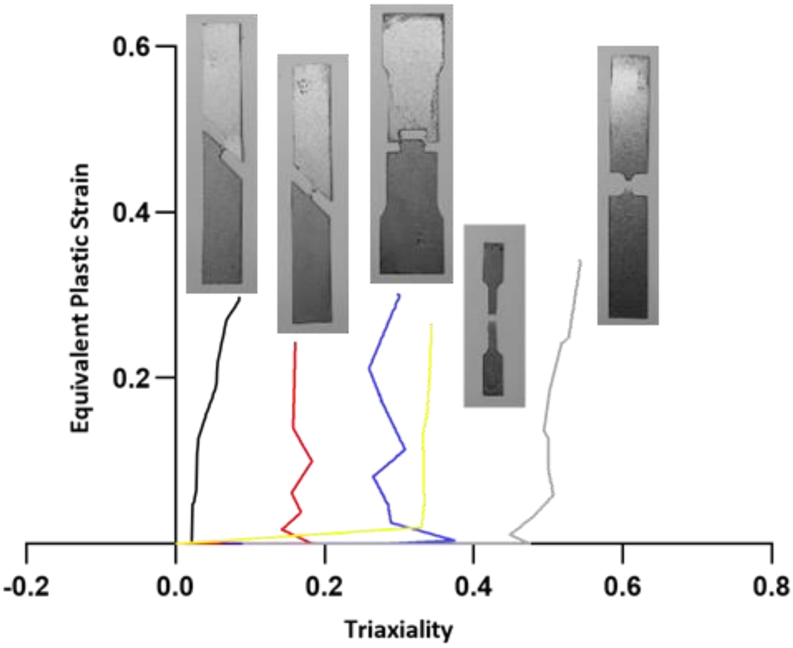


Figure 5. The triaxiality strain path of mild steel with 5 different geometries.

Results and Discussion

The simulations were executed with material model MAT_PIECEWISE_LINEAR_PLASTICITY, which is generally used in car crash simulations in order to reach the preliminary behaviour while identifying the GISSMO parameters.

Determination of Damage Parameters

To recognize the failure and failure behaviour of the test specimens, another material model is added, which is MAT_ADD_EROSION. This material includes the GISSMO parameters and curves that can be found via LS-OPT environment. The optimization is executed with respect to force displacement curves of experimentally achieved results. Along with optimization studies, transition models to enhance compatibility of finite element analysis vs. experimental results have been built. In this context, the force displacement curves of five specimens illustrated in figure 5 are used. 20 iterations have been established and for each iteration 50 simulations have been conducted in order to improve the accuracy of results. In figure 6, the material failure and instability curves are illustrated.

Determination of Parameters with Different Mesh Size

In crash simulations, much course meshes are used, so the characteristic element length differs in fading and regularization curves and necessitates to regularize those curves using larger mesh sizes. Regarding to this, uniaxial tensile test geometry is used beginning from 1 mm to 10 mm mesh size. The mesh size and the regularization curves are demonstrated. Since the parameters of these mesh dependent curve parameters, the optimization could be easily figured out via LS-OPT without having high computational cost.

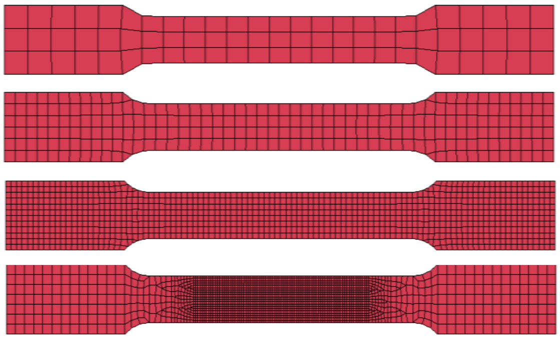
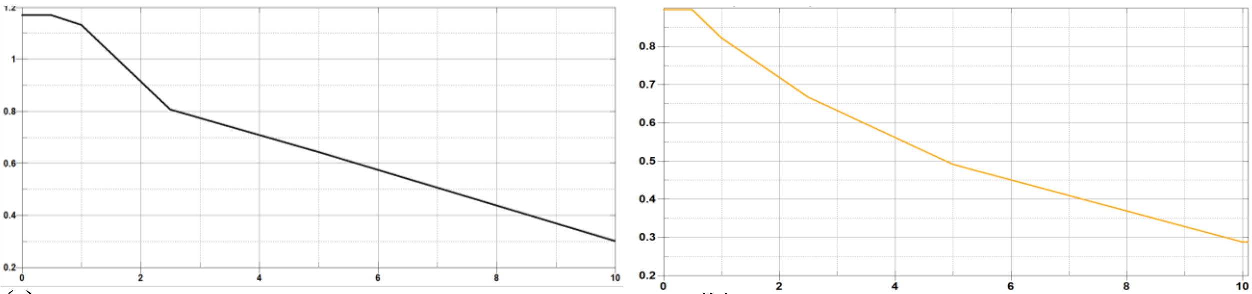


Figure 7. The undeformed test specimens used for mesh dependent modelling of GISSMO card.



(a) (b)

Figure 8. Fading curve after meshing dependent optimization (a) and regularization curve (b)

Validation of Damage Parameters on a Physical Testing Specimen

To verify the applicability of the identified parameters and the regularization curves, the GISSMO model is used in a real tensile test specimen. The test specimen is modelled with 1 mm mesh size with 5 number of through shell thickness integration points. The mesh size and deformation result of galvanized sheet strip are illustrated in figure 9.

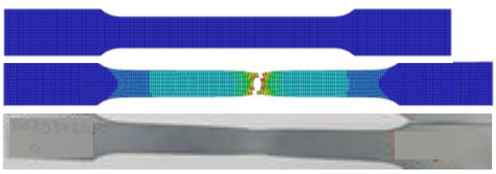


Figure 9. Equivalent plastic strain results at different localized necking regions.

According to the test results, the comparison of the force-displacement and engineering stress &strain curves show good agreement between the experiment and the simulations, figure 10. As can be seen in figure 10, the finite element test result of GISSMO material model after fine tuning operation is in the test results interval in all directions. The FEA result from both graphs matched well in diagonal test direction test specimen result.

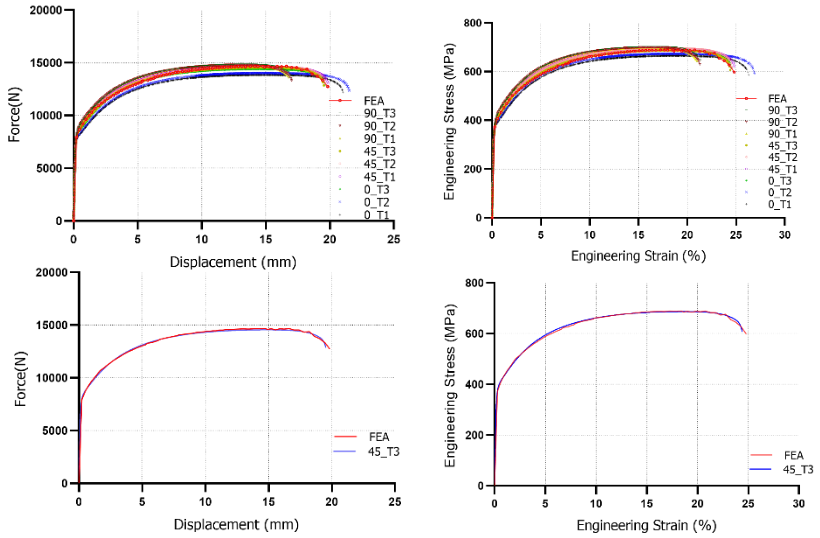


Figure 10. The comparison between FEA and experimental results after fine tuning of GISSMO material model.

Conclusion

In this study, an inverse identification method for the GISSMO damage model parameters has been considered and the damage model GISSMO-Generalized Incremental Stress State dependent damage model has been investigated and the onset of fracture has been figured out with specimen optimization. The use of high strength steels instead of conventional lightweight steels has a major role with predictive modelling methods in finite element analysis. Crashworthiness analysis in finite element environment depends on the accuracy of damage and material model parameters description. The onset of fracture has been shown via finite element analysis. At a certain region of the material failure curve is modelled using different geometric specimens. In regularization curves and fine tuning of damage parameters fine and homogeneous discretization with an element size of 0.5 mm has been used and the mesh dependent parameters have been regularized by using the uniaxial tensile test. It has been concluded that the experimental results have good agreement with finite element analysis results.

Recommendations

Especially in high formable deep drawing operations it is possible to decide which damage parameter could be offered to end-user with the execution of numerical analysis. As future work, fracture mechanism of optimized specimens should be investigated via fractography.

Acknowledgements or Notes

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Scientific Ethics Declaration

The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

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Author Information

M. Emin TAMER
Borcelik Celik Sanayii Ticaret AS
Ata, 125 Nolu Sokak No:1, 16601 Gemlik/Bursa, Turkey
Contact e-mail: *emint@borcelik.com*

Almila Gulfem OZGULTEKIN
Borcelik Celik Sanayii Ticaret AS
Ata, 125 Nolu Sokak No:1, 16601 Gemlik/Bursa, Turkey

Beyzanur AYDIN
Borcelik Celik Sanayii Ticaret AS
Ata, 125 Nolu Sokak No:1, 16601 Gemlik/Bursa, Turkey

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