A Study to Improve the Crash Performance of Plastic Materials Considering the Strain Rate and Fracture Characteristic

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Abstract

The numerical simulation of structural parts made from plastics is becoming increasingly important nowadays. The fact that almost any structural requirement can be combined in a lightweight, durable and cost effective structure is the driving force behind its widespread application. More and more structural relevant parts are being constructed and manufactured from plastics. It is difficult accurately to predict the reliability according to finite element analysis, because plastics materials show the complex material behaviour. Thus, it is demanded for reliable and obvious methods to design these parts and to predict their material behaviour. For the finite element simulations of polymeric materials mathematical models are needed which cover all the phenomena of the material.

In this paper, it is possible to describe accurately the mechanical behaviour of thermoplastic materials using a new constitutive model termed as SAMP-1(Semi-Analytical Model for Polymers) in LS-dyna. We performed the high speed tension tests (strain rate: 0.001/s, 0.1/s, 1/s, 50/s, 100/s) for the characterisation of the plastics material. Also, the parameters of the SAMP-1 model were identified by using multi-directional mechanical tests such as uniaxial tension, simple shear, and compression tests. As validation purpose, the SMAP-1 model was compared to the existing models for predicting the stress-strain behaviour in the test specimens and the dynatup impact test.

Keywords

High speed tension test, SAMP-1, Finite element method

1 Introduction

Automobile interior parts usually consist of plastic and composite materials to keep the vehicle lightweight and to meet quality expectations in appearance. Plastic material is particularly widely used for automobile interiors parts because of the advantages of its lightness, low price, and outstanding formability. However, the various material characteristics exhibited by plastic due to its molecular structure, mixing conditions, manufacturing environment, etc. make it difficult to satisfy the crashworthiness and strength requirements for automobiles(Pawlak et al.,2005; Klompen et al.,1982; Clausen et al., 2011).

With recent improvements in the reliability of forming analyses as well as crash and structural analyses using computer simulation, many studies have been conducted to evaluate the vehicle's structural stability and formability at the stage of research preceding automobile design. However, plastic material has characteristics such as softening, volumetric change, pressure dependence and anisotropy that make it difficult to perform material modelling for crash testing and analysis. For plastic material modelling, the Von-Mises yield criterion and the isotropic hardening model are commonly used, but these are not suitable for accurately simulating the characteristics of plastic. Therefore, for the material modelling of plastic, we need to develop a material model that can represent the characteristics of plastic and a material testing and modelling method for this purpose(Avalle et al., 2010;).

S. Kolling and three others (2005) conducted a phenomenological analysis of the mechanical characteristics of plastic and applied the characteristics of softening, volumetric change, pressure dependence and strain rate dependence to the material model (Koling et al., 2005). They also applied a damage model to express behaviour under loading and considered fracture strain, triaxiality of stress, and element size as fracture factors in the expression.

Kunio Takekoshi, in collaboration with one other researcher (2012), used the test data for the SAMP-1 material model to present the conversion formulae for true stress and true strain and introduced the procedure for deriving the Poisson's ratio in the plastic region (Takekoshi et al., 2012). In metal materials, the Poisson's ratio is generally assumed to be 0.5 in the plastic region, but in the case of soft plastic, in which softening occurs, the change in the Poisson's ratio results in volumetric change. To take account of this, an analysis was first performed with the initial Poisson's ratio assumed to be 0.5 and based on these results, sequential analyses were performed while adjusting the Poisson's ratio in the plastic region. One disadvantage of this approach, however, is that errors can occur in the process of adjusting the parameter using an unverified analysis model and there is a delay because of the sequential nature of the analyses. One study aiming to improve plastic material testing was performed by F. Grytten and three others (2009). They used a DIC (Digital Image Correlation) technique to obtain and apply the data for true stress, true strain, and Poisson's ratio and performed verification analysis by defining the yield stress for each strain rate (Grytten et al., 2012). Gang-Wook Lee and two others (2006) performed a study of the dynamic characteristics of plastic for collision analysis (Lee et al., 2006). Based on the sample's deformation, Lee et al. expressed the correlations among true stress, true strain, nominal stress, and nominal strain and presented a series of test/analysis procedures required for establishing the failure criteria of plastic.

In this study, we compared and analysed various material models applicable to plastic and researched methods of application for the SAMP-1(Semi Analytical Model for Plastics-1 model, which uses a phenomenological approach to simulate the material's behaviour. To use the SAMP-1 model, we performed the high-speed tensile test on plastic material and used a range of material tests to derive the material parameters for the SAMP-1 model. We also performed the Dynatup impact test and analysis and compared the results for application in collision analysis.

2 Material Characteristics and Experiment

The major characteristics of plastic include anisotropy, pressure dependence, volumetric change, etc. Plastic has a molecular structure in a chained form, and therefore it exhibits different properties depending on the direction. Pressure dependence refers to the phenomenon whereby the material exhibits different properties depending on the pressure applied to the object, and this phenomenon appears in plastic. In the case of metal materials, the mechanical characteristics of the material generally do not change depending on the pressure applied, but plastic material has the characteristic of exhibiting different yield stress depending on the applied pressure. In other words, the yield stress will vary depending on the stress state of the material, and to take account of this pressure dependence in finite element analysis, we need a technique for defining the mechanical characteristics according to varying stress states. Another characteristic of plastic material is that the Poisson's ratio changes in correlation to volumetric change. In the case of metal materials, the Poisson's ratio is generally assumed to be 0.5 in the plastic deformation region following the yield stress, applying the law of constancy of volume whereby the volume does not change. In plastic, however, the Poisson's ratio changes along with the volume changes in the plastic deformation region. The softening behaviour phenomenon caused by this characteristic in plastic can be seen in the stress-strain rate diagram: as the strain rate increases, the stress decreases. In this study we performed material tests with varying stress conditions to take into account the characteristics of plastic material and we performed a high-speed tensile test to evaluate the mechanical characteristics depending on the strain rate. For information in material testing, please refer to **Table 1.** Material tests can be divided into static tests and dynamic tests: static tests include uniaxial tension, uniaxial compression, shear and loading-unloading tests. The loading-unloading test measures the phenomenon whereby the modulus of elasticity decreases as the strain rate of the plastic increases. Dynamic tests included the high-speed tensile test, in which we evaluated the tensile behaviour at the strain rates of 50/s and 100/s. The sample used in the high-speed tensile test is shown in **Fig.1**.

Quasi-static Test			
Test	**Specimen**	**Test equipment**	**Output data**
Uniaxial tension	ASTM D 638 (type-5)	INSTRON 5882	Stress-Strain curve
Poisson's ratio	ASTM D 638 (type-5)	ARAMIS_DIC	Plastic Poisson's ratio
Uniaxial compression	Ref. ASTM & JIS	Cyclic tension/compression tester	Stress-Strain curve
Loading-unloading			Damage curve
Simple shear	ASTM D 7078	INSTRON 5882	Stress-Strain curve
Destructive	R-notched specimen (R:10mm)		Load-disp. curve
Dynamic Test			
High speed tension	No standard	INSTRON VHS-65/80-25	Stress-Strain curve

***Table 1**: Material test*

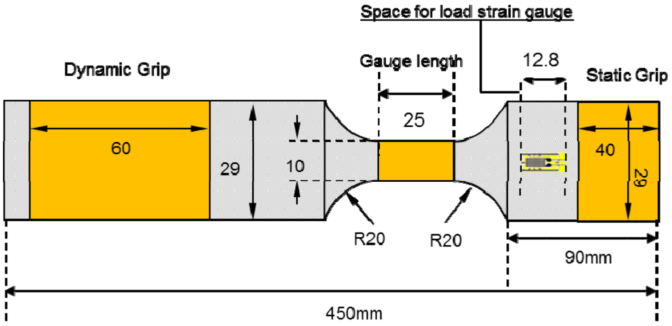


***Figure 1**: Specimen for high speed tension*

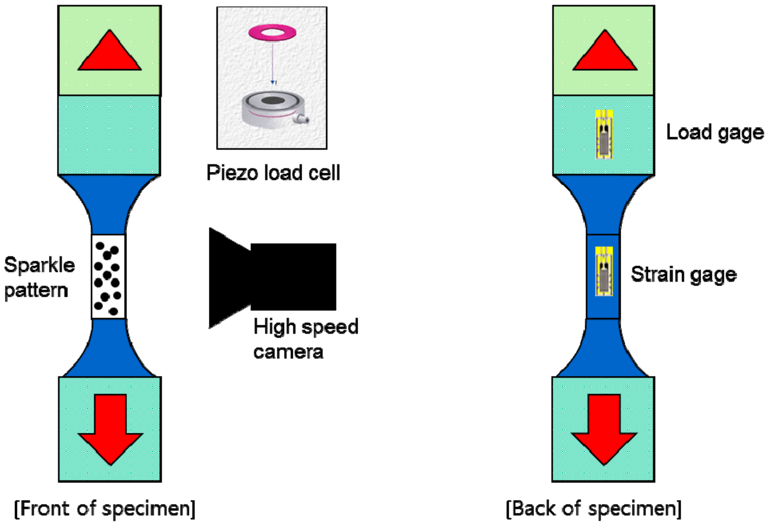
The fast-jaws grip system has been adopted as a method of grip in high-speed tensile test. In the fast-jaws grip system, the grip module is not in contact with specimen prior to the test, and eventually comes into contact with specimen and the test proceeds once the actuator reaches its target speed. This system has its merits of preventing materials from being damaged by high pressure on the grip module before the material is tensile-strained, and of ensuring precise test speeds.

In general, a material testing machine adopts two different methods of measuring loads: closed loop and open loop. The closed loop allows testing machines to control speeds while exchanging signals between them and mostly uses the strain gauge load cell while the open loop does not exchange signals between testing machines and usually uses the Piezo load cell. The high-speed tensile test adopts the Piezo load cell that does not exchange signals each other as it occurs within the extremely short period of time. Measuring loads using the Piezo load cell has a drawback of incurring severe load ringing.

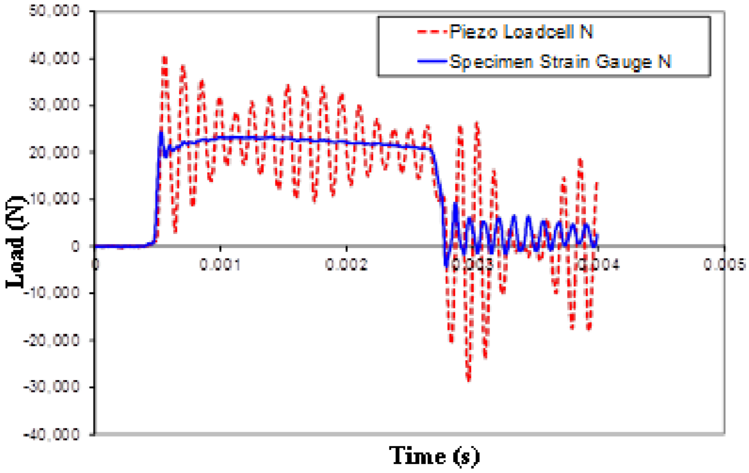
To avoid or minimize the load ringing phenomenon caused by vibration between the specimen and jig, and the jig and the load cell, this study has measured loads with the strain gauge attached to top of the specimen as illustrated in **Fig. 2 (a)** below.

A comparison of the results of measuring loads using the load cell and loads at the strain gauge attached to the specimen is illustrated in Fig. 2 (b) below. It is found that the load ringing phenomenon, which occurs in measurements using the load cell, is relieved in load measurements using the strain gauge, which ensures precise measurements of loads.

The results of the plastic material tests are presented in Fig. 3 and Fig. 4. In the high-speed tensile test, to minimize load ringing, a strain rate measuring device was attached to the upper grip of the sample in a manner designed to reduce the ringing that occurs when measuring the load. In addition, to eliminate the noise that occurs when performing the high-speed tensile test measurements, we used the adjacent-averaging method. In the results of the uniaxial tension test, we found that as the strain rate increased, the stress increased while elongation tended to decrease. The measurements of changes in the Poisson's ratio of plastic material showed that the Poisson's ratio tends to decrease over time, and the modulus of elasticity also tends to decrease as the strain rate increases.

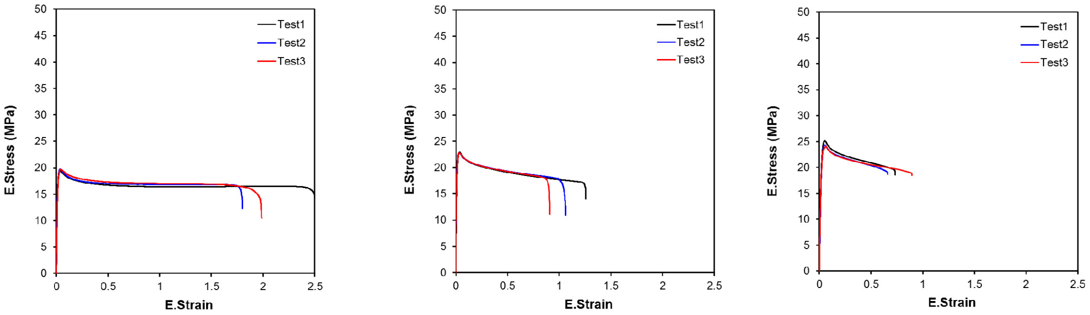


(a) Methods of measuring loads and strain

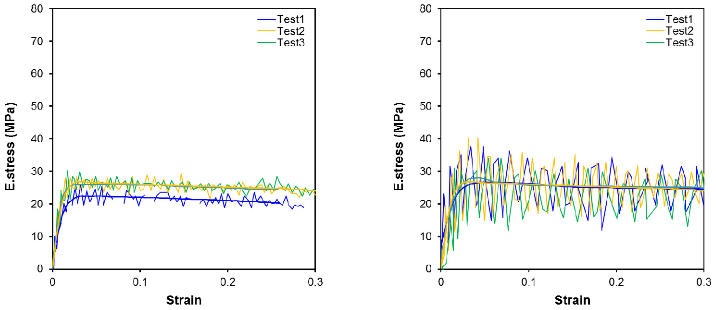


(b) A comparison of the results of measuring loads

Figure 2: *Load measurement method in high-speed tensile test*

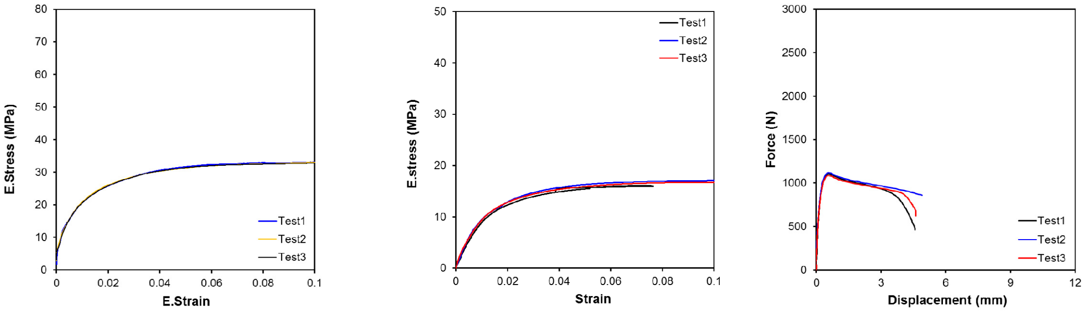


(a) 0.01/s (b) 0.1/s (c) 1/s

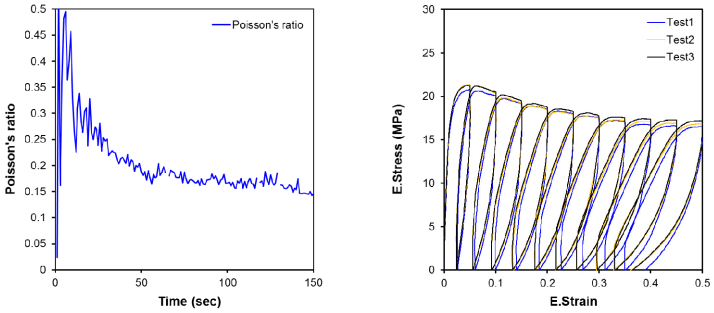


(d) 50/s (e) 100/s

***Figure 3**: Uniaxial tension test result (quasi-static and dynamic)*



(a) Compression test (b) Shear test (c) R-notch tension test



(d) Poisson’s ratio (e) Loading-unloading test

***Figure 4**: Material test result*

3 Material Modeling for SAMP-1

The SAMP-1 model (MAT 187) phenomenologically explains the polymer material from a macro perspective. This model, developed by Paul Du Bois, is suitable for non-reinforced plastic and applies a yield surface based on the Isotropic C-1 smooth yield surface. The majority of the parameters required for thermosoftening plastic are approximately taken into account.

The SAMP-1 model can take into account pressure dependence by applying a yield function that can define the yield stress correlating to each pressure, and can apply changes in the Poisson's ratio to express volumetric change and softening in the plastic region. By applying the damage curve based on the plastic deformation rate, we can simulate the behavior when the load is removed, and by applying the stress-strain rate curve for each strain rate and using the Cowper-Symonds model, we can consider the effects depending on speed.

In the SAMP-1 model, the yield surface is internally modified according to the number of the stress-strain rate curves for each mode of the pressure obtained from the material test and the yield criteria is divided into 3 types as shown in Table 2. If only one mode of the material data is applied as the input, the von-Mises yield criterion is applied, whereas if two modes of material data are applied, the Drucker-Prager yield criterion is applied. To apply the yield criterion sought in the SAMP-1 model, it is necessary to apply 3 types of material data—the tensile, compressive and shear modes—and the plastic's characteristic of pressure dependence can be considered approximately. The yield criterion for each condition can be confirmed based on the pressure-stress relation, as shown in Fig. 5.

Yield criterion	Tension	Shear	Compression	Biaxial
Von-Mises	O	X	X	X
Drucker-Prager	O	O	X	X
	O	X	O	X
	O	X	X	O
SAMP-1	O	X	O	O
	O	O	X	O
	O	O	O	O

***Table 2**: Yield criterion according to the obtained test data*

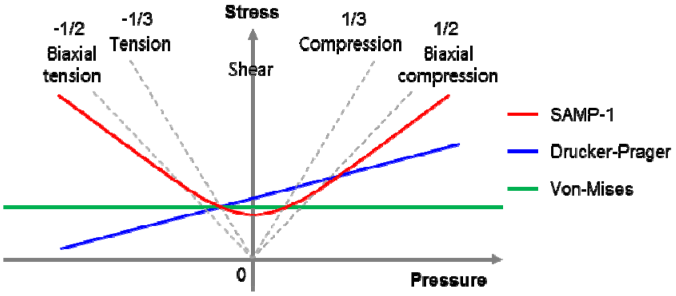


***Figure 5**: Stress-Pressure relationship and differences according to the yield criterion*

4 Dynatup Impact Analysis

To perform plastic fracture analysis using the SAMP-1 fracture model in this study, we constructed the Dynatup impact analysis model as shown in **Fig. 6**. We used a 100mm*100mm square shaped sample, with the thickness set at 2.9 mm. The load in the impact shaft was 22.43 kg, and the diameter was set at 12.7mm and the fall speed at 3270mm/sec. To evaluate differences according to the material model, we used the MAT187 (SAMP-1) fracture model and the MAT24 (Von-Mises) model and compared the results. Dynatup impact analyses can be divided into analyses which apply the fracture model and those which do not apply the fracture model and the results for each are shown in **Fig. 7.** Upon measuring the reaction of the impact shaft, it was found that in the case of MAT24 the initial load inclination was similar to the test results but in the load results after a displacement of 5mm, there were significant disparities from the actual test. It was also confirmed that there was a large error in the time point of fracture. By contrast, in the SAMP-1 model, the load and fracture time tended to be similar to those of the actual test.

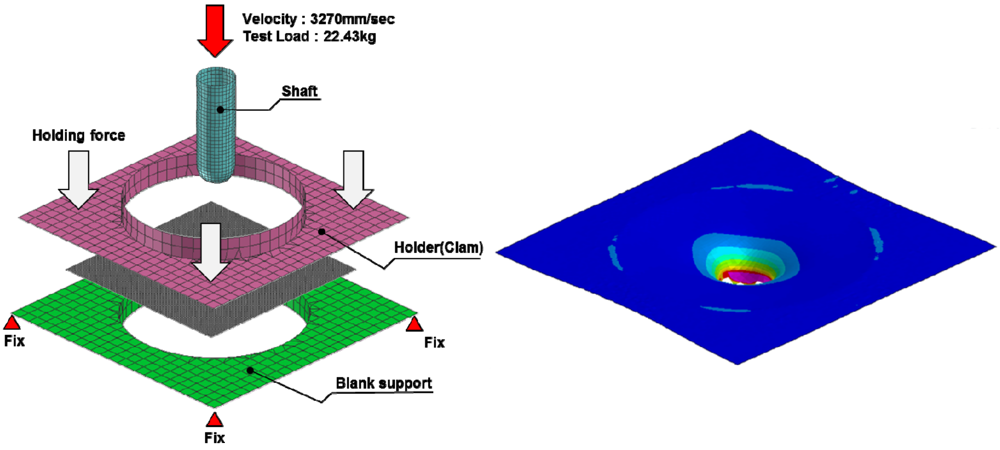
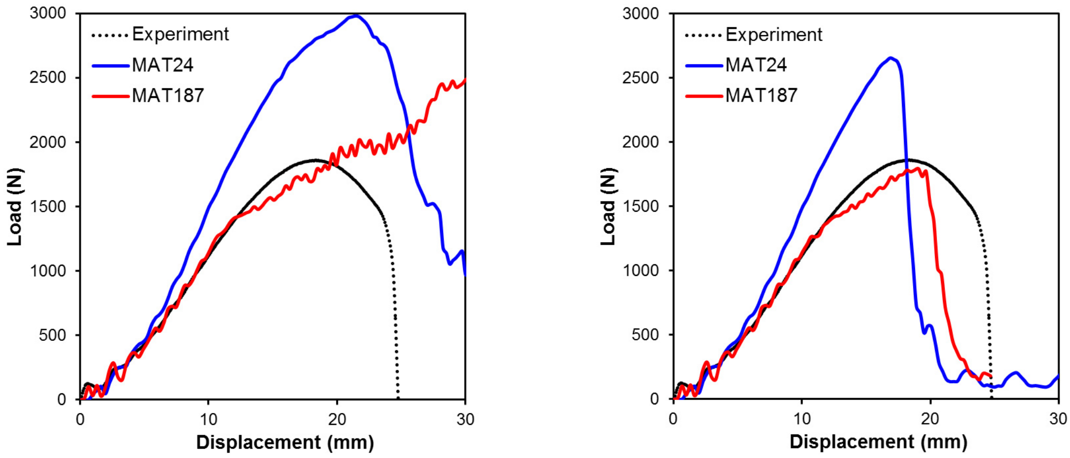


***Figure 6**: Dynatup analysis*



(a) Without fracture model (b) With fracture model

***Figure 7**: Comparison of load-displacement curve*

5 Conclusion

In this study, we performed a high-speed tensile test and material tests under varying stress states to analyse the fracture characteristics of plastic, taking account of the strain rate. We also used the Mat187 SAMP-1 model of the LS-dyna analysis program, a material model capable of expressing the behaviour of plastic material, to perform the Dynatup impact analysis and verified the reliability of the material model. Our analysis using the SAMP-1 model yielded simulated results confirmed to be similar to the actual test results and there were few errors in the fracture time point.

Acknowledgment

This study was made possible by support provided by the analysis team of Hyundai MOBIS and the National Research Foundation of Korea (NRF) BK21Plus project (Kangwon National University, No.22A20130012864)

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