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# Application of the Virtual Fields Method to determine dynamic properties at intermediate strain rates

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**Abstract.** Crash analysis simulation is now very important in automotive industry to assess automotive crashworthiness and safety. In order to acquire reliable crash simulation results, precise material behaviors at intermediate strain rates should be used as input data. To determine the stress-strain curves at various strain rates, the number of expensive and complicated experiments is large. The present study aims at determining the stress-strain curves of sheet metals at various strain rates from a single dynamic experiment. A new type of high speed tensile tester for sheet metal specimens was built and high speed tensile tests were carried out. Full-field heterogeneous strain fields were measured by a digital image correlation technique using a high-speed camera. The load data was acquired from strain gauges attached to the elastic deformation region on the specimen. Then, an inverse identification scheme with a rate dependent hardening law was applied to retrieve dynamic parameters. The stress-strain curves of advanced high strength steel at intermediate strain rates (100 /s - 300 /s) were successfully obtained from a single experiment.

## 1. Introduction

Crash analysis using finite element (FE) simulation is now essential in auto companies to evaluate automobile crashworthiness. In order to acquire reliable simulation results, precise material behaviors at intermediate strain rates should be fed as input. Commonly, the mechanical properties of the material change depending on the strain rate and for automotive advanced high strength steel (AHSS), as the strain rate increases, the flow stress tends to increase. Therefore, in order to determine the stress-strain curves at various strain rates, the number of required experiments increases significantly. The present study aims at proposing a new method to obtain the stress-strain curves at various strain rates from a single dynamic experiment. The Virtual Fields Method (VFM) with a rate dependent hardening law was adopted to determine the true stress-true strain curves at intermediate strain rates, which are very important for car crash simulation in practice. The VFM is an inverse analytical tool for deriving the mechanical properties of materials based on the principle of virtual work. A new type of high speed tensile tester for sheet metal specimens was built and high speed tensile tests were performed. Digital image correlation technique using a high-speed camera was utilized to measure strain and acceleration fields so that the identification is carried out from the measured quantities. An advanced rate dependent hardening law was chosen to derive the stress-strain curves at various intermediate strain rates. First, the

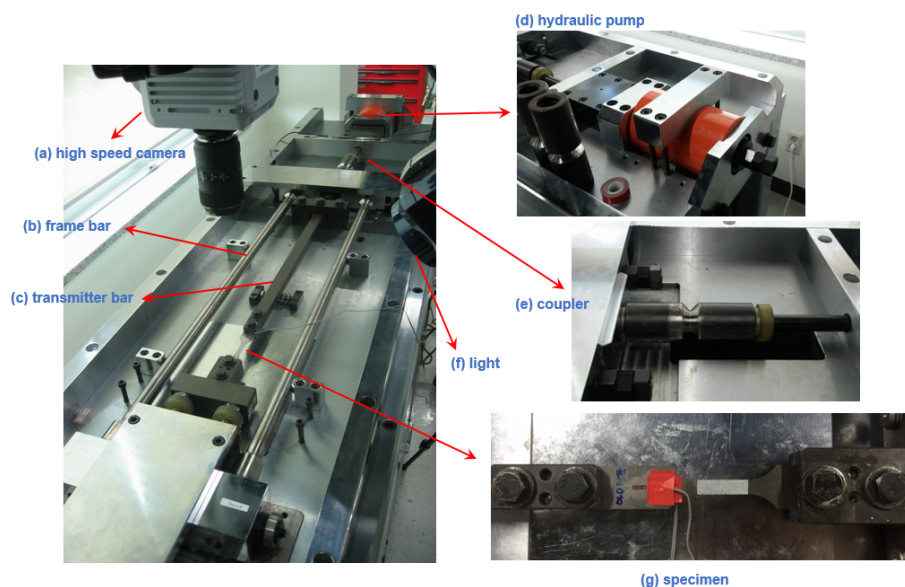


proposed methodology is introduced and the preparatory work and data processing methods to be applied to the actual experiment are explained. Then, experiment results using the VFM with a rate-dependent model are shown.

## 2. Methodology

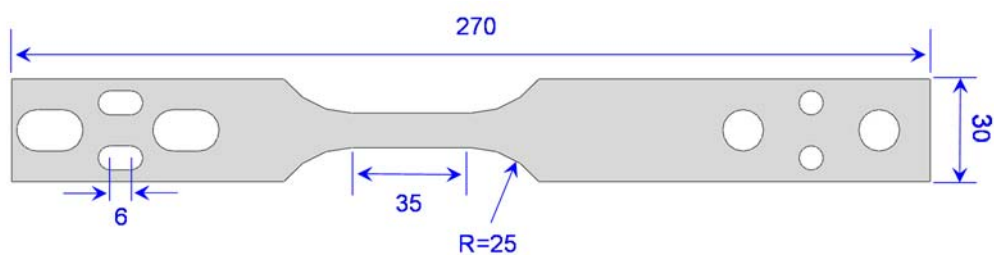
### 2.1. Impact frame high speed test (IFHS test)

In order to validate the proposed methodology in the experiments, a novel high speed tensile tester for sheet metal materials based on [1] has been developed, and the experimental set-up is shown in figure 1. In the high speed tensile tester, two metallic frame bars are connected to a hydraulic pump through a coupler, which is designed to be broken when it is put under a certain amount of load. When the pump starts to impose tensile load on the coupler, the coupler endures the load until it reaches to critical load value and elastic strain energy is accumulated in the frame bars at the same time. If the load is increased to break the coupler, the energy within the frame bars is released so that the specimen connected to a frame module is pulled in tension and acceleration fields are generated on the specimen.



**Figure 1.** The experimental set-up for sheet metal IFHS tests.

A special “dog-bone” type specimen was used for the IFHS tester, as illustrated in figure 2. The holes on one grip side are round, and the holes on the other side are rounded rectangular. For the experimental application, Dual Phase (DP) 780 AHSS material was used. The sheets were 1 mm thickness, and all the specimens were cut in the rolling direction (RD).



**Figure 2.** Specimen geometry for the IFHS tests (unit: mm).

## 2.2. Digital image correlation (DIC) with a high speed camera

In the experiments, high speed tensile tests on sheet metal specimens were conducted and full-field in-plane displacement fields were measured by a digital image correlation (DIC) technique using a high-speed camera (Photron FASTCAM SA-X2). The parallel gauge section was selected as the area of interest (AOI) and speckle patterns were drawn for DIC analysis. The initial size of the AOI was 10 mm (width)  $\times$  35 mm (initial gauge length). The Vic-2D software ([www.correlatedsolutions.com](http://www.correlatedsolutions.com)) was used for DIC analysis. Logarithmic (true) strain fields were obtained from the deformation gradient.

## 2.3. Constitutive model

In this study, von Mises yield criterion under plane stress and Lim-Huh model [2] for an advanced rate dependent hardening law were chosen to retrieve the relationship between stress and strain. The associated flow rule was assumed.

The Lim-Huh model is composed of quasi-static and dynamic terms and the dynamic part contains two strain rate sensitivities of  $q$  and  $m$ .

$$\sigma_s = \sigma_r \frac{1 + q(\varepsilon_p)\dot{\varepsilon}^m}{1 + q(\varepsilon_p)\dot{\varepsilon}_r^m} \quad \text{where} \quad q(\varepsilon_p) = q_1(\varepsilon_p + q_2)^{-q_3} \quad (1)$$

where  $\sigma_s$  current yield stress and  $\sigma_r$  and  $\dot{\varepsilon}_r$  are the flow stress and the equivalent plastic strain rate at quasi-static state and  $\dot{\varepsilon}$  is the current equivalent plastic strain rate. Any hardening equation can be used for  $\sigma_r$ .

## 2.4. The virtual fields method (VFM)

In this study, the virtual fields method (VFM) [3] was used for an inverse method to retrieve the constitutive parameters from the measured deformation fields. The VFM makes use of the principle of virtual work which describes the condition of global equilibrium. The equilibrium equation in the case of elasto-plasticity for dynamic loading, and in absence of body forces, can be written as follows:

$$- \int_V \left[ \int_0^t \frac{d\sigma_{ij}}{dt} dt \right] \varepsilon_{ij}^* dV + \int_{S_f} T_i u_i^* dS = \int_V \rho a_i u_i^* dV \quad (2)$$

where  $d\sigma/dt$  is the stress rate tensor which is a function of  $\dot{\varepsilon}$  (actual strain rate),  $\sigma$  (actual stress) and unknown constitutive parameters,  $V$  the measurement volume,  $T$  the distribution of applied forces acting on the boundary of the specimen  $S_f$ ,  $\varepsilon^*$  the virtual strain field derived from  $u^*$  (the virtual displacement field),  $\rho$  the density and  $a$  the acceleration. The summation convention applies on repeated indices.

Dynamic hardening parameters can be determined by choosing proper virtual fields. In this study, simple virtual fields were applied to find the material parameters as in equation (3).

$$u_x^* = 0, u_y^* = L \quad (3)$$

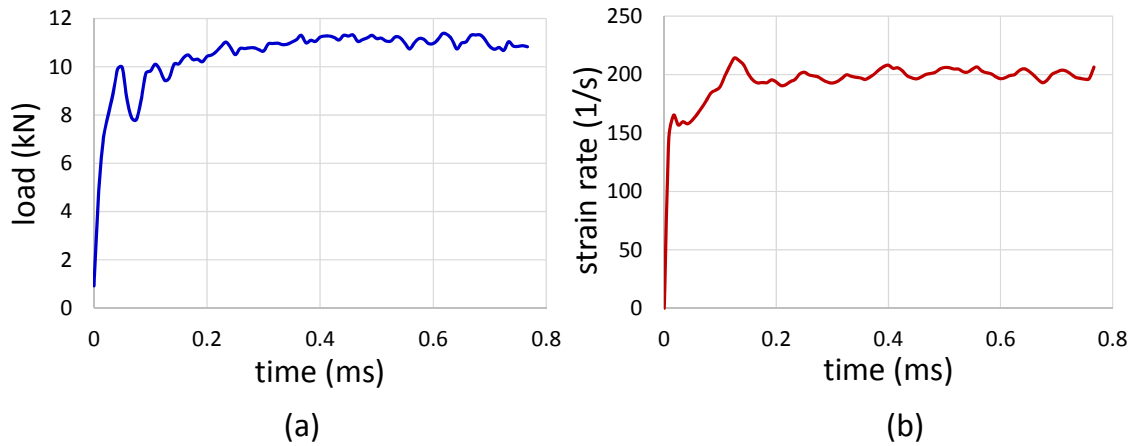
where  $x$  and  $y$  are the horizontal and vertical coordinates and  $L$  is the current longitudinal length of the AOI in the deformed configuration.

## 3. Results

In order to determine the dynamic parameters of Lim-Huh model, it is required to measure the true stress-plastic strain curves  $\sigma_r$  (see equation (1)) from quasi-static tensile tests. The true stress-plastic strain curves at quasi-static were obtained by 0.2 % offset method in the standard uniaxial tensile test and quasi-static strain rate of 0.002 /s was selected for the tests.

In this study, strain gauges were attached to the grip part where the deformation is in linear elastic for load acquisition. It was found that the specimen vibrated in the vertical direction during the experiments due to dynamic effects. To compensate the bending effect, strain gauges were attached to both sides of the specimen at the same position (front and back). Then, the elastic strain data was

extracted from the average voltage and the elastic strain was also converted to load using Hooke’s law. The measured load data obtained from the strain gauges was plotted as a function of time in figure 3 (a) and the evolution of average strain rate is presented in figure 3 (b).



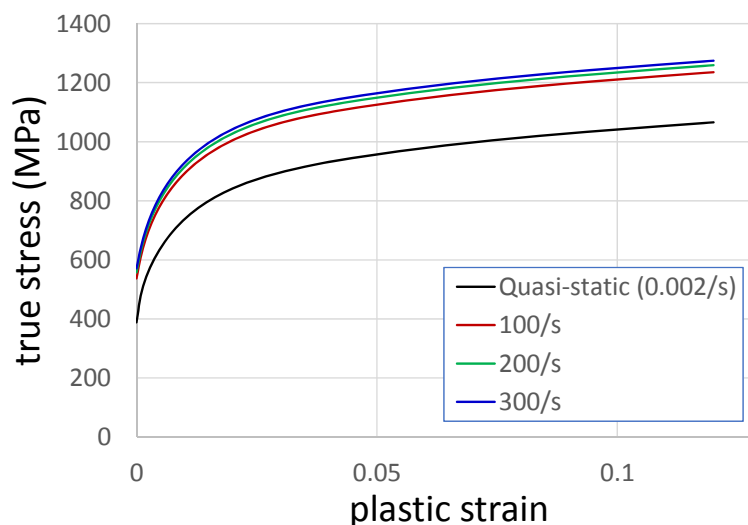
**Figure 3.** (a) The measured load data (b) evolution of average strain rate in the loading direction.

Deformation fields (strain, strain rate and acceleration) were extracted from DIC analysis and used for the VFM analysis. The dynamic parameters of Lim-Huh model were identified as shown in table 1.

**Table 1.** Identified parameters of Lim-Huh model using the VFM.

Parameters	$q_1$	$q_2$	$q_3$	$q_4$
Identified Value	0.077	$4.2 \times 10^{-5}$	0.12	0.16

The resulting stress-strain curves based on the determined Lim-Huh model parameters for strain rates of 100 /s, 200 /s and 300 /s are shown in figure 4 and compared with the quasi-static curve.



**Figure 4.** The identified stress-strain curves at the chosen strain rate for DP780.

#### 4. Conclusion

In this study, a new methodology has been applied to determine the dynamic true stress-strain curve of sheet metals using the virtual fields method (VFM). A new high speed tensile tester was built and high speed tensile tests were carried out on sheet metal specimens using a high-speed camera. The validation of the proposed methodology against experimental measurements was performed. The stress-strain curves of advanced high strength steel at intermediate strain rates (100 /s - 300 /s) were successfully obtained from a single experiment.

#### References

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