# Strain Rate Effects Investigated in Simulation of Dynamic Crush of the Rectangular Beam

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**Abstract:** In vehicle crash simulations, the strain rate effect of different materials has gained more and more attention and application nowadays, which further appeals more understandings on its influence on the modeling results. The paper deals with strain rate effects in impact to the beam under the high strain rate evaluated by simulations combined with experiments. The Cowper-Symonds model is used to describe the dynamic plastic behavior of materials as a function of strain rate. The strain rate distribution is mapped on the beam, and the effect on the deformation, deceleration and the energy absorption is discussed.

**Keywords:** beam; simulation; crash; strain rat

## 1. Introduction

Under the high strain rate, the Yield limit and instantaneous stress of the elastic-plastic material will be higher than under the quasi-static conditions. If the FE material model didn't consider the strain rate, the whole FE models tend to soften especially when the element size increases to about 6-9mm [1,2]. To consider this softening trend and to simulate the vehicle crash physics more accurately, strain rate effects must be taken into account. In addition to better representation of the material response, strain rate sensitivity has an added benefit in promoting computational stability of simulations. During high speed vehicle crash, the strain rate reaches the magnitude of $10^{-3}$ /s to $10^{3}$ /s in the main deformation zone. In one study it was shown that, the principal difficulties are interpretation and reconciliation of the data about material properties obtained from various experimental apparatus [3]. In addition, the material properties in the strain rate orders of magnitude between $10^{1}$/s and $10^{2}$/s have been very difficult to obtain. This range of the strain rate is observed during the where vehicle crash when important events take place.

In many of the previous studies a size of the finite elements could not conform to the detailed features of the vehicle crush due to limitations of computational resources. This large size of finite elements made the structures relatively stiff [3]. In such simulations it was not obvious to consider the effects of strain rate. With the continuous development of computer technology, the FE models become more and more accurate. New structural experiments, accompanied by FE models have shown how these experiments can be used for material characterization of the deformation modes [4]. The new method described above has been used to study the crush of tube by the FE model at the ranges of strains and strain rates in the condition of different element sizes. When the element size decreases, the range of strain and strain rate will increase. In this study the simulation results were compared to experimental one from drop tests. It seems that such approach is very efficient in studies dealing with material properties loaded dynamically with high strain rate.

Therefore in the current study we decided to use this approach applied it in investigation of properties of rectangular welded beam and type of material as found in one production car. Two simulations of the impact to this beam at three velocities that are common in car crashes were performed with FE model and we compared the results with ones from experiment. The analysis was performed about strain rate effects simulated by Cowper-Symonds model by mapping the strain rate distribution on the beam. Moreover we studied the effects of strain rate on the behavior of simulated vehicle structure such as deformation, section force, deceleration and the internal energy absorption.

## 2. Methodology

The strain rate effects were evaluated by comparison of results from simulations and experiments at three various speeds. The main attention was put on the speeds of impact that are representative to these from car collisions. Three frontal collision experiments were conducted; the speed was 25 km/h, 35 km/h, and 50 km/h to simulate the low, middle and high car speed, respectively. The installation of beam in impact experiments is shown in Fig. 1.

**Figure 1. The installation of beam in impact experiment**

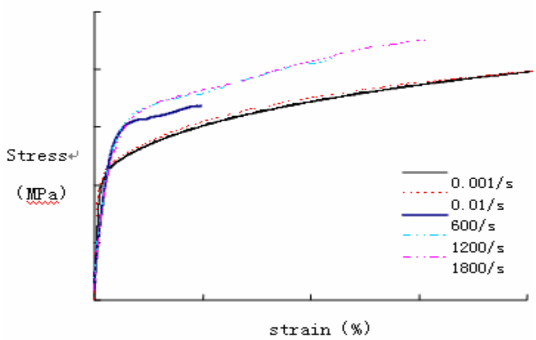
National "863 Program" (2006AA110101), the MOE & SAFEA of the P.R. China "111 program" (111-2-11), the MOF "ZQ Project" (2007-237), Hunan University SKLVB (60870004).

The beam was selected from production car. The length of this beam is 470 mm; it is a composition of front and rear parts connected by laser- welding. The material of front part is B340-590DP, and rear one is SAPH440. The experimental stress-strain curves are shown in Fig. 2. On each side of the beam the two energy absorption cylinders were added for protection of the sled. The length of these tubes at the case of 50 km/h was 300 mm, and for other velocities 200 mm. The simulated weight of the car was 1020 kg.

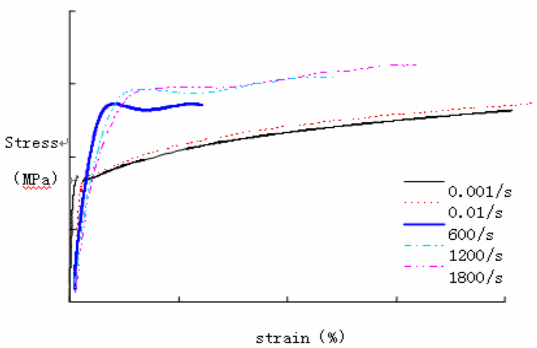
The corresponding FEM model of the beam is shown in Fig. 3. The element size used is 5×5 mm according to the reference literature [4]. There are a number of constitutive models that have been proposed and successfully used to describe the dynamic plastic behavior of materials as a function of strain rate, and MAT-24 (Piecewise Linear Plasticity) is the most common used. At current study, we selected the commonly used constitutive equation for strain rate sensitivity, the Cowper-Symonds model [5]:

$$\sigma_y = \sigma_0[1 + (\frac{\dot{\varepsilon}}{C})^{\frac{1}{p}}]$$

Where $\dot{\varepsilon}$ is the strain rate, $\sigma_y$ is the dynamic yield stress, $\sigma_0$ is the quasi-static yield stress. C and P are material parameters for strain rate effects. Both parameters C and P can be obtained from quasi-static and dynamic tensile test results presented in Fig 2. They are C=1.8, P=3.0 for the frontal part of the beam, and for the rear one C=8, P=5.




B340-590DP




SAPH440

**Figure 2. Stress- stain curves at different strain rate**

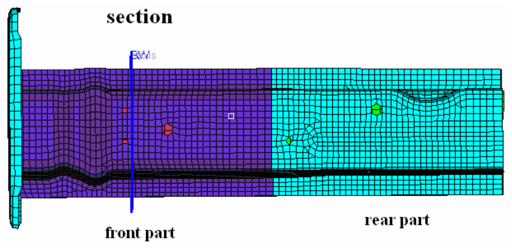



**Figure 3. FEM model of beam**

The main idea of the study is that we can use the acceleration of the sled to validate the FEM model response when strain rate dependency is or not considered by comparison with simulation results. Secondary from the same simulations considering strain rate we made mapping of the distribution of this strain rate within the beam in two directions (width and length). When mapping strain rate distribution on the width of the beam we selected three cross section areas corresponding to wave crest, wave through and equilibrium as shown in Fig. 4a. When mapping strain rate distribution on the length we selected two positions: edge-line and midline as shown in Fig. 4b. Analyzing this distribution the areas with highest strain rate were found. Further we compared deformation pattern regarding the shape of deformation and the pattern of all folds. Finally the cross sectional force in the area with the highest strain rate was also compared between the simulations with and without strain rate.

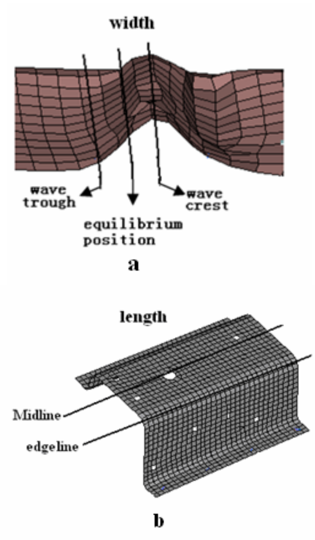
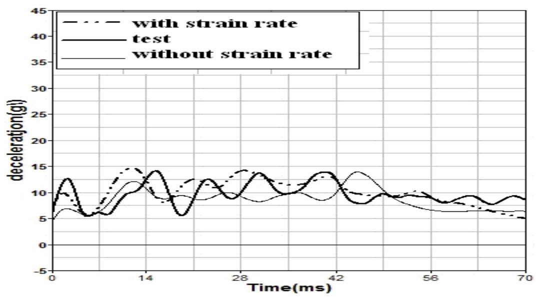



**Figure 4. Selection the places of mapping the strain rate distribution**

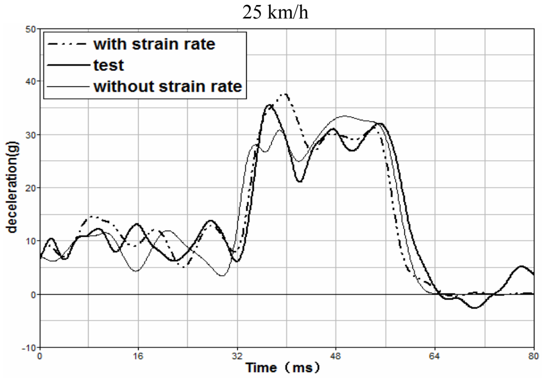
## 3. Results

### 3.1. Model Validation by Comparison of Sled Deceleration

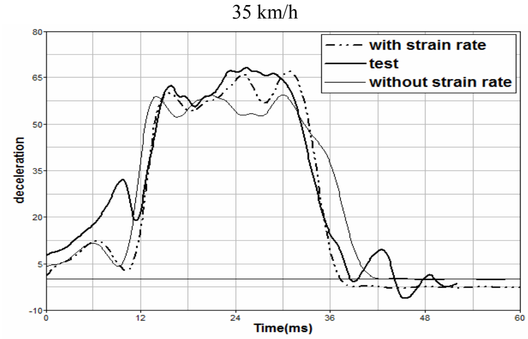
The deceleration curves under various impact velocities are shown Fig. 5. The profile and maximum value of the deceleration curve, when strain rate effect is considered, are closer to the test data than from the simulations without strain rate dependency in which computed deceleration curve is evidently on lower level than that from the experiment. Especially when discussing the peak value of acceleration we can found that difference between simulations is about 20%, which is a large difference. When the deformation is reaching the cylindrical tubes the deceleration curve increases dramatically. In both simulations at 35 km/h and 50 km/h deceleration curve starts to increase rapidly, in the cases without strain rate dependency earlier than in the cases with strain rate dependency. The main reason causing this phenomenon is that the yield limit in cases without considered strain rate dependency is lower than in cases when strain rate dependency is simulated. Therefore the finite element model without strain rate dependency seems be too soft in relation to data from experiments when the model considering strain rate is reliable.




25 km/h




35 km/h

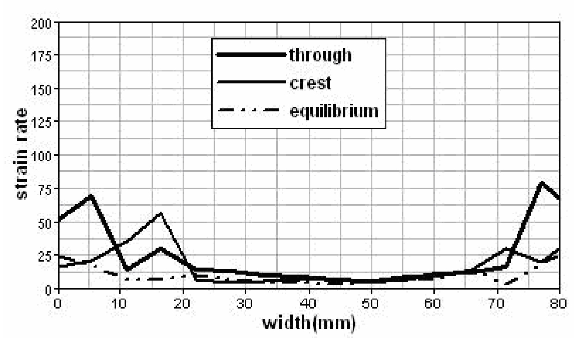



50 km /h

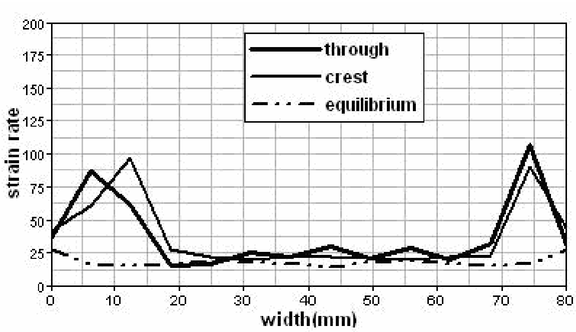
**Figure 5. The deceleration curve under various impact velocities**

## 3.2. Strain Rate Distribution mapped on the Beam Width

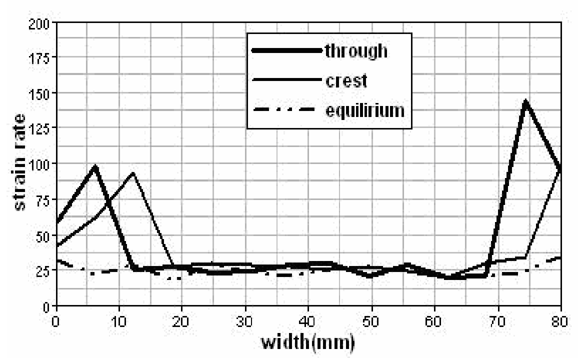
Fig. 6 shows the maximum strain rate distribution mapped on the original beam width at investigated impact velocities. From the figure it is clear that, in the wave crest and trough, the strain rate at both sides of the beam is greater than in the middle part, and in the equilibrium position is almost at the same level. When the impact velocity increases, the strain rate increases accordingly, but not so much, only $10^1$/s and $10^2$/s.




25km/h




35 km/h




50 km/h

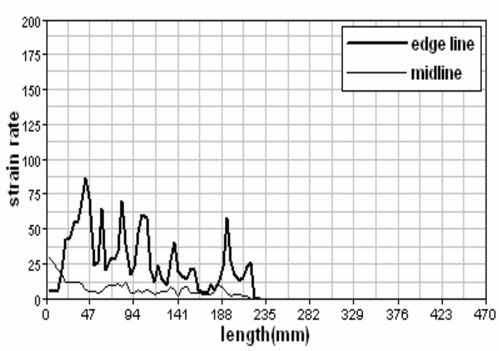
**Figure 6. Maximum strain rate distribution mapped on the beam width**

## 3.3. Strain Rate Distribution Mapped on Beam Length

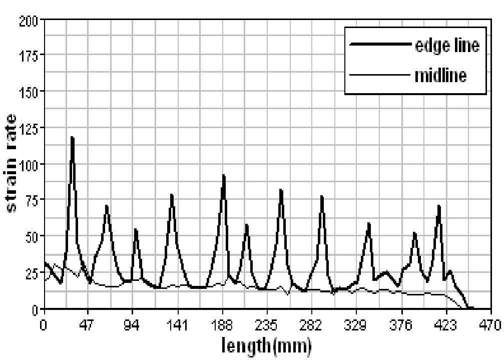
Fig. 7 shows the maximum strain rate distribution mapped on the beam length at investigated impact velocity. On the edge line of the beam, the strain rate distribution is in form of waves; there are obvious peaks and valleys, generally the largest peak corresponds to beginning of deformation. The positions of the strain rate peaks correspond to the beam's folding wave crests and troughs, and the positions of the strain rate troughs correspond to the beam's folding equilibrium positions. With the increase of impact velocity, the peak values of strain rate increase. In the simulation at 50 km/h the maximum strain rate appears in the second wave crest and reached 168/s. On the middle line of the beam the differences between strain rates at investigated velocities are basically small, and maintains at the same level without obvious peaks and valleys over whole length of the beam. The results show that, the stress and strain at edges is much larger than in the middle section of the beam and energy absorption in the edge region play a major role. Similarly to the investigation of the strain rate distribution on the beam width, when the impact velocity increases, the strain rate increases accordingly over beam length, but not so much, only $10^1$/s and $10^2$/s. The front and rear of the beam has different materials in the simulation, but the magnitude of the strain rate is at the same level.

### 3.4. Comparison of Deformation Shape

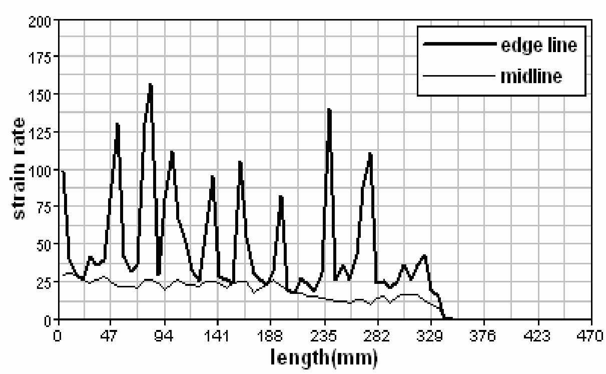
Fig. 8 shows the comparison of deformation at investigated impact velocities. When the strain rate is considered the deformation is close to the experiment. The deformation in simulation without strain rate dependency



25 km/h



35 km/h



50 km/h

**Figure 7. Maximum strain rate distribution mapped on the beam length**

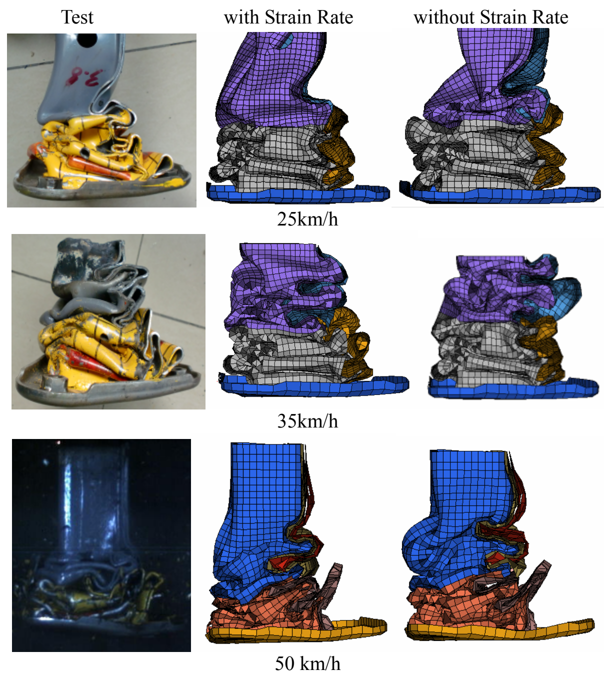



**Figure 8. Comparison of deformation at various velocities**

shows larger difference. Especially in edge area of the rear segment, the folding deformation is deviate. We can see that the model considering the strain rate dependency is proved to be effective also in prediction of the deformation. To make easier to see the differences between simulations with and without strain rate dependency Fig. 9 shows the profiles of deformation at investigated impact velocities.

### 3.5. Strain Rate Effect on the Energy Absorption

Table 1 shows the comparison of internal energy; it is obvious that the strain rate has significant effect on the energy absorption by the structure during the impact. With the increase of velocity, the energy ratio increases accordingly. At impact velocity of 50 km/h, the difference of energy absorption can reach 24%.

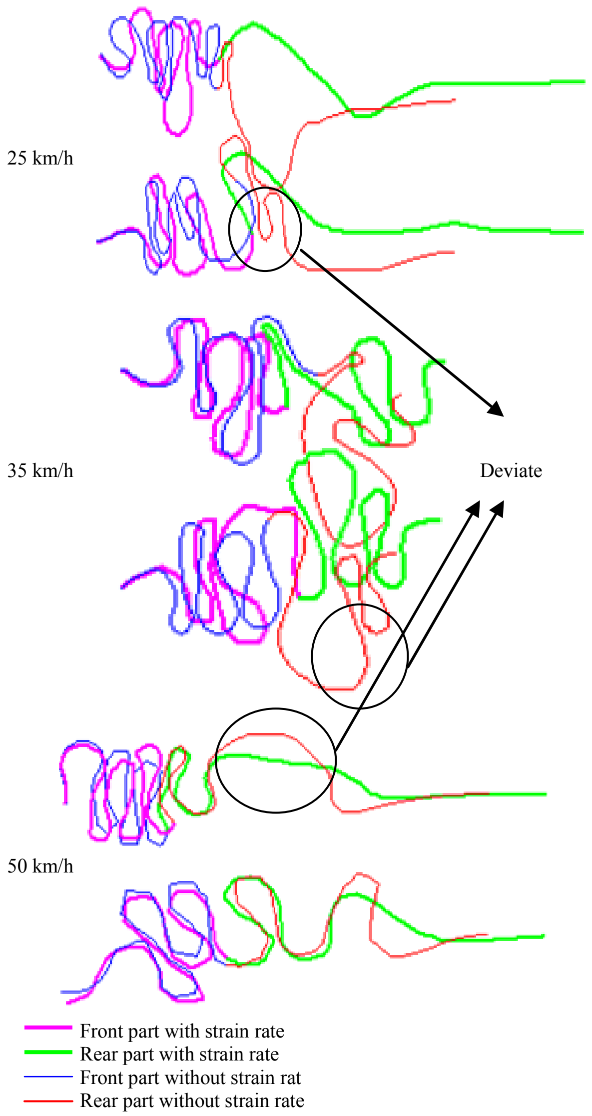



**Figure 9. Profiles of deformation at various impact velocities**

**Table 1. Component internal energy at various velocities**

| Velocity [km/h] | With strain rate[J] | Without strain rate[J] | Energy Ratio |
|---|---|---|---|
| 25 | 25246 | 23149 | 1.09 |
| 35 | 35843 | 30789 | 1.14 |
| 50 | 42389 | 34032 | 1.24 |

### 3.6. Comparison of Cross-Section Force

The Fig. 10 shows the cross-section force at investigated impact velocities. From the point of view of car crashes, this force in simulation at 25 km/h without strain rate dependency is basically close to that including strain rate. When impact speed increases to 35 km/h, the deformation of the component becomes more complex. With the increase of impact speed, the difference between the results computed with and without strain rate becomes larger and more evident, for example at the speed of 50 km/h, the difference between these two peaks reached 34%. Also it can be observed that the time occurrence of the peak without strain rate is earlier than with strain rate, about 5 ms.

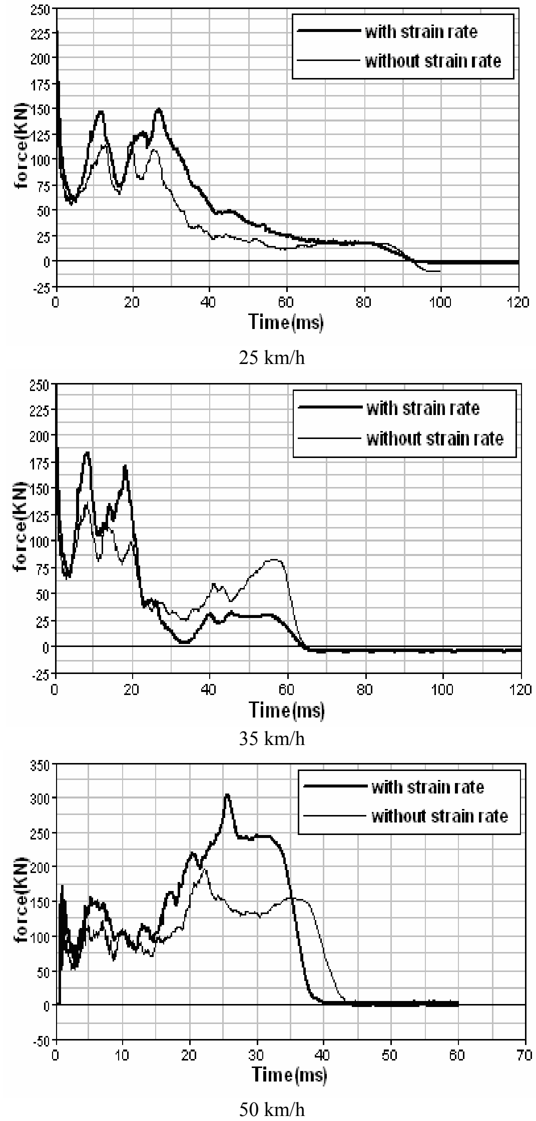



**Figure 10. Comparison of cross-section force**

## 4. Discussion

We found in the study that the distribution of high strain rate is mainly near the beam edges, and the magnitude is between $10^1$s and $10^2$/s. The folding deformation in simulation without strain rate is more obvious, and for example in the rear segment, this deformation deviate, as SAPH is more sensitive to the strain rate than 590DP.

## 5. Conclusions

The analysis performed within the study shows that, strain rate sensitivity is an important component of the material models and needs to be commonly used in the crashworthiness models. The analysis of results from FEM simulations of the impact to rectangular beam model showed that the strain rate distribution mapped on the beam is in the range $10^1$/s and $10^2$/s. With the increase of velocity, the magnitude of the strain rate is also increased and the highest values, which are in form of waves, are observed in the edge area of the beam. The magnitude of the strain rate of the both materials of the beam is at the same level. Strain rate dependency has great influence on the deceleration, section force, and it's mainly reflected in the peak values of these curves. The difference between deceleration two peaks of with and without strain rate reached 24%, and the section force reach 34%. We found the important differences between the two models in general for all the parameters evaluated within the study.

## Acknowledgement

The study is sponsored by the Ministry of Science and Technology in National "863 Program" (2006AA110101), the Ministry of Education and State Administration of Foreign Expert Affairs of the P.R. China in "111 program" (111-2-11), the Ministry of Finance in "ZQ Project"(2007-237), Hunan University State Key Lab of Advanced Design and Manufacturing for Vehicle Body in "Autonomous Project" (60870004).

## References

[1] Needleman, A. Material rate dependence and mesh sensitivity in localization problems. Computer Methods in Applied Mechanics and Engineering, vol. 67, no.1, p. 69-85, 1988.

[2] Mahadevan K., Fekete J. R., and Liang P., Effect of strain-rate in full vehicle frontal crash analysis, SAE Paper 2000-01-0625.

[3] Tam, L.L., Calladine, C.R. Inertia and strain-rate effects in a simple plate-structure under impact loading International Journal of Impact Engineering, vol. 11, no. 3, p 349-377, 1991.

[4] Simunovic S., Nukala P Kumar V. V., Fekete J., Meuleman D., Milititsky M., Modeling of Strain Rate Effects in Automotive Impact. SAE Paper, 2003 - 01 - 2383, 2003.

[5] Ls- Dyna, Keyword User's Manual Version 970, 2003.

[6] Xie S.G., Xu L.W., Fang K.H., Wu S.R.: Discussion on Strain Rate Effects in Numerical Simulation of Vehicle Crash, SAE Paper, 2008 - 01 - 0504,

[7] Bleck W., Schael I., Determination of crash-relevant material parameters by dynamic tensile tests Steel Research, vol. 71, no. 5, p 173-178, 2000

[8] Mahadevan K., Fekete J. R., and Liang P., Effect of strain-rate in full vehicle frontal crash analysis, SAE Paper 2000-01-0625.

[9] Liang, R.Q., Khan, Akhtar S., Critical review of experimental results and constitutive models for BCC and FCC metals over a wide range of strain rates and temperatures, International Journal of lasticity, vol 15,no. 9, p 963-980, 1999.

[10] Mahadevan K., Fekete J. R., Schell B., McCoy R., Faruque O., Strain-Rate Characterization of Automotive Steel and the Effect of Strain-Rate in Component Crush Analysis, SAE paper 982392, 1998.