Simulation and analysis of vehicle rear-end collision based on virtual proving ground technology

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ABSTRACT. *To develop a reliable method for vehicle collision simulation, this paper carries out the computer simulation on rear-end collision of a passenger car based on the explicit dynamic finite-element theory. Firstly, a finite-element model of vehicle real-end collision was established by the virtual proving ground (VPG) technology and grid meshing. Next, a simulation of vehicle real-end collision was conducted according to the safety regulations of the United Nations Economic Commission for Europe (UNECE). The data on stress distribution, body deformation, body acceleraton and dummy injury were captured by the explicit dynamics analysis software LS-DYNA, and plotted into curves and cloud maps. The results show a stress concentration on the rear-ended vehicle, calling for structural improvement, and reveal the robustness of the VPG-based finite-element model in the prediction of vehicle crash safety. The research findings lay a solid basis for the evaluation of vehicle quality.*

RÉSUMÉ. *Pour développer une méthode fiable de la simulation de collision des véhicules, cet article effectue la simulation par ordinateur de la collision par l'arrière d'une voiture de tourisme basé sur la théorie d'éléments finis explicites dynamiques. Tout d'abord, un modèle d'éléments finis de collision par l'arrière des véhicules a été établi grâce à la technologie de terrain d'essai virtuel (VPG, le sigle de « virtual proving ground » en anglais) et au maillage de grille. Ensuite, une simulation de collision par l'arrière des véhicules a été réalisée conformément au règlement de sécurité de la Commission économique pour l'Europe des Nations Unies (CEE-ONU) (en anglais United Nations Economic Commission for Europe, UNECE). Les données sur la répartition des contraintes, la déformation du chassis d'un véhicule, l'accélération de véhicule et les blessures de dispositif anthropomorphe d'essai ont été capturées par le logiciel d'analyse de dynamique explicite LS-DYNA, puis tracées dans des courbes et des cartes de nuages. Les résultats montrent une concentration de contraintes sur le véhicule par l'arrière en demandant une amélioration structurelle, et révèlent la robustesse du modèle à éléments finis basé sur le VPG pour la prévision de la sécurité en cas de collision.*

Les résultats de la recherche constituent une base solide pour l'évaluation de la qualité des véhicules.

KEYWORDS: *vehicles, safety performance, rear-end collision, virtual proving ground (VPG) technology, explicit dynamic finite-element theory.*

MOTS-CLÉS: *véhicules, performances de sécurité, collision par l'arrière, technologie de terrain d'essai virtuel (VPG), théorie d'éléments finis explicites dynamiques.*

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1. Introduction

With the explosive growth of car ownership, recent years has seen an upsurge in the number of traffic accidents in China. Against this backdrop, vehicle crash safety has become a hot topic in the academia. Statistics show that the rear-end collision is major type of traffic accidents, next only to front and side collisions. As a result, automakers are competing to improve vehicle safety from this angle (Wang *et al.*, 2016).

Traditionally, vehicle crash studies mainly rely on real vehicle collision test and trolley collision test (Chen *et al.*, 2010; Lin *et al.*, 1998). The former is a destructive test on the sample vehicle, while the latter is an approximate test. Despite the long cycle and high cost, the real vehicle collision test often outputs unrealistic and recurring results. The trolley collision test is less costly and more efficient than the real vehicle collision test. Nevertheless, the analytical results of this test are faced with a large error.

To overcome the limits of traditional approaches, many scholars have implemented the computer simulation technology into vehicle collision research (Gong *et al.*, 2000). Early in the research and development (R&D) phase, a virtual vehicle model can be built on the computer for simulation and analysis. With the aid of this model, the researchers manage to simulate collision modes that cannot be realized in real vehicle collision test in a short cycle and at a cheap cost. In addition, popular collision simulation software, such as PAM-CRASH, MADYMO, LS-DYNA3D and VPG are constantly updated (Li, 2005; Chen *et al.*, 2016), laying a solid basis for rational, convenient and accurate vehicle simulation.

In accordance with the safety regulations of the United Nations Economic Commission for Europe (UNECE), this paper constructs a finite-element model for vehicle rear-end collision based on the virtual proving ground (VPG) technique. Then, the model was solved by the LS-DYNA to achieve accessible and reliable simulation of vehicle rear-end collision in computer. The research findings contribute greatly to the development of automotive products.

2. Vehicle collision CAE simulation technology

Currently, major auto makers at home and abroad have widely been using virtual prototype software to make practical studies on vehicle collision. By contrast, VPG technology mainly features (Gao, 2011; Wang *et al.*, 2011).

The VPG/Structure module allows user to create a multi-body dynamics model of a mechanical system on the accounts of the vehicle's flexibility characteristics, and is superior to other simulation software in the terms of accuracy and reliability of the simulation model.

The VPG/Safety module integrates the safety regulations, 17 articles in total, of FMVSS in the United States and ECE to streamline complex simulation analysis. And more importantly, there are various obstacles, dummies, pendulum and seat belts and other models in the collision tools library, so that it outperforms other software in the terms of practicability and accessibility.

3. Establishment of finite element model of vehicle collision

In general, the nonlinear finite element method is generally used in the study to discretize the continuous spatial system and connect various parts of vehicle from the nodes in order to create the full vehicle modeling. The curves can be plotted for part deformation, speed and acceleration, stress and strain based on the calculation. In order to improve computational efficiency, a hybrid modeling method that integrates the rigid multi-body dynamics and non-linear finite element now prevails (Yang, 2006).

3.1. Deformation theory of collision system

The vehicle is composed of quality points. The deformation of a vehicle refers to the process that a mass point *A* shifts from the position coordinate X_A at the initial moment to the $X_B(X_A, t)$ within time *t*, where X_B is the function of coordinate X_A and time *t*.

3.2. Momentum equation of the collision system

The vehicle meets the momentum conservation law during the collision. According to cauchy momentum equation, the Eq.(1) holds:

$$\frac{\partial \sigma_{ij}}{\partial x_j} + \rho f_i = \rho \ddot{x}_i \tag{1}$$

Where: σ_{ij} is the cauchy stress tensor; x_j is the mass point coordinate; f_i is the body force; ρ is the instantaneous density of object; $\ddot{x}_i$ is the acceleration.

3.3. Energy equation of collision system

The total energy during the vehicle collision is determined by Eq.(2) (Qian *et al.*, 2017):

$$E=1/2(mv^2) \tag{2}$$

Where: v is the speed; m is the mass.

The plastic strain energy during vehicle collision can be determined by Eq.(3) (Trancossi et al., 2016; Biserni and Garai, 2016):

$$\dot{E}_1 = \int_V S_{ij}\dot{\varepsilon}_{ij}dV \tag{3}$$

Where: V is the volume; S_{ij} is the stress deflection tensor; $\dot{\varepsilon}_{ij}$ is the strain rate tensor.

3.4. Contact collision finite element theory

Contact in the analog computation of vehicle collision is in fact the contact force, determined by Eq. (4) (Cao *et al.*, 2015; Mohammed and Ali, 2016):

$$m\ddot{s} = F_e + F_c - F_i \tag{4}$$

Where: m is the mass matrix; $\ddot{s}$ is the acceleration vector; F_e is the external force vector; F_c is the contact force vector; F_i is the internal force vector.

4. Establishment of vehicle collision simulation model

4.1. Establishment of complete vehicle collision simulation model

The 3D model built by the CAD system is imported into the VPG software to construct the finite element model (Feng, 2016).

The model element type is defined. The vehicle body is spliced by welds after sheet stamping and is defined as a Shell 163 unit. The other parts are defined as the Solid 164 unit. S/R Hughes-Liu algorithm is adopted for units. Grid partition is achieved by using Topology technology.

Properties of model material are defined. Since the structural strength of vehicle body is highly required, the body is mainly made of mild steel sheet with high tensile property, defined as Piecewise-Linear-Plasticity material. The Cowper-Symbols model allows for the impact of material strain rate (Zhao, 2008; Huang *et al.*, 2016). The stress-strain curve is shown in Fig.1.

Window glass is defined as a brittle material, and the foam is used as the energy absorbing material in the front of the vehicle. The basic parameters of several materials are shown in Table 1.

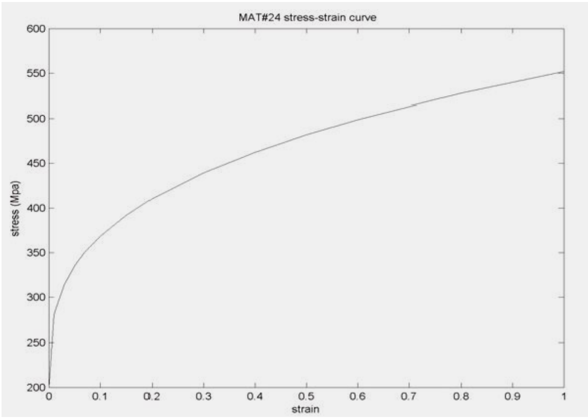

Figure 1. Stress-strain curve of Piecewise-Linear-Plasticity material

Table 1. Material parameters

	Elastic modulu (GPa)	Yield limit (MPa)	Density (kg/mm^3)	Poission raito
Steel	207	235	8.613×10^{-6}	0.28
Glass	7	150	2.5×10^{-6}	0.3
Foam	1	1000	2.56×10^{-6}	0.3

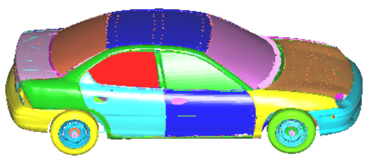

Figure 2. Complete vehicle finite element model

The connection method is defined. Body cover, skeleton is generally jointed by spot welding. During the collision simulation, the locations of solder joints and their failure conditions have a certain impact on the reliability of the collision results. In VPG, the welding spot is defined by the Spot-Weld unit. The number of vehicle welding spots are 2505.

After the model element type, the material properties and the connection mode are all defined, the complete vehicle finite element model is shown in Fig.2.

4.2. Establishment of crash dummy model

The dummy model in the VPG dummy library is chosen, whose H-point shall be defined to coincide with the R-point of the seat. After the position of the dummy in the vehicle is determined, the sitting posture of the dummy is adjusted according to the cab space and the seat position, including the adjustments of the dummy H-point position, torso angle, legs and feet; dummy arms; dummy restraint system; dummy and relative position adjustment of dummy in the vehicle (Han and Wang, 2006). After adjustment, the relative position of dummy in the vehicle is shown in Fig.3.

Figure 3. Full vehicle model after dummy position adjustment

4.3. Establishment of model contact interface

When the rear-end collision is treated, two commonly used contact forms are selected. The body self-contact is defined as Auto-Single-Surface-Contact (ASSC), and the interbody contact as Automatic-Surface-To-Surface (ASTS). The penalty function method is used to create the contact interface and solve the contact collision problem.

4.4. Simulation test system

The test vehicles are imported into the VPG simultaneously. All parts of two vehicles are set up Part Set, respectively, and then turn off one of them. The VPG "Transform" command is used to adjust the other vehicle to make both of them as close as possible or moderately.

After the vehicle model is established with appropriate contact and the constraint system as set, this system for collision simulation test is shown in Fig.4.

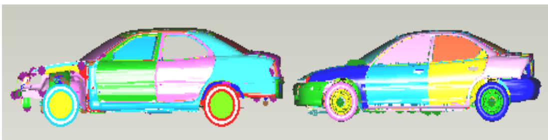

Figure 4. System for collision simulation test

5. Analysis of simulation results

According to the requirements of the ECE system of European Collision Regulations, the static rear-end simulation test is performed with the rear speed of 36km/h and the front car as stationary. Dynamic rear-end simulation tests show that the car speed before collision is 10km/h and the car speed after collision is 60km/h. The data of stress distribution, body deformation cloud, body acceleration and dummies injuries during the collision of the two vehicles are obtained, and the safety of the simulated vehicle is evaluated.

5.1. Analysis of body stress

In the static rear-end collision simulation test, the stresses nephogram of two collision vehicles at 0ms, 54ms, 90ms are shown in Fig.5.

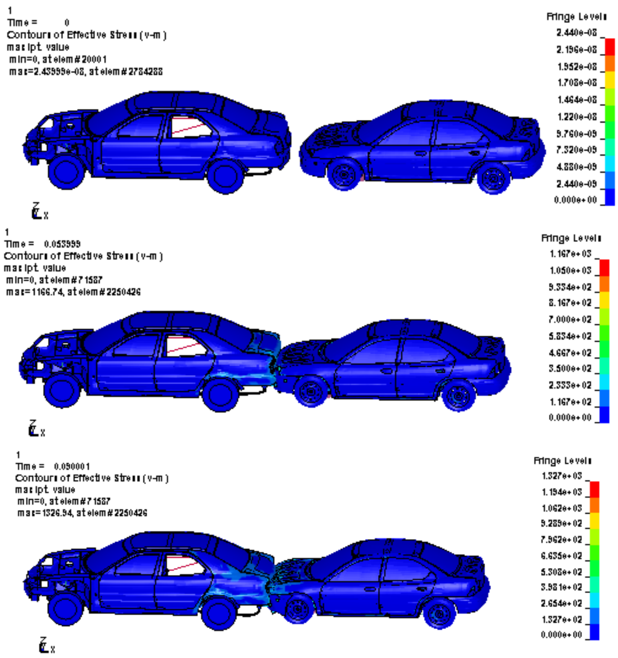

Figure 5. Stress nephogram of vehicle body in static rear-end collision simulation test

We can learn from the above figure that in the whole rear-end collision process, the stress distribution of the vehicle exterior cover is more reasonable without concentration phenomenon. The maximum stress unit is the rear bumper at 265Mpa.

In the dynamic rear-end collision simulation test, the stresses of two collisions at 54ms, 90ms are shown in Fig.6.

The disassembly of rear-end process is shown in Fig.7.

As shown above, the rear bumper on the rear-ended vehicle is crushed in the whole collision process, with the maximum stress of 342Mpa, while there is a stress concentration phenomenon on the engine compartment of the rear vehicle in the front part. The floor is wrinkled.

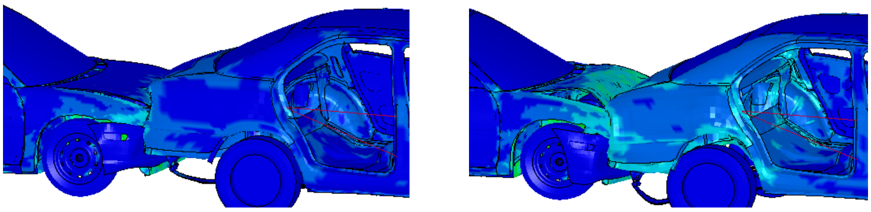

Figure 6. Body stress in the dynamic rear-end collision simulation test

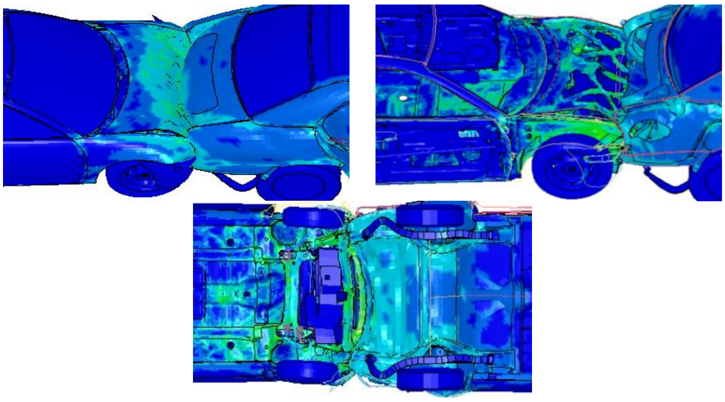

Figure 7. Disassembly of stress distribution in dynamic rear-end process

5.2. Body deformation analysis

In the static rear-end collision simulation test, the deformations of two vehicles at 54ms, 90ms are shown in Fig.8.

It can be seen from the figure that after the rear-end collision, the rear bumper of front vehicle suffers great deformation. There is a large deformed displacement in the middle part, which, together with deformed area, continuously increases at 54ms-

90ms. We can learn from the energy equation of the collision system that in the collision process, the stress that the huge impact force acts on the body far exceeds the yield limit of the material so that a greater plastic deformation occurs. The system kinetic energy converts into internal energy.

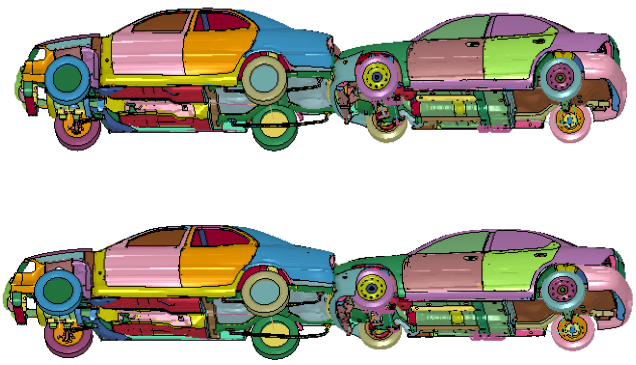

Figure 8. Vehicle body deformation of static rear-end collision simulation test

In dynamic rear-end collision simulation test, the deformations of two vehicles at 54ms, 90ms are shown in Fig.9.

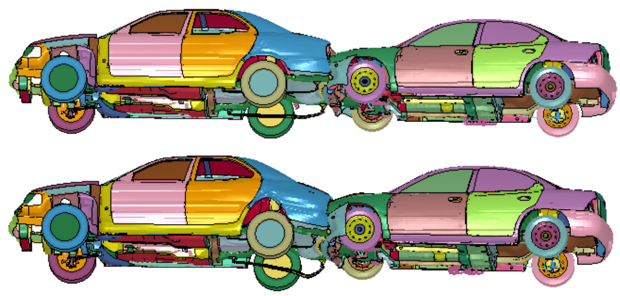

Figure 9. Body deformations in dynamic rear-end collision simulation test

As shown in figure, at 54ms, the rear part of the body has been severely deformed, and at 90ms, the dramatic deformation occurs on the rear body, the trunk cover and the rear fender severely distort and deform. Since the rear cabin does not form a closed bearing structure, and the frame absorbs much less energy during the collision, most of the collision energy is applied to the trunk cover, the rear side member and the rear fender.

5.3. Analysis of body energy

The curves of kinetic energy, internal energy and total energy of vehicles during the rear-end collision are shown in Fig.10.

As can be seen from the figure, the kinetic energy and the internal energy in the process of collision are basically offset from each other, while the total energy curve slightly moves down. This shows that part of the energy loses during the collision, but the overall energy is still conserved.

According to the law of energy conservation, it is proved that the simulation model constructed in this test meets the standard of real vehicle.

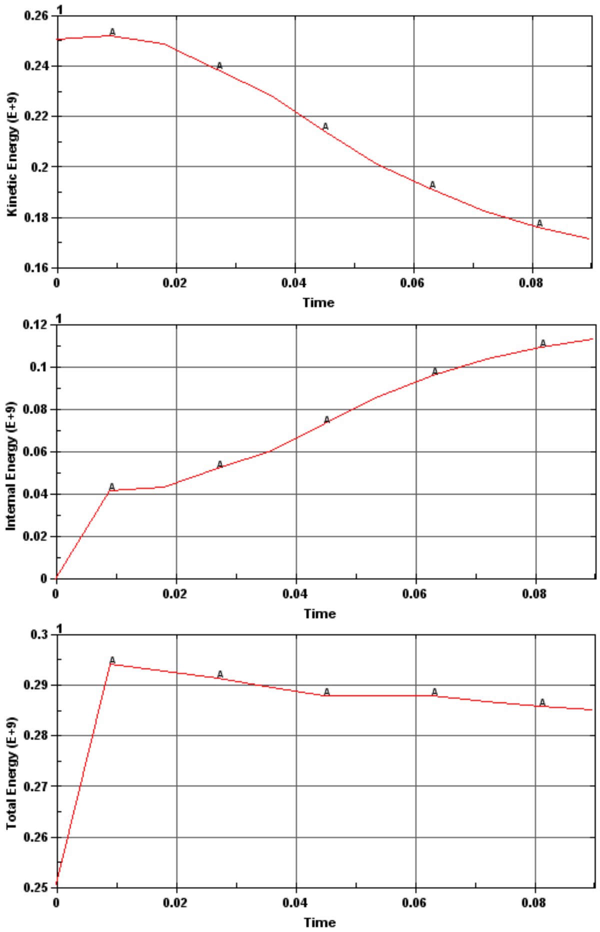

Figure 10. Curves of kinetic, internal and total energies of vehicles during rear-end collision

5.4. Analysis of body acceleration

There are three measuring points set on the bumper of the rear-end collision vehicle and one more added outside B-column of rear-ended vehicle to approximately evaluate the protection capacity for the occupants in the event of a collision. The positions of the three measuring points on the bumper and on the outside of the B-column are shown in Fig.11.

The acceleration curves of three measuring points on the bumper and on the outside of the B- column are shown in Fig.12-14.

As can be seen from the figure, the body acceleration reaches the peak for 4 times, and fluctuates greatly within 0-80ms, which causes a great harm to the driver.

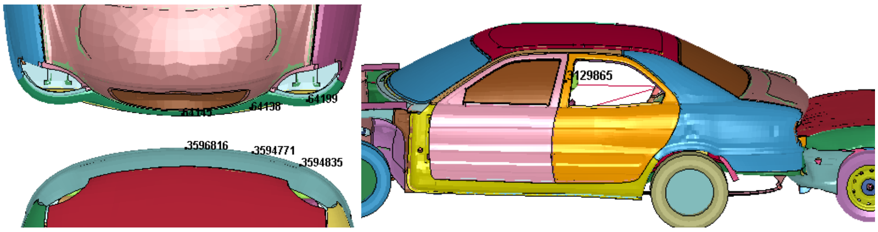

Figure 11. Positions of three measuring points on the bumper and on the outside of B-column

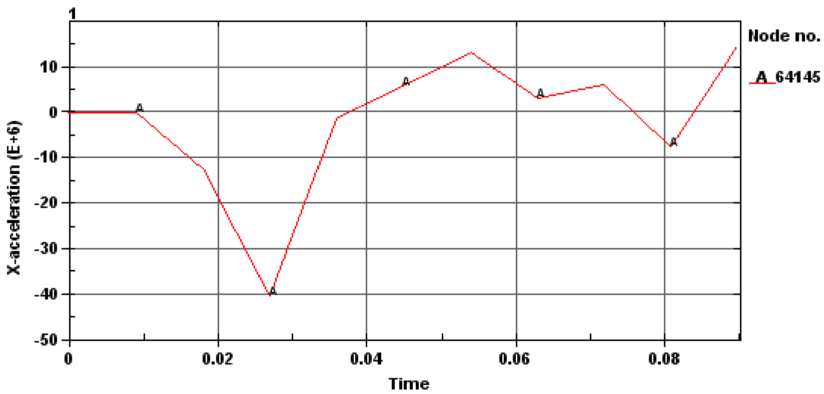

Figure 12. Curve of central point on rear bumper of rear-ended vehicle

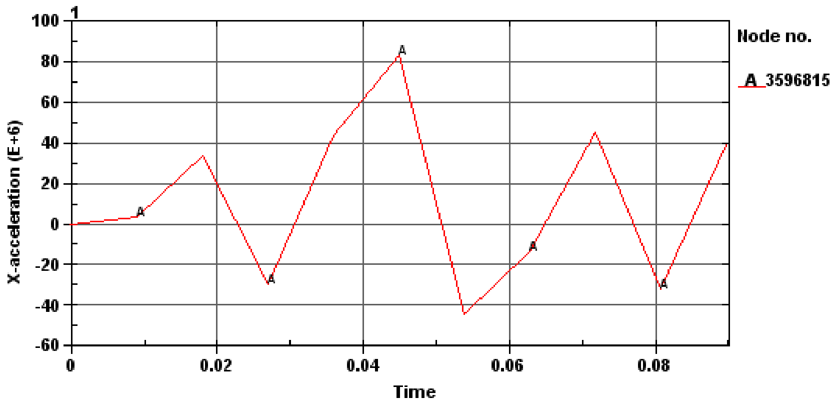

Figure 13. Curve of central point on front bumper of rear-ended vehicle

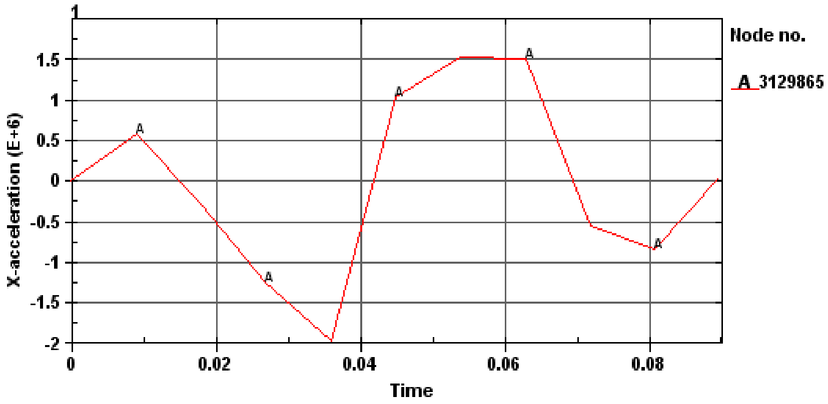

Figure 14. Curve of measuring point outside B-column

5.5. Evaluation of dummy injury index

Dummy neck injury index is used as a key parameter to evaluate the passive safety of rear-end vehicle.

An example of the dynamic rear-end collision simulation test is given in this paper to probe into the dummy injuries caused by rear-end collision. The dummy does not touch the rest of the vehicle during the collision, except for the seat. In accordance with the relevant regulations, it is believed that other parts of the dummy comply with the relevant standards. When the maximum deformation occurs on the body during rear-end collision, the shapes of the dummy and seat are shown in Fig.15.

Figure 15. Shapes of dummy and seat

In the dynamic rear-end collision simulation test, the acceleration curve of dummy neck is shown in Fig.16.

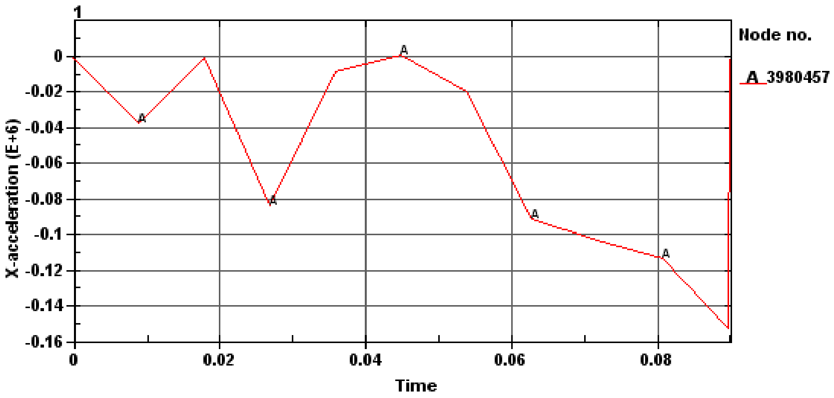

Figure 16. Acceleration curve of dummy neck

As shown in the figure, the peak value of the dummy neck acceleration appears at 10ms, 26ms and 90ms, and gradually increases and rebounds within 30-45ms, which shows that the simulation vehicle structure has a certain resistance to deformation and attenuates the impact. It is proved again that the simulation and dummy models are in line with real vehicle conditions.

6. Conclusion

The virtual simulation model is established for vehicles based on VPG technology. The LS-DYNA calculates the simulation results on the stress, deformation nephogram, acceleration produced during vehicle collision. The study shows that: the finite element model for vehicle rear-end collision established based on the VPG technology is proven to have a high precision and truly reflect the actual working condition of the real vehicle, so that the real-vehicle collision test can be replaced to some extent, and the development cycle is effectively shortened. It indeed has some important practical significance.

In the process of collision, the rear-ended body stress is distributed more uniformly without concentration phenomenon which, however, appears on the rear of the rear-ended vehicle. It is recommended that the energy absorption should be designed between the middle and rear parts of frame so that it can absorb part of the collision energy during the rear-end collision, in order to improve the safety of the whole vehicle.

In the process of collision, the body deformation mainly concentrates to the rear tank of the rear-ended vehicle, the rigidity of which should be strengthened to reduce the deformation and provide prevention against the risk caused by the leakage of the tank during the rear-end collision so as to ensure personal safety of the occupants.

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