Sociedad Mexicana de Ingeniería Mecánica
Fecha de recepción: 18-11-2015
Fecha de aceptación: 23-12-2016

INGENIERÍA MECÁNICA
TECNOLOGÍA Y DESARROLLO
Vol. 5 No. 5 (2016) 431 - 439

Evaluation of passive safety, a sled's platform case study

M. Jimenez-Martinez

Universidad de las Américas Puebla, Departamento de Ingeniería Industrial y Mecánica.
Sta. Catarina Martir, Cholula, 72810, Puebla, México
moises.jimenez@udlap.mx

Resumen

La seguridad pasiva se ha evaluado a través de pruebas experimentales, así como los modelos virtuales. La correlación entre los resultados experimentales y de simulación es importante porque sienta las bases para utilizar el modelo de elementos finitos para evaluar diferentes condiciones de carga. Con el fin de mejorar la correlación, es necesario no sólo evaluar en el modelo de elementos finitos el tamaño y tipo de malla, sino también analizar las condiciones de frontera. Este trabajo es un caso de estudio de una plataforma para pruebas de trineo simulando un pulso de desaceleración de un choque frontal, comparando la respuesta de una plataforma en los resultados experimentales con la simulación numérica y la mejora de la correlación a través del análisis de señales. Este análisis contiene fuente de no linealidad debido al contacto entre la varilla y la plataforma del desacelerador. El análisis no lineal se realizó usando el programa comercial de elementos finitos Abaqus V6.12-3. La correlación entre la simulación y los resultados experimentales se ha mejorado a través de una serie de modelos y mediante el ajuste de la velocidad con un análisis de la señal de ambas respuestas. El análisis de la señal es importante en la realización de la simulación de elementos finitos no lineal y es esencial para realizar el ajuste de los modelos virtuales.

Abstract

Passive safety has been evaluated through experimental tests as well as through virtual models. The correlation between experimental and simulation results is important because it paves the way to use the finite element model to evaluate different load conditions. In order to improve the correlation, it is necessary not only to evaluate the size and kind of mesh in the finite element model, but also to analyze the boundary conditions. This work is a case study of a platform for sled test simulating a frontal crash deceleration pulse, comparing the response of a platform in experimental results with numerical simulation, and improving the correlation through signal analysis. This analysis contains a source of nonlinearity due to the contact between the decelerator rod and the platform. The nonlinear analysis was carried out using Abaqus V6.12-3, a commercial finite element software. The correlation between the simulation and the experimental results was improved through a series of models and by adjusting the speed with a signal analysis of both responses. The signal analysis was important in performing the nonlinear finite element simulation, and is essential to perform the fine tuning of the virtual model.

Palabras clave:

Pruebas de trineo, correlación, análisis de señales, pulso de desaceleración, análisis no lineal.

Keywords:

Sled test, correlation, signal analysis, deceleration pulse, nonlinear analysis

Introduction

Traffic accidents are one of the leading causes of mortality in society. In order to minimize the effect of accidents, manufacturers have incorporated a wide range of safety devices and features into their vehicles, including airbags, energy absorbing steering columns, side door beams [1], and mechanical absorbers [2]; as well, exterior components like bumpers have to meet Federal Motor Vehicle Safety Standard (FMVSS) regulation for a 5mph front rigid wall impact and the regulations protecting a pedestrian's lower leg in the event of impact [3]. As electromobility is an increasing trend for passive safety, the Rechargeable Energy Storage System (REESS) is a kind of technology that poses a considerable risk in the event of a collision [4].

Car-pedestrian accidents cause thousands of deaths annually worldwide [5]. Two methods exist for assessing the pedestrian friendliness of vehicle design. The first is through the use of a subsystem impactor, and the second is through the use of a full-scale dummy model. In the first method, three human body parts, the head, pelvis and leg, are considered separately in three simple models, headform, upper legform, and the legform, which were developed by the European Experimental Vehicles Committee (EEVC) [5].

The car body must be lightweight [6], but also stiff enough to satisfy crashworthiness requirements in front, side [7], rear, and rollover crashes[8,9,10]. The interlayer of windshield plays an important role in the crash safety of automotive and protection of pedestrian or passenger, due to its energy absorption capability [11]. Therefore, the goal of crashworthiness is

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to optimize the vehicle structure to absorb crash energy through controlled vehicle deformations [12], while maintaining adequate space, so that the residual crash energy can be managed by the restraint systems to minimize crash load transference to the vehicle's occupants, with the restraint systems providing additional protection to reduce injuries[1].

The deceleration pulse is obtained from a crash test where acceleration versus time is recorded. Figure 1a shows the frontal crash test in a car, while figure 1b shows it in a truck; this kind of test can also be performed in high speed trains [13]. The pulse is the response of the velocity impact material, its configuration and the velocity at impact [14].

(a) (b)

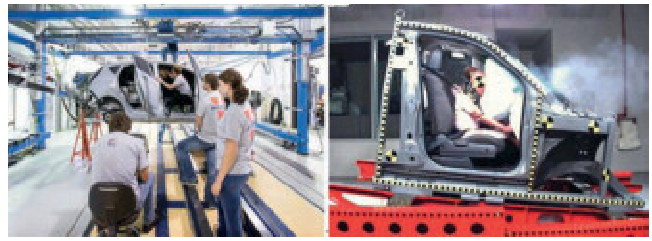
Figure 1. Crash test. (a) car and (b) truck. [15,16].

Some structures exhibit unstable characteristics in their load-displacement relationships, the load to initiate the plastic deformation is high, but the resistance of the structure decreases with the increase of its plastic deformation, so its load-displacement curve displays a kind of softening effect. To find out an accurate dynamic structural response requires the knowledge of the actual loading pulse. In the stage of structure design, however, simple pulse shapes such as rectangular pulse or triangular pulse are usually adopted in the analysis, while in reality various impact conditions may produce more complex shaped pulses [17].

This pulse is reproduced in a test stand called "Sled", where deceleration behavior can be used to evaluate components of passive safety [18, 19, 2]. The primary objective of a sled test is to determine the impact severity and the effectiveness of the restraint system in reducing loads transferred to the occupant. In this kind of test, high speed videos show the response of the structure in a crash simulation. The response of the model in acceleration has to follow the acceleration pulse in a crash event.

Sled Test

In a sled test, engineers use the car body or a device representing the passenger compartment (Figure 2) with all or some of its interior components such as the seat, instrument panel, steering system, seat belts, and air bags, as the anthropomorphic test devices or "dummies" are seated to simulate a driver and passenger. In this test, the car body deformation is simulated through the deceleration pulse with a hydraulic decelerator, although there is any energy deformation in the car body, the passive safety systems work as if the car is in a crash.



(a) (b)

Figure 2. Sled Test, (a)rollover, (b) Frontal. [20,21]

The biomechanical response of the dummies in the head, neck, chest and lower extremities are evaluated [22,23]. King and Chou [24] present a review of mathematical models simulating biodynamic response to understand the injury mechanism in impact.

Head Injury Criterion (HIC) is used to assess the head injury risk quantitatively. For deceleration during the crash with normal braking, modern cars reach values from 8m/s2 to 11m/s2, that is about acceleration due to gravity, g; racing cars reach values up to 5g. According to the FMVSS specification 208, the maximum calculated HIC value shall not exceed 1000 [1]. Neck injuries are typically caused by tension or compression and neck rotation angle, while femur injury is a common injury in pedestrians in vehicle collisions. Most pedestrians suffer femur injury resulting from impact with the frontal leading edge of the car, being femur fracture the most serious injury. The contact between the tibia and the bumper of a car typically represents the first impact between a car and a pedestrian. The knee shear displacement is a major reason for knee injury in pedestrians. Ankle injuries occur due to the bending of the tibia on impact with the bumper: the bending moment combined with the friction force between the foot and ground cause the ankle joint to bend and rotate following the tibia impact [11].

This kind of test is expensive and for safety reasons all the devices have to be strong enough, so that they do not affect the test; the proper function of structures and mechanical components can be suddenly brought to a halt by the presence of a shock load [14]. To prevent damages in test devices, four points of the platform have been evaluated in order to know the maximum stress reached in the maximum deceleration, which must be done with a numerical analysis, as the test itself is complex. In this kind of test there is contact [25], when the front part of the platform touches the decelerator rod and the force is transmitted across their common surface. A nonlinear analysis must be used for this source of nonlinearity. To perform this kind of analysis, the steps are broken down into many levels through an iterative process [2]. Although the target of this analysis is to know the maximum stress value in four points, it is necessary to evaluate the deceleration response which is the parameter used to calibrate the finite element model.

Test stand

The sled test platform shown in Figure 3 has a length of 4126.5mm and a width of 1410mm. The total mass mounted is 0.9345 ton (car body, dummies, dashboard, air bags, etc.). These components are for simulating a frontal crash at a speed of 56 km/hr (15555.5mm/s).

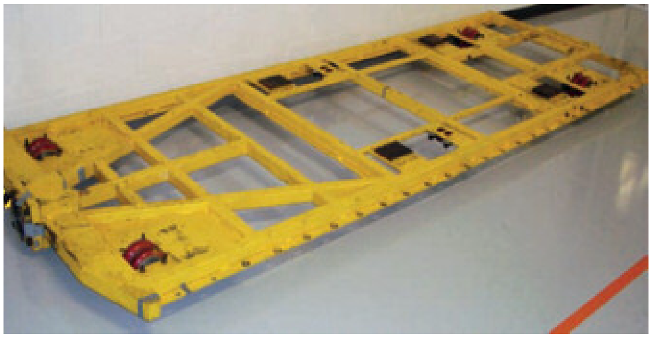


Figure 3. Platform for sled test.

This deceleration event is modeled in Figure 4 using a Kelvin model. It has two masses connected with a spring and damper. It can be used to simulate collisions between vehicles as well as vehicle to barrier, the latter is the approach to this work, considering an underdamped system (1<ζ<0) [26,27].

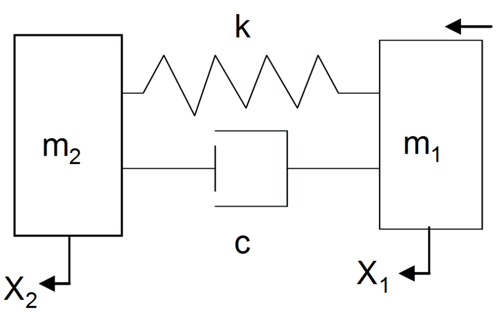


Figure 4. Kelvin model

The equation of motion is:

$$\ddot{\alpha} + 2\zeta\omega_e\dot{\alpha} + \omega_e^2\alpha = 0 \tag{1}$$

Where

$$\zeta = \frac{c}{2m\omega_e} \tag{2}$$

$$\omega_e = \sqrt{\frac{k}{m}} \tag{3}$$

For underdamped system the transient responses are:

$$\alpha(t) = \frac{v_0 e^{-\zeta\omega_e t}}{\sqrt{1-\zeta^2}\,\omega_e}\sin\left(\sqrt{1-\zeta^2}\,\omega_e t\right) \tag{4}$$

$$\dot{\alpha}(t) = v_0 e^{-\zeta\omega_e t}\left[\cos\left(\sqrt{1-\zeta^2}\,\omega_e t\right) - \frac{\zeta}{\sqrt{1-\zeta^2}}\sin\left(\sqrt{1-\zeta^2}\,\omega_e t\right)\right] \tag{5}$$

$$\ddot{\alpha}(t) = v_0\omega_e e^{-\zeta\omega_e t}\left[-2\zeta\cos\left(\sqrt{1-\zeta^2}\,\omega_e t\right) + \frac{2\zeta^2-1}{\sqrt{1-\zeta^2}}\sin\left(\sqrt{1-\zeta^2}\,\omega_e t\right)\right] \tag{6}$$

Where equation (4) is the displacement or dynamic crush, equation (5) is the velocity and (6) is the deceleration respectively.

In the analogy of a spring mass system, it is assumed that all the kinetic energy is changed to deformation energy; however, in a crash test, just before the rebound, zero velocity is reached after the maximum deceleration. Therefore, all the kinetic energy has been changed to deformation energy and mechanical work [28]. In sled test, the crash is simulated using a deceleration pulse, and for this reason, deformation is not present.

Experimental test.

The platform was controlled through a triaxial piezoresistive accelerometer. Subsection a) in Figure 5 shows the general view of the front part of the platform, while subsection b) shows the detail of the accelerometer and subsection c) shows the data acquisition system (Messring of 40 channels).

(a) (b) (c)

Figure 5. Experimental test set-up: (a) General view, (b) detail of accelerometer and (c) data acquisition system.

The response was analyzed with a filter for structural analysis, which is a CFC60 filter that is a low pass of 100Hz [19,22], and the integral was obtained to determine the speed (Figure 6). The maximum deceleration value was 98.79g in millisecond 52.

The importance to apply the correct velocity at the moment of impact is described by Kim et al., 2011[29], who describe that a perturbation mark is occasionally produced on the velocity indicator of the cluster panel of a vehicle during a vehicle collision. This mark can be used to estimate the velocity of the vehicle at the moment of the vehicle's impact.

Although the test time signal was recorded since the platform started its movement, the deceleration pulse began at 0 contact, which was defined by the trigger mounted on the front part of the platform, and activated with the rod. Acceleration from 0 contact to millisecond 32 was the first part of the deceleration pulse. At this point, the speed decreased from 15,555.5mm/s to 12,684mm/s, and the maximum deceleration value was reached at millisecond 52.8. After this point, deceleration value decreased, and platform rebound occurred in millisecond 67.5ms.

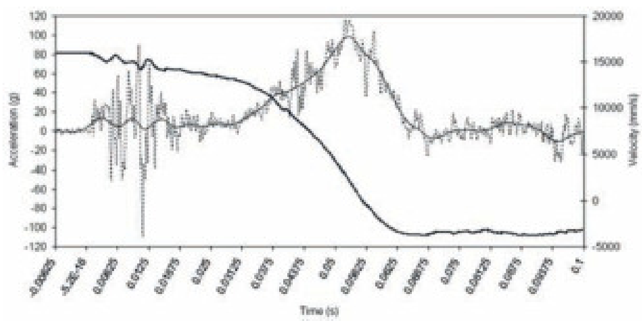


Figure 6. Signal analysis in experimental test.

Nonlinear Finite Element Simulation.

In this case study, a nonlinear analysis is performed; the main difference between linear and nonlinear analysis is how the equations are solved.

Material properties.

The mechanical properties of the A36 structural steel used in the finite element for the platform is shown in Table 1: the material is homogeneous, continuous and free of residual stress.

Table 1. Mechanical properties.

Property	Steel
Poisson´s ratio	0.3
Yield (MPa).	248
Density (ton/mm^3).	7.85e-9
Young´s Modulus (MPa)	210,000

First Finite element model

The commercial finite element software Abaqus V6.12-3 was used to carry out the nonlinear explicit analysis. The mesh model (Figure 7) was constructed with linear elements of 10mm, mainly with solid elements (hexahedron and tetrahedron), and the rectangular profiles were made of shell element. The finite element model characteristics are shown in Table 2.

Table 2. Characteristics of the finite element model

Component	Element Type	Element	Nodes
Platform		103,731	158,515
	Hexahedron & Tetrahedron	83,711	
	Shell	20,020	
Rod	Shell	336	338

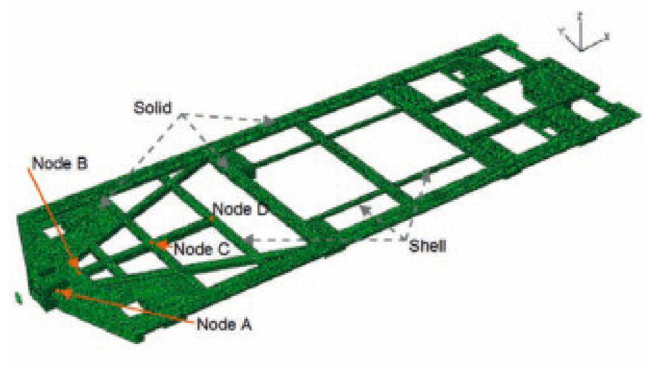


Figure 7. Isometric view of the finite element model.

The front part of the platform and the rod were built with a normal contact. The spatial constraints had the following characteristics: BC1 Uz= 0, BC2= Uy = 0 and BC3=Ux=0 [30], Fig. 8.

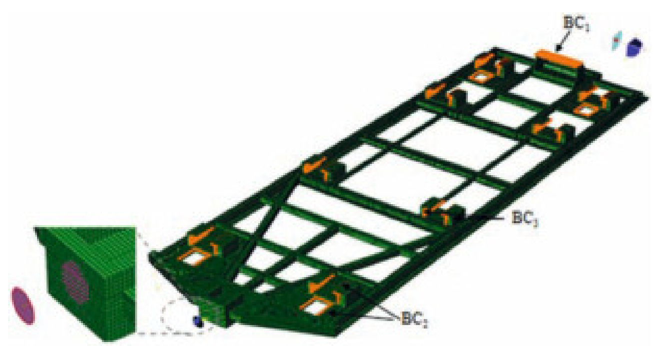


Figure 8. Spatial constraints and contact

The rod moved at a speed of 15555.5mm/s in direction x (SAE J182, 2005) and the other degrees of freedom were constrained. There were 44 element masses applied in the model: 38 elements simulating the car body and test devices and 6 elements simulating the data acquisition equipment (Figure 9).

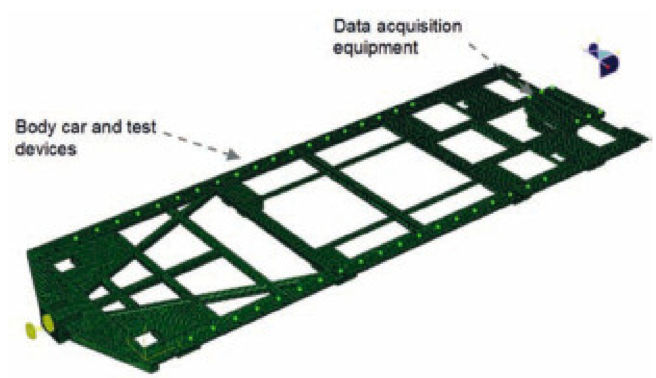


Figure 9. Masses in the model

Second finite element model.

The second mesh model (figure 10) had the characteristics in Table 2 plus 462,000 hexahedral elements of 5mm for the rails.

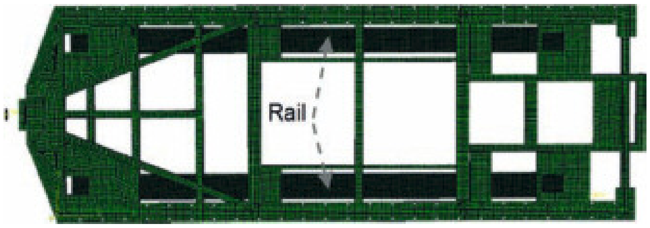
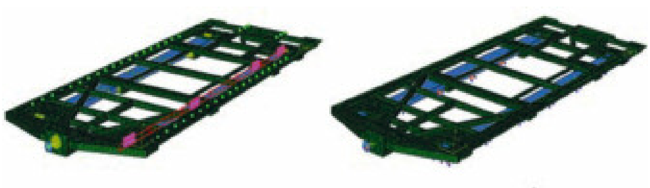


Figure 10. Second finite element model

The model also included normal contact between the platform and the rod (Figure 8). In addition to the normal stress transmitted, a small amount of shear stress was transmitted in a tangent contact to simulate the slide of the platform with the rails. The tangent contact has been modelled without friction (Figure 11a), spatial constraints for the rails are shown in Figure 11b.



(a) (b)

Figure 11. Finite element model with rails, (a) Tangent contact and (b) Spatial constraints.

Results

According to the first model, the results for the worst case are shown in Figure 12. In millisecond 0 (subsection a), the rod is moving to the platform; in millisecond 8 (subsection b), the rod begins to have contact with the platform; in millisecond 10 (subsection c), deceleration is propagated to the rest of the platform. Stress value per Node: Node A = 152.3MPa, Node B = 174.16MPa, Node C = 100.2MPa, and Node D = 109.58 MPa.

Stress results for the second model are shown in Figure 13(a,-b,c). These were obtained after performing the signal analysis and adjusting the speed. Stress value per Node: Node A = 214.1MPa, Node B = 236.1MPa, Node C = 182.5MPa, and Node D = 107.1MPa

The acceleration responses in the first and second models are shown in Figure 14. A CFC60 filter was used in both responses. For the first model the filtered response had a maximum value of 1,126,194mm/s^2 (114.80g), and for the second model it was 970,192mm/s^2(98.89g).

Discussion

In this case study the main target was to evaluate the structural response in the worst case. The first hypothesis assumes that this happens with maximum speed. A maximum value of 114g was obtained by performing a signal analysis from the experimental results, and it was detected that the speed before going up in the maximum deceleration response was not 15,555mm/s, but rather 12,684mm/s. By changing this parameter in the analysis and making a more complete finite element model, a maximum value of 98.89g was obtained, in comparison to the 98.7 value obtained in experimental results. With this finite element result, a correlation of 99.8% was reached.

The maximum stress in the simulation is the result of the singularity in the front part of the platform, and the stress points reported are the points to be evaluated. Although the speed applied to the final model is lower than the first one, three of the stress points are higher, and only one of the stress points is lower than the one in the first model.

Conclusion.

In this case study, a nonlinear finite element analysis has been presented. The correlation was improved in it through a series of models: the simplified model helped to understand the mechanical behavior without using a lot of computational resources, and the correlation in the final model was improved after tuning it up to the speed applied to the model according to the result of signal analysis in experimental results.

- In structural analysis it is important to perform a signal analysis in both experimental and simulation case results to improve correlation between these results, as it is important to eliminate unnecessary information, such as noise.
- The boundary conditions have to be selected carefully, but there must be also an analysis of the responses and the expertise of the analyst. A good technical background is essential for performing any kind of analysis. This case study shows that the finite element analysis is a reliable tool.
- The process can be used to evaluate test devices as well as passive safety systems.
- Velocity is a basic parameter to evaluate mechanical components, and it can be obtained from a mark in a velocity indicator [29] or through signal analysis.

Acknowledgement

M. Jimenez would like to acknowledge the support of the Durability and Passive Safety Test Area of Technical Development of Volkswagen Mexico, for their support in this study.

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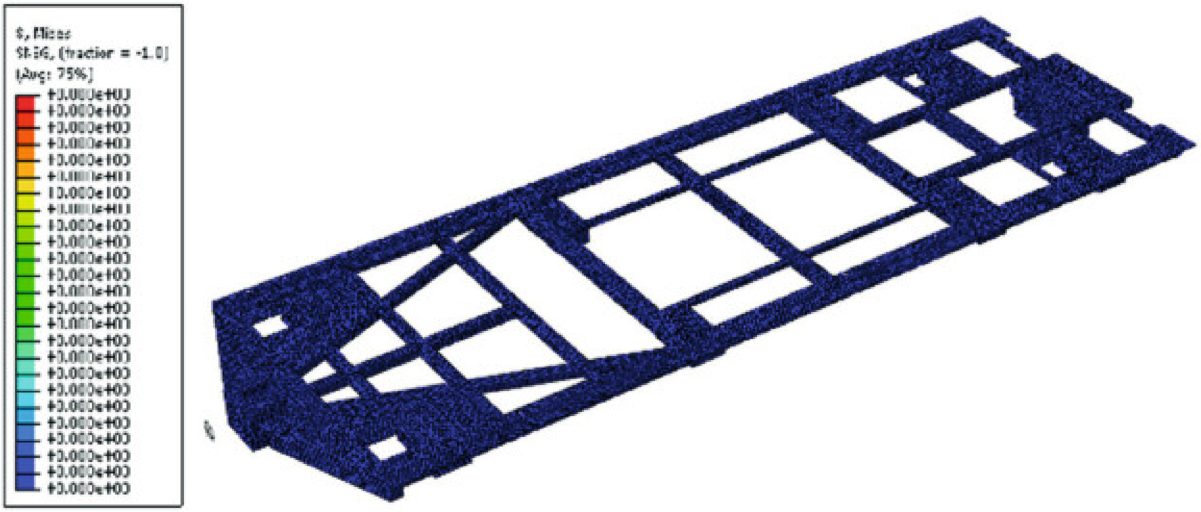
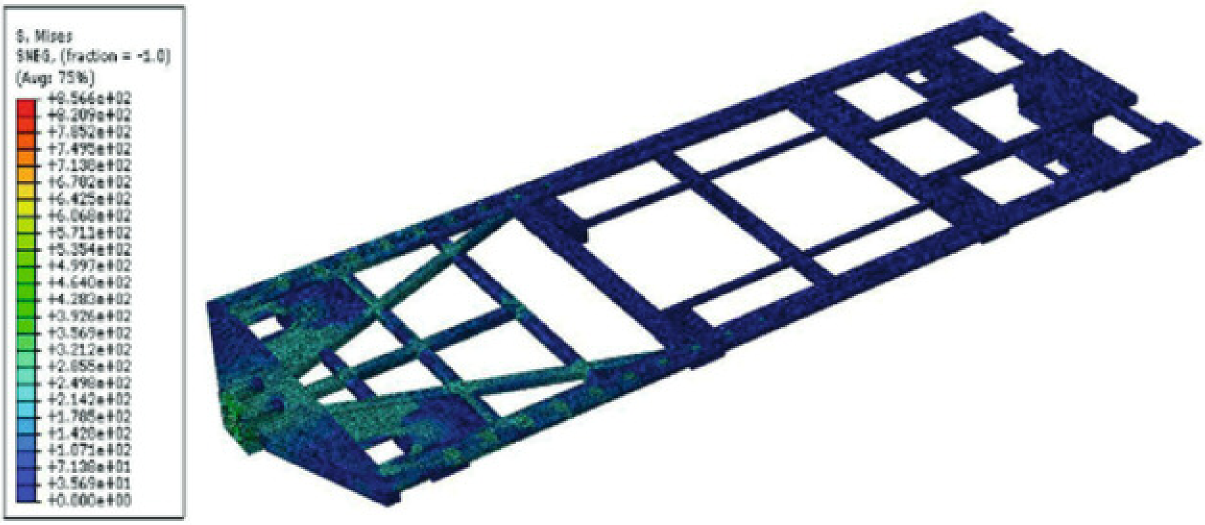


(a)



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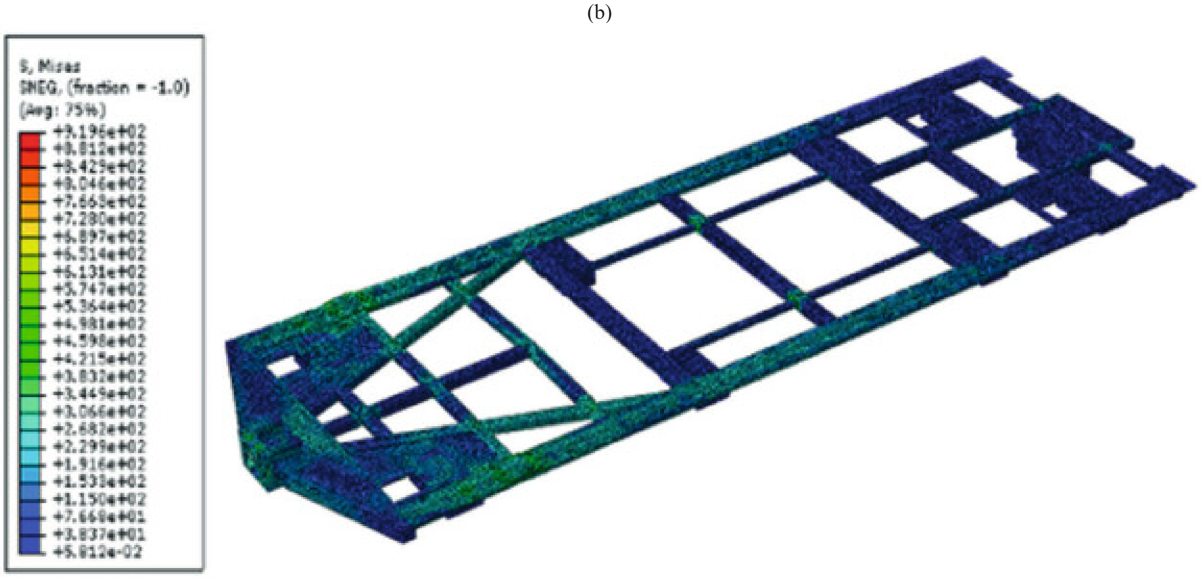
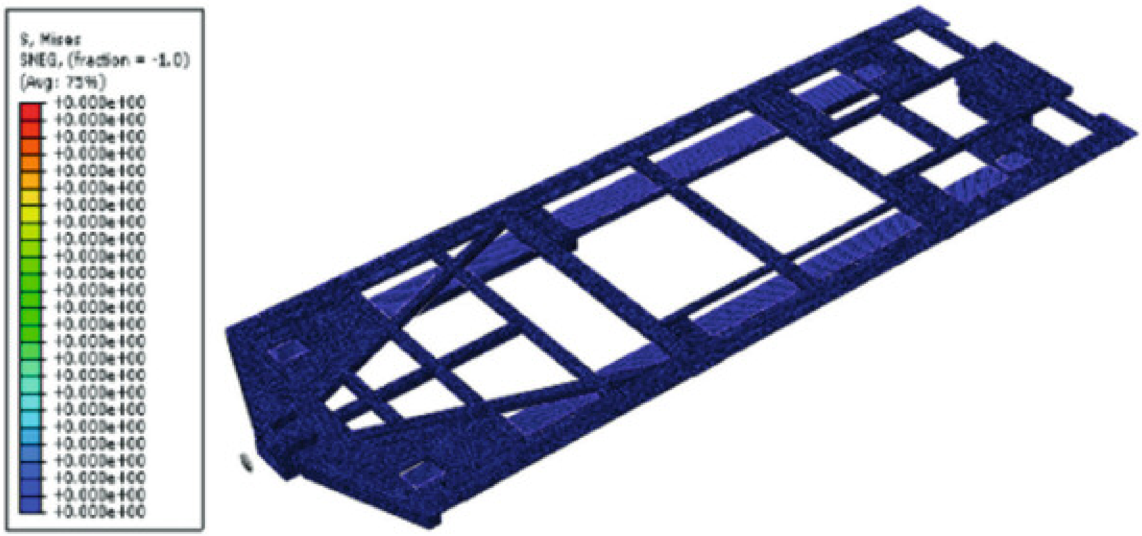
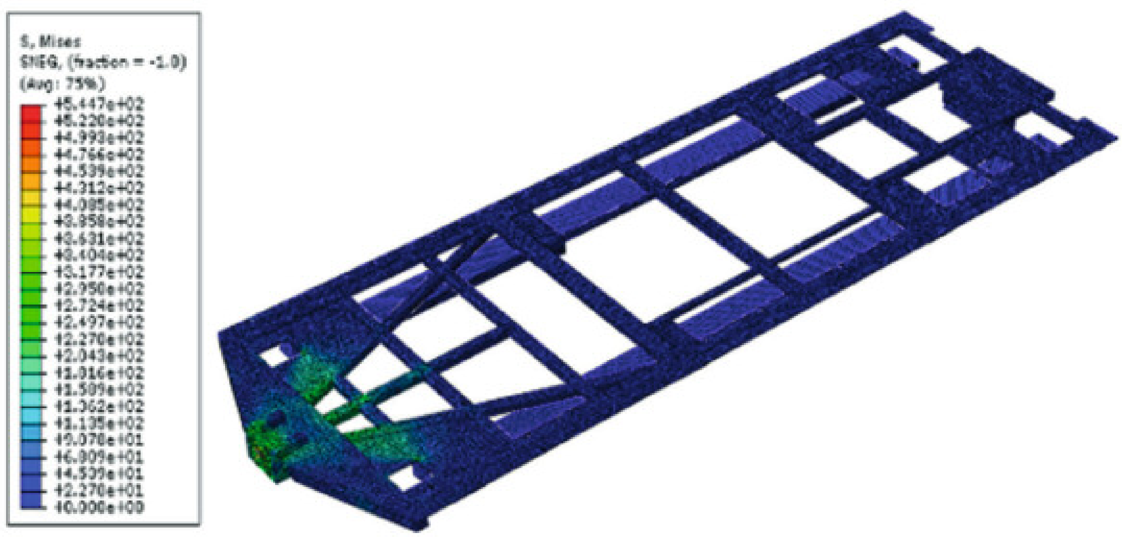


(c)

Figure 12. Results first model, (a) 0ms, (b) and (e) 10ms.



(a)



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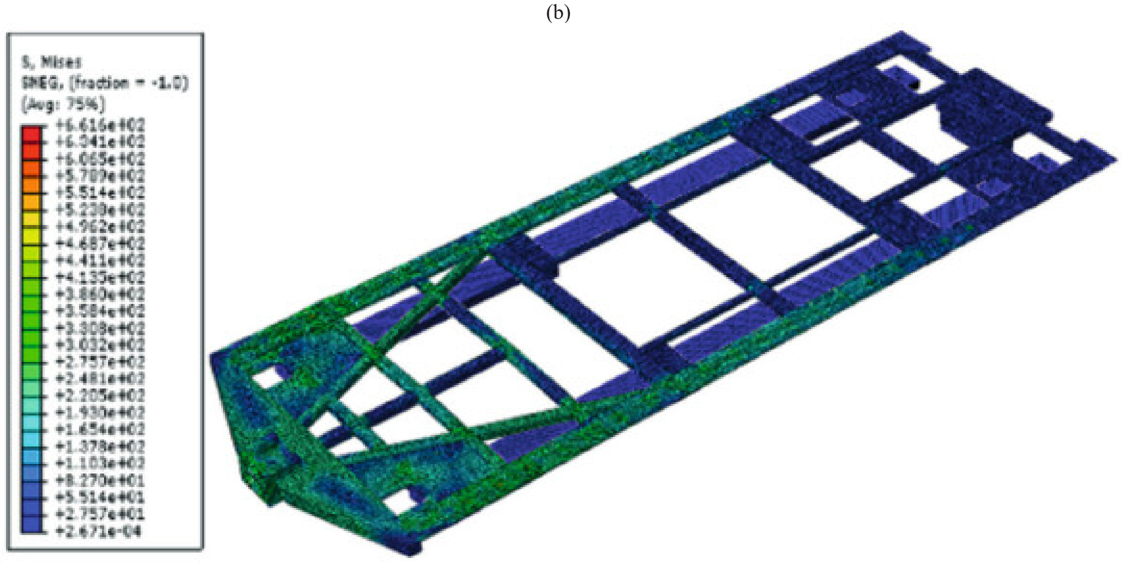

(c)

Figure 13. Results second model, (a) 0ms, (b) 8ms and (c) 10ms second model.

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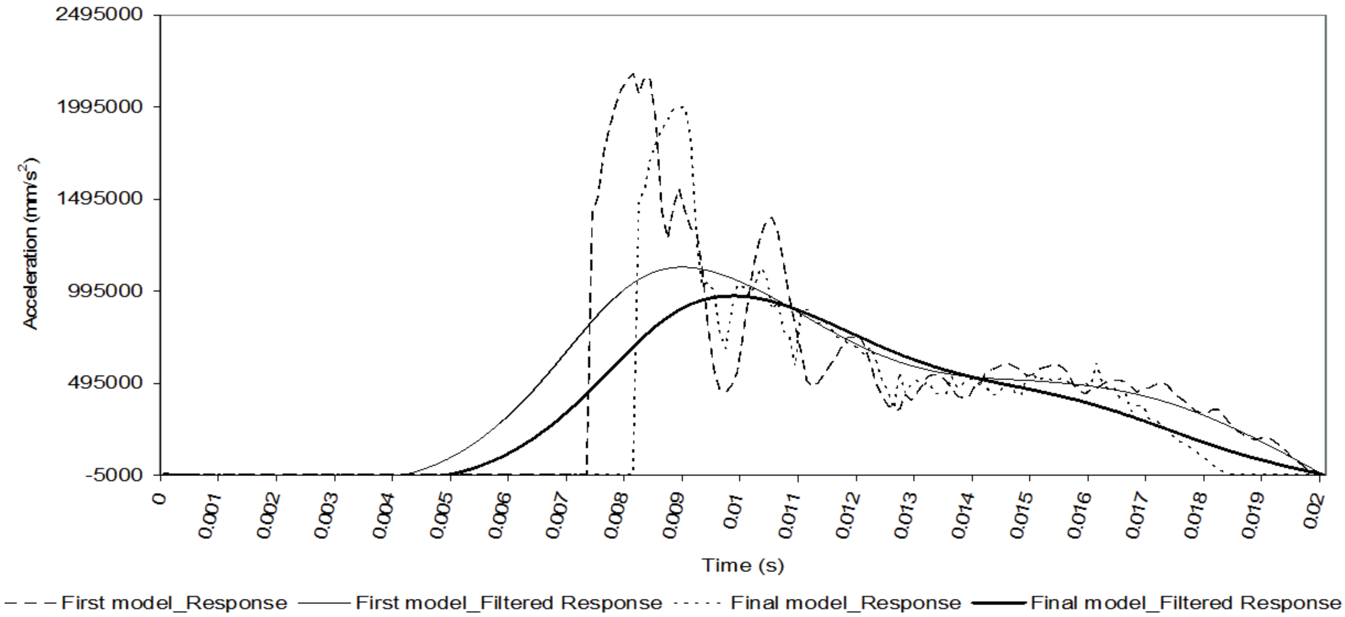

Figure 14. Deceleration Pulse from the Finite element simulation

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