10.26411/83-1734-2015-2-38-7-18

Material definition to design vehicle components, application to crashworthiness

Alexis Rusinek
Lorraine University, Metz, France

Ramon Zaera
University Carlos III of Madrid, Spain

In this paper a short description is reported allowing to take into account some aspects to design structures used for automotive industries. It allows to define correctly the behaviour of a vehicle and mainly the passive structures to absorb energy during an accident or an impact. The main aspect related to the behaviour is the strain rate sensitivity coupled to the process of elastic wave propagation.

Key words: Elastic waves, plasticity, impact, crash

1. INTRODUCTION

Steel sheets of relatively high strength are currently used in automotive industry, to enhance the energy absorption of components like a crash-box. The task of this kind of structure is to absorb high energy during an accident, mainly in order to assure security of passengers by limiting the maximum deceleration level. Therefore, the structure must deform by the process of collapse and sequential folding during plastic deformation. During the collapse of the structure, in the present case the "crash-box", the process of plastic deformation must be controlled.

In this paper different numerical analyses of dynamic buckling and collapse of a crash-box are reported taking into account both the elastic waves and plasticity effects. It has been observed that a strong competition exists between the elastic wave propagation and the local plasticity appearing during the first stage of impact. This competition defines the collapse site. The main idea is to assure a high plastic stress level under high strain rate to prevent any buckling on the opposite side of the crash-box.

2. MATERIAL DESCRIPTION AND BOUNDARY CONDITIONS EFFECT

To produce a vehicle such as a truck or a car, several materials may be used, Fig. 1. Therefore, it is necessary to define and to have a correct understanding on the material behaviour in terms of the relation defining the stress σ in terms of the strain ε, the strain rate $\dot{\varepsilon}$ and the temperature T, given as a function $\sigma(\varepsilon, \dot{\varepsilon}, T)$ Depending on the applications, the material may be subjected to low or high strain rate, but also to a large range of temperature. The temperature changes may be due to the process of large plastic deformation during a crash $\varepsilon^p > 1$ or due to the initial condition when the vehicle is parked on a parking place during winter or summer $-20°C < T_0 < 100°C$. In term of strain rate, the maximum value reached during few microseconds is close to $\dot{\varepsilon}^{max} \sim 10^3\ s^{-1}$.

In general, the material is nonlinear with the strain rate and the temperature. The first one increases the stress level, and the second one induces a decrease of the strength due to thermal softening. Therefore, a competition exists between the strain rate sensitivity m, the temperature sensitivity v and the hardening n. These parameters are defined as follows, Eq. 1.

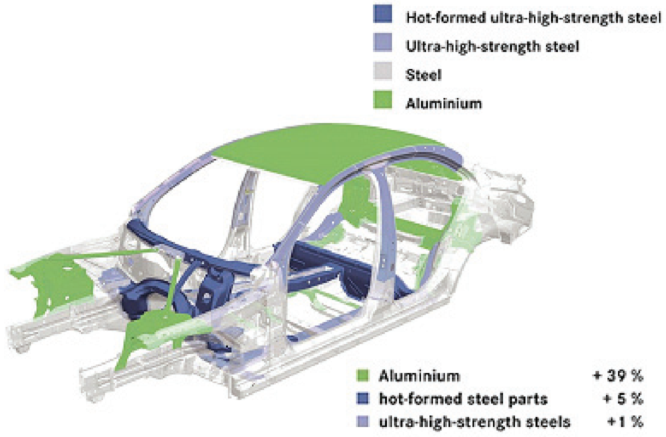


Fig.1. Car body description using different materials, source [1]

$$m = \left.\frac{\partial \log \sigma}{\partial \log \dot{\varepsilon}}\right|_{\varepsilon,T} \qquad \nu = \left.\frac{\partial \log \sigma}{\partial \log T}\right|_{\dot{\varepsilon},T} \qquad n = \left.\frac{\partial \log \sigma}{\partial \log \varepsilon}\right|_{\dot{\varepsilon},T} \tag{1}$$

Based on the previous definition of sensitivities, the material behaviour $\sigma(\varepsilon, \dot{\varepsilon}, T)$ may be defined using a power law constitutive relation as follow, Eq. 2, which includes all sensitivities discussed previously, Eq. 1.

$$\sigma = K(\varepsilon^{n}, \dot{\varepsilon}^{m}, T)^{-\nu} \tag{2}$$

Where K is a constant of the material.

When the material is well defined with the constitutive relation based on experiments, numerical simulations may be performed to estimate how the structure will behave during a crash test or an accident. Several studies have been performed to analyze how the passive structures are behaving during a crash test [4-7]. In general, the passive structures such as a crash box must absorb a maximum of energy by buckling to avoid to transfer the kinetic energy to human organs. This kind of structures is mainly welded on the car body corresponding to a complete embedded of the structure, Fig. 2-a. However, depending on the boundary conditions (BCi, Fig. 2-b) due to some defect, the process of buckling may be changed.

Thus, when a vehicle is impacted during an accident for example for an initial velocity of $V_0 = 16\ m/s$, an incident elastic wave $\varepsilon_I(t)$ is travelling along the crash-box. Considering for example a rod bar, the equation of elastic waves propagation is defined by Eq. 3.

Where u is the displacement, A is the section

$$-\frac{\partial}{\partial x}\left(AE\frac{\partial u}{\partial x}\right) + \rho A \frac{\partial^2 u}{\partial t^2} = 0 \qquad for \quad 0 \le x \le L \tag{3}$$

area, ρ is the density of the material used, E is the Young modulus of the material and L is the length of the structure

When the wave reaches the opposite side of the structure, the wave is reflected $\varepsilon_R(t)$ and depending on the boundary condition, Fig. 2, the stress intensity may be equal to zero or equal to twice the initial value σ_I. The incident stress value is defined as follows, Eq. 3.

where C_0 is the elastic wave celerity corresponding

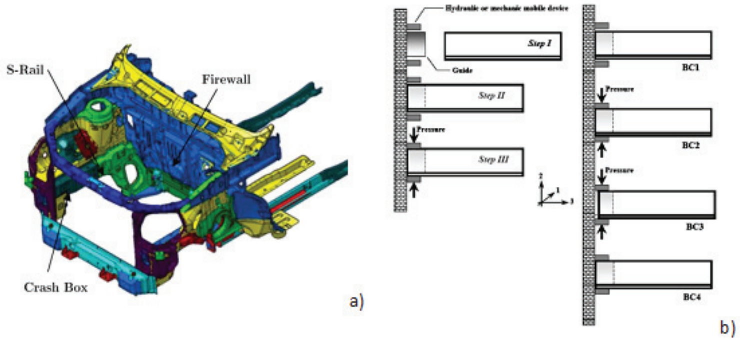


Fig.2. Crash box description (passive security element), source [2];
b- Description of the boundary conditions [3]

$$\sigma_I = \frac{1}{2}\rho C_0 V_0 \text{ with } C_0 = \sqrt{\frac{E}{\rho}} \quad (3)$$

to 5000 m/s for steel structure.

Thus the stress level induced to the opwposite side and due to the embedded condition induced by welding, is equal to, Eq. 4.

$$\sigma(x=L) = 2.\sigma_I = \rho C_0 V_0 \quad (4)$$

$$\text{with } \sigma_I\big|_{V_0=16 \text{ m/s}} = 624 \text{ MPa}$$

If the strain rate sensitivity m is not correctly defined, the stress level due to impact is lower in comparison with the value reached for $\sigma(x=L)$, Eq. 5. In this case, the structure is collapsing on the opposite side close to the embedded area. In contrary, if the material is strain rate sensitive and if the constitutive relation is available to consider it during numerical simulations, the collapse is observed on the impact side directly after impact.

$$\sigma(x=L)2.\sigma(\varepsilon,\dot{\varepsilon},T)$$

for low or no strain rate sensitivity (5-a)

$$\sigma(x=L)<\sigma(\varepsilon,\dot{\varepsilon},T)$$

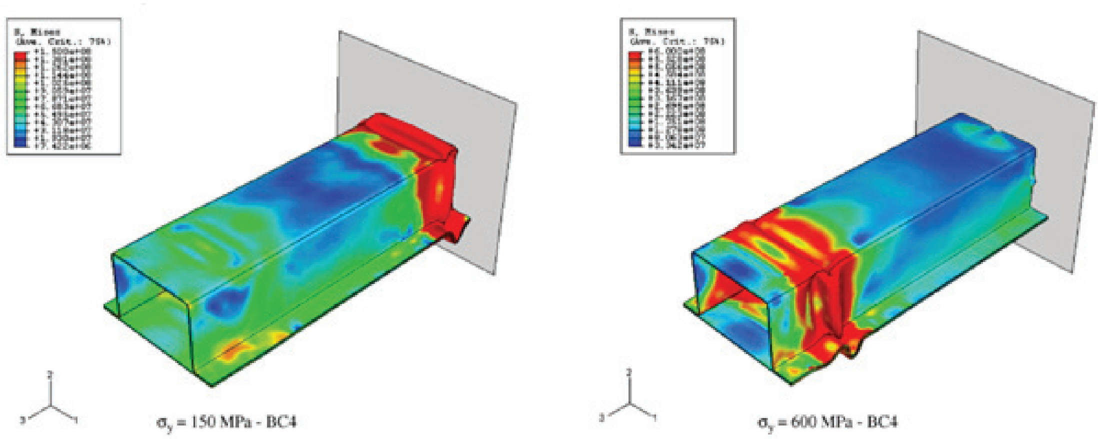
for strain rate sensitivity (5-b)

Some numerical results are reported in the following picture, Fig. 3, corresponding to the cases described previously, Eq. 5-a-b. A complete analysis of all cases is reported in [3]. Therefore, to design passive security elements included in a vehicle by numerical simulations, it is necessary to have a complete understanding of the process of elastic waves propagation and of the material behaviour. These effects are strongly coupled. Decoupling does not allow to design correctly the collapse and experiments will be in disagreement with numerical simulation predictions.

The best way to validate this effect is to use a material with no strain rate sensitivity in the range of strain rates studied. In this specific case, the buckling of the structure is located on the opposite side of the impact as demonstrated and discussed in [3].

3. CONCLUSIONS

The main objective in the crashworthiness studies is to design components that allow absorbing and dissipating high energy, allowing improvements of the survivability of passengers in vehicles. To



σ_y = 150 MPa - BC4

σ_y = 600 MPa - BC4

Fig.3. Effect of elastic waves propagation on the process of buckling and competition with the strain rate sensitivity [3]

that aim, the effect of elastic wave propagation combined with plastic behaviour on the collapse site of a rectangular tubular structure made of steel sheet has to be analyzed. To demonstrate the strong coupling between the effects of strain rate sensitivity, accounted for in the constitutive relation which is used in numerical simulations, with the process of elastic wave reflection on the boundary conditions a series of numerical simulation was performed. It is shown in this numerical study that the strain rate sensitivity influences the position of the first collapse site. Moreover, the first collapse initiation of a structure defines the level of power absorption. Since the process of folding may be combined with bending of the structure, in this non-axial case the energy absorption decreases and the effectiveness of the structure to the energy absorption may become insufficient.

This numerical study clearly indicates a problem if the material applied to design the crash-box has in tension/compression close to zero or even negative, like Al alloys, strain rate sensitivity. High strength steels introduced recently into the automotive industry have such features.

REFERENCES

[1] Source :http://www.car-engineer.com/fr/conception-carrosserie-future-mercedes-c-180/

[2] Source : http://www.scielo.br/scielo.php?script=sci_arttext&pid=S1679-78252014000800003

[3] A. Rusinek, R. Zaera, P. Forquin, J.R. Klepaczko, Effect of plastic deformation and boundary conditions combined with elastic wave propagation on the collapse site of a crash box, Thin-Walled Structures 46 (2008), 1143–1163

[4] O.M. Qureshi, E. Bertocchi, Crash behavior of thin-Walled box beams with complex sinusoidal relief patterns, Thin-Walled Structures 53 (2012), 217-223

[5] O.M. Qureshi, E. Bertocchi, Z. Qaiser, K.A. Awan, Frequency embedded box beam crash absorbers under oblique impacts, Thin-Walled Structures 75 (2014), 1-7

[6] S.A. Meguid, F. Yang, P. Verberne, Progressive collapse of foam-filled conical frustum using kinematically admissible mechanism, International Journal of Impact Engineering 82 (2015), 25-35

[7] C.P. Kohar, A. Zhumagulov, A. Brahme, M.J. Worswick, R.K. Mishra, K. Inal, Development of high crush efficient, extrudable aluminium front rails for vehicle lightweighting, International Journal of Impact Engineering 95 (2016), 17-34

Date submitted: 2018-05-01
Date accepted for publishing: 2018-05-22

Prof. Alexis Rusinek
the University of Lorraine, Metz, France
Laboratory of Microstructure Studies and Mechanics of Materials

Prof. Ramon Zaera
the University Carlos III of Madrid, Spain
UC3M Department of Continuum Mechanics and Structural Analysis