INFLUENCE OF STRAIN RATE EFFECTS ON THE ANALYSIS OF STEEL SECTIONS UNDER BLAST LOADS

Vasilis Karlos
Scientific officer
European Commission, Joint Research Center (JRC), Institute for the Protection and Security of the Citizen (IPSC), European Laboratory for Structural Assessment (ELSA)
Via Enrico Fermi 2749, 21027, Ispra VA, Italy
E-mail: vasileios.karlos@jrc.ec.europa.eu

George Solomos
Project leader
European Commission, Joint Research Center (JRC), Institute for the Protection and Security of the Citizen (IPSC), European Laboratory for Structural Assessment (ELSA)
Via Enrico Fermi 2749, 21027, Ispra VA, Italy
E-mail: george.solomos@jrc.ec.europa.eu

1. ABSTRACT

At the present paper the response of structural steel components under explosive loading is numerically investigated. First the procedure for determining the pressure loads to be applied on a structure after an explosion is briefly described. The importance of the material model and its capability of including the high strain-rate effects in the numerical analysis is studied by comparing simulations by the FEM code EUROPLEXUS with published data of real blast experiments. These comparisons are made with respect to the material models, utilizing the Cowper-Symonds law, the Johnson-Cook constitutive equation, a dynamic increase factor for the yield strength or only the static stress values. It is shown that the more comprehensive modelling can adequately reproduce the experimental data.

2. INTRODUCTION

Over the last decades considerable attention has been raised on the behaviour of engineering structures under blast or impact loading. The use of explosives by terrorist groups around the world that target civilian buildings and other structures is becoming a growing problem in modern societies. Usually the casualties from such a detonation are not only related to instant fatalities as a consequence of the direct exposure to the blast pressure, but mainly to structural failures that might occur and could result in extensive life loss. Famous examples of such cases are the bombing attacks at the World Trade Center in 1993 and on the A. P. Murrah Federal Building in Oklahoma City in 1995. After the events of the 11 September 2001 that led to the collapse of the World Trade Center in New York it was realized that civilian and government buildings, as well as areas with high people concentration (metro and train stations, means of mass transportation, stadiums etc.) are becoming potential bombing targets of terrorist groups.

The scientific community over the last years has been investigating the response of various structural members under explosive loads. These types of loads and their influence on engineering structures have been studied mainly from military services and this is the reason why in most cases the relevant documents are not accessible to the public and are only restricted for military use. From the various documentation that are available for public use, EN 1991-1-7 [1] refers to the case of accidental loads and internal explosions and is mainly focused on impact actions, such as collisions from vehicles in general without mentioning the case of external blast loads and how they should be calculated. From the sources that can be found in the open literature the most quoted references today are some USA military publications, such as the Technical Report by Kingery and Bulmash [2] and the Army Technical Manual 5-1300 [3].

In the current paper an overview of the design procedure for structures under blast loading is provided. The behavior of steel structural members under blast loading will be also illustrated through analyses of a series of blast tests performed at McMaster University in Canada [4]. The current simulations are conducted using the explicit finite element code EUROPLEXUS and employing several of its modelling capabilities.

3. BASIC FEATURES OF EXPLOSIONS

2.1 Blast wave characteristics

Explosions are very fast chemical reactions during which a rapid release of energy takes place. The phenomenon lasts only some milliseconds and results in very high pressures due to large quantity of the produced hot gases that tend to occupy all the available space. Fig.1 shows the pressure time history at a point located at some distance from the detonation. From the diagram one can see that the pressure surrounding the element is initially equal to the ambient pressure P_o, and it undergoes an instantaneous increase to a peak pressure P_{so} (also known as side-on or peak overpressure) at the arrival time t_A, when the shock front reaches that point. After its peak value, the pressure decreases with an exponential rate until it reaches the ambient pressure at t_A+t_o, t_o being called the positive phase duration. Following the positive phase, the pressure becomes smaller (referred to as negative) than the ambient value. The negative phase is longer than the positive one, its minimum pressure value is denoted as P_{so}^- and its duration as t_o^-. This phase is usually not taken into account for design purposes as it has been verified that the main structural damage is connected to the positive phase whose pressure values are much higher than those of the negative phase. Clearly the characteristic values and shape of the curve of Fig.1 depend on the type, size, weight and distance of the explosive and also on the presence of obstacles between the detonation and the point considered.

Fig.1 shows the pressure time history at a point in mid air (incident pressure). When the blast wave interacts with a rigid surface, the diagram will be different as the blast wave will be reflected, leading to higher acting pressure values, as shown in Fig.2. These are usually the pressures to be considered for structural design. The percentage of increase of the pressure value depends mainly on the incident overpressure and on its angle of incidence to the surface.

The most important parameters that influence blast loading are the charge size and its distance from the structure considered. The peak pressure and the velocity of the blast wave decrease substantially with distance. In order to take into account this effect on the blast characteristics, the scaling law of Hopkinson-Cranz is used so as to generalize blast results from a certain experimental setup to different ones. The scaled distance parameter *Z* is introduced by using eq. (1).

$$Z = \frac{R}{\sqrt[3]{W}} \tag{1}$$

where, *R* is the distance from the detonation source to the point of interest [m] and
W is the weight (more precisely: the mass) of the explosive [kg].

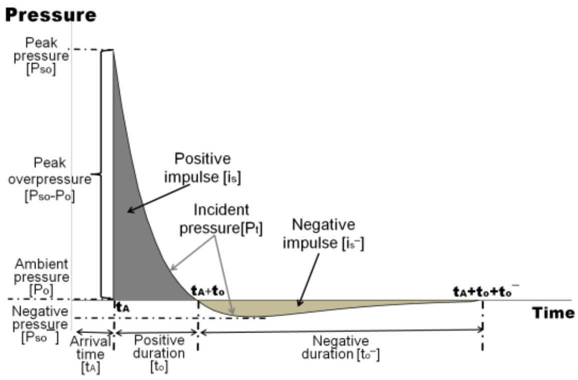


Figure 1: Ideal blast wave pressure time history

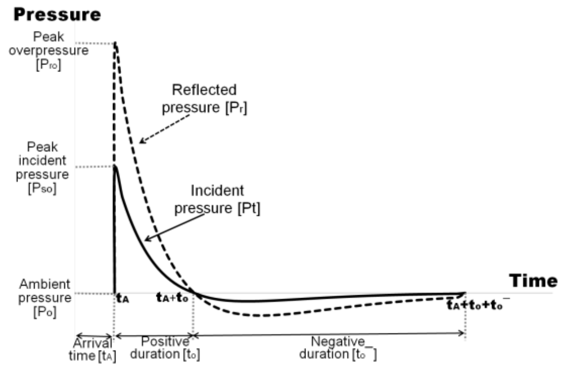


Figure 2: Reflected wave pressure time history

Since there is a vast variety of explosive types, TNT (Trinitrotoluene) has been chosen as a universal quantity to which all the explosives are referred to. An equivalent TNT weight is computed according to eq.(2) linking the weight of the chosen design explosive to the equivalent weight of TNT by utilizing the ratio of the heat energy produced during detonation:

$$W_e = W_{exp} \frac{H^d_{exp}}{H^d_{TNT}} \tag{2}$$

where, W_e is the TNT equivalent weight [kg],
W_{exp} is the weight of the actual explosive [kg],
$H^d{}_{exp}$ is the heat of detonation of the actual explosive [MJ/kg], and
$H^d{}_{TNT}$ is the heat of detonation of the TNT [MJ/kg].

2.2 Types of explosions

Explosions can be distinguished in three basic types depending on the relative location of the structure and the detonation point. During a <u>free-air burst</u> the explosion takes place in the air and impinges directly on a structure. At an <u>air burst</u> the wave before impinging on the structure has also interacted with the ground. The last type is the <u>surface burst</u> during which the explosive is placed on the ground so that the blast wave interacts instantly with it taking a hemispherical form.

In terrorist bombing attacks the most common case is that of a surface burst, where the explosive device is situated usually in a vehicle, transported to the target site and activated through a remote control. In this case there is an immediate reflection from the ground, leading to the creation of a single reflected blast wave. When the blast wave reaches the target structure it engulfs it and loads not only its front surface, but also the roof, the side and the rear walls. Fig.3 contains the diagrams for determining the positive phase blast parameters for a surface burst and Fig.4 the parameters for the negative phase. Some of the parameter curves in the diagrams are scaled, so in order to derive the absolute value of the parameter, the scaled value has to be multiplied by the factor $W^{1/3}$. By using these values the pressure time history acting on every face of a structure can be obtained. These values are really important for design purposes as they constitute the loads which the studied structure has to withstand. A more detailed analysis of the steps that have to be followed for studying a structure under an external blast load can be found in [5].

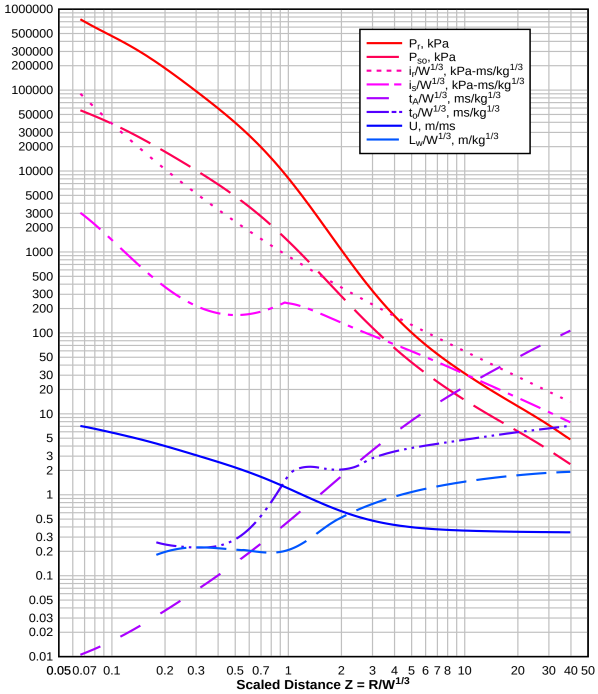


Figure 3: Positive phase parameters for hemispherical TNT charges (modified from [3])

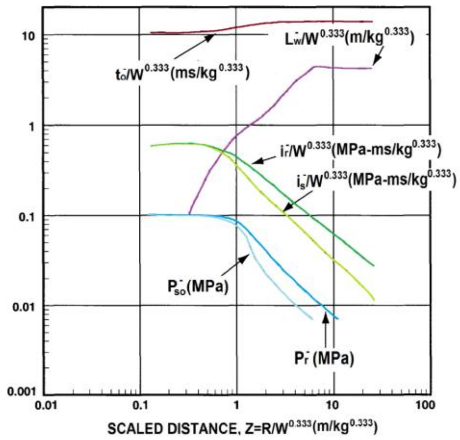


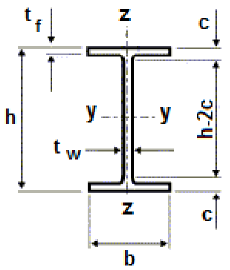
Figure 4: Negative phase parameters for hemispherical TNT charges (modified from [3])

4. RESPONSE OF STEEL BEAMS AND COLUMNS UNDER BLAST LOADS

3.1 Geometrical setup

When designing a structure for blast loading, taking into account the material’s behavior under high strain rates is of great importance for simulating the structure’s response. The influence of material models when simulating a steel section that undergoes loading due to an explosion, will be shown by using test data from various experiments performed at McMaster University [4]. For analyzing the experiments addressed in this work the finite element program EUROPLEXUS has been used, jointly developed by CEA and JRC and particularly capable of handling fluid-structure interaction problems. The program uses an explicit algorithm for the discretization in time, which makes it suitable for fast transient dynamics, such as the explosions for the current experiments.

The steel sections which were loaded through a detonation of explosives at certain distances were 2,4m long Canadian profile (W150x24), whose characteristics are shown in Fig.5. The static properties of the steel material, as provided by the manufacturer, were 393MPa for its yield strength and 537MPa for its ultimate strength. The steel sections were pinned at one end and simply supported at the other, as shown in Fig.6. For some of the members an axial load (270kN) was introduced by prestressing appropriately attached wires. Only the surface facing the detonation point was loaded as the rear and side surfaces were protected from the blast wave. The charge was ANFO with an explosive energy of 3717 kJ/kg which is 82% of the energy produced during the detonation of 1kg of TNT. The members that were studied as beams (without axial load) were rotated so that they were loaded along their weak axis by 100kg of ANFO at a distance of 10,30m. When an axial load was present the members were loaded along their strong axis by 150kg of ANFO at a distance of 9,00m.



h= 160 mm
b= 102 mm
t_f= 10.3 mm
t_w= 6.6 mm
c= 22 mm
$h\text{-}2c$= 116 mm
B= 0.235 kN/m
I_y= 13.4x10^6 mm^4
I_z= 1.83x10^6 mm^4
A=3050 mm^2

Figure 5: Properties of W150x24 steel section

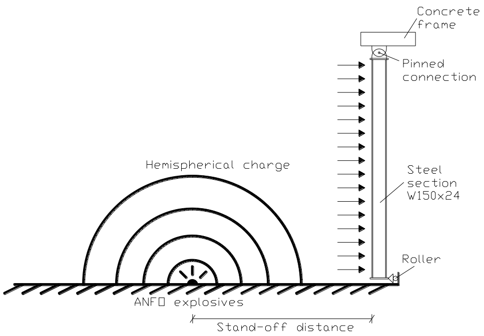


Figure 6: Side view of the geometrical setup

3.2 Material models

The mechanical properties of steel materials can be significantly different from their static ones when the strain rate increases. To illustrate the importance behind the selection of a proper material model for simulating a blast event, the data from the blast tests are compared with results from finite element models that may or may not take into account the phenomenon of increase in the yield and ultimate limit of the steel material. This is accomplished by employing in the analysis the Cowper-Symonds law, the Johnson-Cook constitutive equation and a dynamic increase factor as proposed by UFC-3-340 [3].

Dynamic assessment manuals, such as the UFC-3-340 [3], include dynamic increase factors to take into account the rise in yield strength as a result of high strain-rates. Such a diagram is shown in Fig.8, which proposes increase factors for the dynamic yield stress for two American steel grades. Several other relationships exist in the literature for describing the effect of high strain-rates on the flow stress of steel, some of which derived from relevant experiments of hot-rolled reinforcing steels but also adopted for the case of structural steels. Two of the most common relationships are those of the CEB information bulletin No. 187 [6] and Malvar [7], which are represented graphically in Fig.7 and Fig.8.

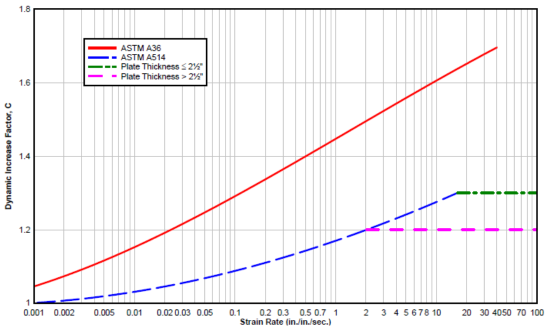


Figure 7: Dynamic increase factor for two American structural steels [3]

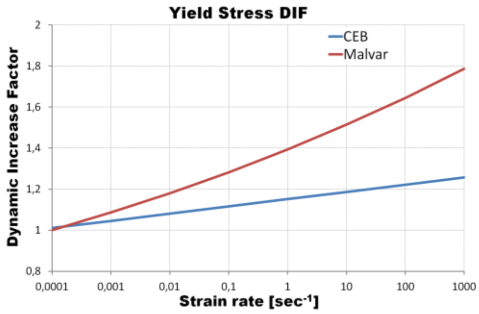


Figure 8: Dynamic increase factor for yield stress according to [6] and [7]

Two of the most popular equations for describing the behavior of metallic materials under high strain-rates are the Cowper-Symonds law [8] and the Johnson-Cook model [9], represented by eq.(3) and eq.(4), respectively.

$$\sigma_{0d} = \sigma_{0s}\left[1+\left(\frac{\dot{\varepsilon}}{D}\right)^{\frac{1}{q}}\right] \tag{3}$$

where, σ_{0d} is the dynamic flow [MPa] stress at $\dot{\varepsilon}$ strain-rate,
σ_{0s} is the static flow stress [MPa] and
D, q are constants of the Cowper-Symonds equation.

$$\sigma_{0d} = \left(\mathrm{A}+\mathrm{B}\left(\varepsilon_p\right)^n\right)\left(1+C\ln\frac{\dot{\varepsilon}_p}{\dot{\varepsilon}_o}\right), \tag{4}$$

where, A is the yield stress [MPa] of the material (at temperatures below T_f),
B, n are material parameters describing the effects of strain hardening,
C is a coefficient relating to the effect of strain-rate,
$\dot{\varepsilon}_o$ is the reference strain-rate under which the test data were collected,
$\dot{\varepsilon}_p$ is the current plastic strain-rate, and
ε_p is the current equivalent plastic strain.

The Cowper-Symonds law has only two material constants which are computed through experimental data and in the case of mild steel are equal to D=40,4sec^{-1} and q=5,0. On the other hand the Johnson-Cook constitutive equation has more material constants, which are usually derived by high speed tension, compression or shear tests, using Hopkinson bar techniques, etc. The constants used in this study are similar to those proposed by Johnson [8] for the 1006 steel, but the yield and ultimate stress values are the ones of the current steel. The temperature term which should be included in eq.(4) is not taken into account since there is no major temperature change at the studied experiments.

3.3 Analyses of steel sections

Fig.9 and Fig.10 show the displacement time history at the steel section's mid-span (1,20m). These displacements have been produced by simulations using 8-node three-dimensional solid elements with 8 Gauss points and are compared with the displacements recorded during the relative experiments. The examined material models include: an isotropic material model with linear hardening, a model using a dynamic increase factor (adjusted through Fig.7 for 0.90 s^{-1}, the maximum recorded strain rate of the experiment), and those proposed by Cowper-Symonds and Johnson-Cook. Fig.9 shows the displacements when no axial load is present and the steel member is loaded normal to its weak axis, whereas Fig.10 is for loading the member axially and with pressurenormal to its strong axis. Both figures show that the shape of the displacement time history is predicted with good accuracy by all material models. However, for the model without the strain-rate effect included the displacements are overpredicted by approximately 10% when no axial load is present and by approximately 20% when an axial load exists. Fig.11 and Fig.12 show the strain time history for a point at steel member's flange at mid-span. In both cases the strains are larger than the yield strain and they match relatively well the experimental results, which means that the computational models are reliable even in cases where large strains are expected.

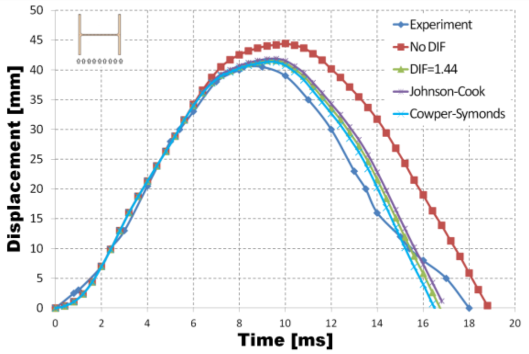


Figure 9: Displacement time history at beam's mid-span for weak-axis orientation

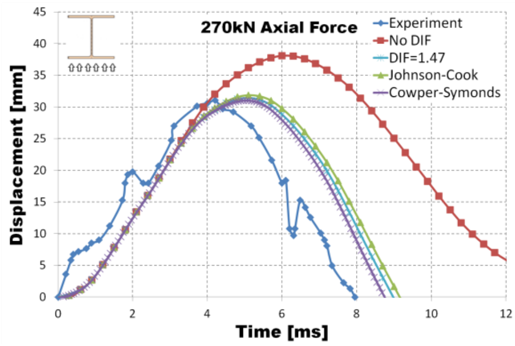


Figure 10: Displacement time history at column's mid-span for strong-axis orientation

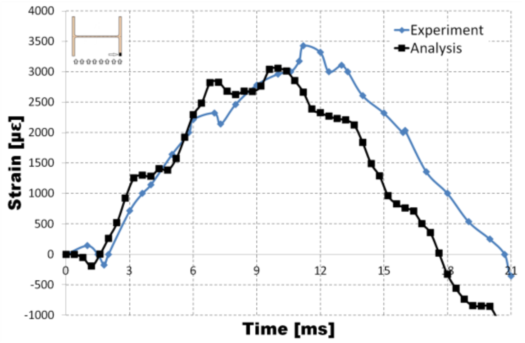


Figure 11: Strain time history at beam's mid-span for weak-axis orientation

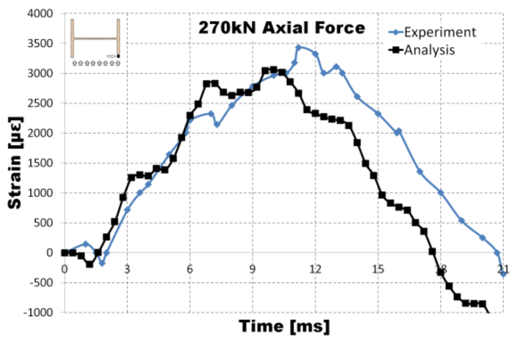


Figure 12: Strain time history at column's mid-span for strong-axis orientation

5. CONCLUSIONS

Technical information relevant to the basic characteristics of external explosion loads has been briefly presented in the current paper. A study focusing on the significance of material modelling when simulating blast effects on structures has been performed. The findings demonstrate the importance of taking into account the strain-rate effect on the steel's flow stress. The relative material models definitely give better results when compared to models that do not have this option, especially when large yielding of the steel section is expected. . Finally, since under high-strain rates usually the yield and ultimate stresses of steel increase, this means that during design a more economical solution could also be achieved.

6. REFERENCES

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ΕΠΙΡΡΟΗ ΤΗΣ ΤΑΧΥΤΗΤΑΣ ΦΟΡΤΙΣΗΣ ΣΤΗΝ ΑΝΑΛΥΣΗ ΜΕΤΑΛΙΚΩΝ ΜΕΛΩΝ ΥΠΟ ΦΟΡΤΙΑ ΕΚΡΗΞΗΣ

Vasilis Karlos[1], George Solomos[2]
[1]Scientific officer, [2]Project leader
European Commission, Joint Research Center (JRC), Institute for the Protection and Security of the Citizen (IPSC), European Laboratory for Structural Assessment (ELSA)
Via Enrico Fermi 2749, 21027, Ispra VA, Italy
E-mail: vasileios.karlos@jrc.ec.europa.eu, george.solomos@jrc.ec.europa.eu

ΠΕΡΙΛΗΨΗ

Κατά τη διάρκεια των τελευταίων δεκαετιών η απόκριση των κατασκευών υπό φορτία έκρηξης προσέλκυσε το ενδιαφέρον των ερευνητών μετά από διάφορες τρομοκρατικές βομβιστικές επιθέσεις, όπως αυτές στο World Trade Center στη Νέα Υόρκη το 1993 και στο A. P. Murrah Federal Building στην Oklahoma City το 1995. Μετά τα γεγονότα της 11ης Σεπτεμβρίου 2001 έγινε ευρέως αντιληπτό ότι δημόσια κτίρια και κυβερνητικές εγκαταστάσεις, καθώς και χώροι μεγάλης συνάθροισης ατόμων μπορούν να αποτελέσουν υποψήφιο στόχο τρομοκρατικών ενεργειών, οπότε υπήρξε η ανάγκη κάποιου κανονισμού ή οδηγίας ώστε να είναι δυνατός ο σχεδιασμός κατασκευών ακόμα και υπό αυτές τις ακραίες καταστάσεις φόρτισης. Μέχρι πρόσφατα οι μόνες τεχνικές οδηγίες για τον σχεδιασμό κατασκευών υπό εκρηκτικά φορτία είναι από στρατιωτικά εγχειρίδια, των οποίων ένα μικρό μόνο μέρος είναι διαθέσιμο προς το ευρύ κοινό καθώς τα περισσότερα προορίζονται για αποκλειστικά στρατιωτική χρήση. Ο EN 1991-1-7 κάνει αναφορά σε τυχηματικές φορτίσεις και εκρήξεις, αλλά εστιάζεται κυρίως σε κρουστικά φορτία, όπως συγκρούσεις από τρένα, πλοία ή άλλα οχήματα καθώς και σε εκρήξεις φυσικού αερίου εντός κτιρίων, χωρίς όμως να δίνει προτάσεις για τον υπολογισμό φορτίων εξαιτίας εξωτερικών εκρήξεων.

Στην παρούσα εργασία δίνονται συνοπτικά οδηγίες σχετικά με τον υπολογισμό των φορτίων που ασκούνται σε μια κατασκευή εξαιτίας μιας εξωτερικής έκρηξης και τον τρόπο με τον οποίο αυτή αναμένεται να συμπεριφερθεί. Σε αυτές περιλαμβάνονται οι βασικές αρχές που διέπουν τη συμπεριφορά μεταλλικών υλικών υπό δυναμικές φορτίσεις με υψηλές τιμές ταχυτήτων παραμορφώσεων, η οποία μπορεί να είναι σημαντικά διαφορετική σε σχέση με την αντίστοιχη υπό στατικές φορτίσεις. Συνήθως υπό εκρηκτικές φορτίσεις παρατηρείται σημαντική αύξηση του ορίου διαρροής και του ορίου θραύσης του υλικού, που εξαρτάται από το μέγεθος και τα χαρακτηριστικά της έκρηξης. Η σημασία της χρήσης του κατάλληλου νόμου υλικού κατά τη διάρκεια της ανάλυσης θα αποδειχθεί μέσω της σύγκρισης των αποτελεσμάτων μοντέλων πεπερασμένων στοιχείων με αντίστοιχα πειράματα τα οποία πραγματοποιήθηκαν στο πανεπιστήμιο McMaster στον Καναδά. Συγκεκριμένα, τα πειραματικά αποτελέσματα συγκρίνονται με αυτά του προγράμματος πεπερασμένων στοιχείων EUROPLEXUS στο οποίο γίνεται χρήση μοντέλων υλικού που ενσωματώνουν είτε ένα δυναμικό συντελεστή αύξησης των τιμών διαρροής και αστοχίας που προτείνεται από τεχνικά εγχειρίδια, είτε το μοντέλο Cowper-Symonds, είτε την εξίσωση των Johnson-Cook.