Analytical simulation of high-speed impact onto hybrid glass/carbon epoxy composites targets

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Abstract

Recently, the authors developed an analytical model, which has been shown valid to simulate accurately high-speed penetration onto composite materials targets. In this paper, the analytical model has been modified to analyse the impact onto hybrid composite material targets. Several equations have been corrected, although the basic structure of the model has been kept intact. The model has been utilized to analyse impact of steel balls, 5.56 mm diameter onto hybrid carbon/glass laminates at impact speeds ranging between about 200 and 600 m/s. Two different S2 glass fibre contents have been analysed, namely 12 and 21\%. Analytical results of both ballistic limit (maximum speed for no perforation) and residual velocity of penetrator after full perforation vs. impact velocity show acceptable agreement with experimental results. We may conclude that modified analytical model is a valuable tool to simulate high-speed impact onto hybrid composite targets, being useful for a first stage design optimization.

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1. Introduction

Fibre reinforced composites, manufactured by a polymer matrix reinforced with high strength fibres are becoming standard materials to produce structural components, thanks to its high specific strength and stiffness.

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Carbon fibres are customarily utilised to reinforce epoxy matrices to produce aerospace structural components in addition to more traditional materials, like aluminium alloys. They are mostly used in the form of laminates, made by stacking composite layers, using either unidirectional or woven fibres.

It is well known, however, that carbon/epoxy laminates are highly susceptible to impact loading, which may damage the component reducing dramatically its mechanical properties [1, 4]. On the other hand, other fibre-reinforced composites show a better performance under impact loading. This fact is attributed to a reduced energy absorption capacity of carbon fibres as compared to that of other fibres, like aramid or glass. Nevertheless, the specific strength and stiffness of carbon fibres are higher than those of its competitors.

Recently, some researches have proposed a solution to improve impact performance of carbon based composites [5, 6]. The idea is based on hybridation techniques, that is, the addition of a small amount of other more efficient fibres (aramid, glass) although not punishing excessively the laminate weight.

High-speed impact behaviour of materials is customarily carried out by experimental approach, i.e. by firing tests. Hybrid composite design optimisation may be helped by an effective utilisation of reliable analytical or numerical simulations, which may be useful for a considerable reduction of experimental effort.

However, as pointed out by Silva et al. [7] numerical simulation of impact behaviour of composite materials is a difficult task, due to the high number of parameters required to achieve reliable results. In such circumstances some parameters are simply adjusted to match experimental results, thus reducing the predictive capacity of numerical simulation which is, in itself, a time-consuming procedure.

Conversely, analytical models are based on laws of mechanics of continuum media, assuming some simplifying hypotheses to derive equations simulating the penetration process.

Over the past decades, several analytical models aiming to simulate high-speed penetration into composite materials targets have been proposed [8, 9, 10]. All these models require the use of at least one parametric quantity with a magnitude that is arbitrarily chosen to match the empirical results. Hence, although those models represented an advance in the knowledge of this complex problem, they had little predictive capacity.

Recently, the authors have developed a new analytical model based on the basic hypotheses first proposed by Smith and Roylance, which has demonstrated acceptable agreement with experimental results of high-speed penetration into composite materials targets [11] not requiring the use of any parametric quantity.

With respect to the impact behaviour of hybrid composite materials, recently Phoenix and co. [12] have developed an analytical model, assuming that the target behaviour can be approximated by a two-dimensional membrane. This model leads to a somewhat complicated set of equations that may correctly reproduce the strain...
distribution in the target. However, for the time being there is no failure criterion, so that the model does not provide information about perforation speed.

In this paper, the authors have modified their analytical model to adapt it for simulation of high-speed penetration into hybrid composite materials targets. Although the main core of the former model remains unchanged, some equations have been changed to take into account the presence of two different reinforcement fibres in the laminate. In the following, a description of the model, including the modified expressions is presented as well as some analytical predictions of impact behaviour of hybrid glass/carbon epoxy composites and the comparison with experimental results.

2. Analytical model

A detailed description of the model can be found in the reference [11]. The basic expressions including the changes introduced for simulation of penetration into hybrid materials are as follows:

2.1. One single-fibre reinforcement

Equation of motion

\[
\left( m_p + \Delta m \right) \frac{dV}{dt} = -4F \cos \theta_o
\]

where \( \theta_o \) is the angle between yarns and penetration direction (see figure 1)
\( m_p \) is the mass of penetrator
\( \Delta m \) is the increase of mass due to target “plug” put in motion.

This parameter is computed as

\[
\Delta m = SD \cdot n_l \cdot (\phi + l)^2
\]

where \( SD \) is surface density of a layer
\( n_l \) is the number of layers
\( \phi \) is penetrator’s diameter
\( l \) is the distance between yarns

and \( F \) is the resistance force (see figure 1) given by

\[
F = N E \varepsilon_o S
\]

where \( E \) is Young’s modulus of the yarns
\( S \) is cross sectional area of the yarns
\( \varepsilon_o \) is the strain of the yarns aside the penetrator
\( N \) is the number of primary yarns, given by

\[
N = \frac{\phi}{l} \cdot n_l
\]

Integration of eq. 1 and thus obtention of penetration history requires determination of quantities \( \varepsilon_o \) and \( \theta_o \). They are derived from the following expressions:

\[
\varepsilon_o = \frac{\sqrt{y_0^2 + l^2} - l}{l}
\]
\[ \tan \theta_0 = \frac{l}{y_0} \]  

Fig. 1. Definitions for impact on woven fabric target.

where the parameter \( y_0 \) is the difference of displacement in the impact direction of the two first cross-overs. This quantity is related to the penetration, named \( y \) by the equation

\[ y_0 = m \, y \]  

(7)

where parameter \( m \) is given by

\[ m = \frac{r(1 + r)^n}{(1 - r)^{n+1} - 1} \]  

(8)

being \( n \) the number of cross-overs reached by the stress wave at the time \( t \) considered:

\[ n = \frac{c \, t}{l} \]  

(9)

being \( c \) sound speed on the yarn and \( r \) being simply

\[ r = \frac{2}{N} \]  

(10)

Deriving the penetration history \( y(t) \) is easily carried out step by step introducing all values of the parameters at a time \( t_i \), and after solving eq.1, obtain the velocity at the end of the time step, and repeat the calculation increasing the penetration \( y_i \) by the increment \( v_i \Delta t \). We use to make coincident the time step \( \Delta t \) with the time required by the stress wave to travel the distance \( l \) between two yarns:

\[ \Delta t = \frac{l}{c} \]  

(11)

This time step is small enough to assume that all quantities are constant for such time interval, and they are corrected at the end of the interval. The calculation ends either when the penetrator velocity is zero (penetrator arrest) or when the yarn strain \( \varepsilon_\text{a} \) reaches a critical value \( \varepsilon_\text{r} \) which is taken for simplicity as the static maximum tensile strain of the yarn (full perforation).

In this latter case, the penetrator velocity after perforation is increased by adding the elastic energy stored in the yarns, released when the target is perforated:
\[ \frac{1}{2} m_p V_f^2 = \frac{1}{2} (m_p + \Delta m) V_r^2 + ESN \varepsilon_r^2 (\phi + 2l) \]  

(12)

where we call \( V_r \) the penetrator speed when the yarn strain reaches the critical value and \( V_f \) the velocity of the penetrator after perforation of the target.

### 2.2. Hybrid fibre reinforcement

In this case, the target is a laminate manufactured by stacking layers of two different fibre reinforcements, for instance carbon and glass. The quantities needed to feed the model are mass \( m_p \), diameter \( \phi \) and impact velocity \( V_o \), of the penetrator Young’s modulus, critical strain, surface density of a layer, distance between cross-overs, fibre density and number of layers of each fibre reinforcement. With all those values the model can be used again introducing small modifications.

First of all, we compare the sound speed values for both fibres. For instance, in the case of carbon fibre \( c_c = 11400 \) m/s and for S2 glass \( c_g = 6440 \) m/s. This means that \( \frac{c_g}{c_c} = 0.5614 \). This parameter, that will be named \( \eta \), is very important for this model, because it relates the distances travelled by the elastic waves for both fibres at a certain time, and also relates the corresponding strains

\[ \varepsilon_c / \varepsilon_g = \eta \]  

(13)

where we call \( \varepsilon_g \) and \( \varepsilon_c \) the strains in the glass and carbon fibres for a definite time.

Now, we compare the relation given by eq. 13 with the critical strains for both fibres \( \varepsilon_{cg} \) and \( \varepsilon_{cc} \). This analysis will indicate which fibre will be the first one broken. For instance, for the fibres under consideration we have \( \varepsilon_{cg} = 0.033 \) and \( \varepsilon_{cc} = 0.011 \). Being \( \eta = 0.5614 \) the eq. 13 indicates that the carbon fibres will reach the critical value first, when the glass fibre strain will be \( 0.011/0.5614 = 0.0196 \). This analysis is useful before starting the computation, because it gives light on the behaviour of the different layers.

The equations of the model for hybrid composite targets are

- Eq. 1 remains unchanged
- Eq. 2 is replaced by

\[ \Delta m = (\phi + l)^2 (SD_g n_g + SD_c n_c) \]  

(14)

where \( SD_g \) and \( SD_c \) are surface densities of glass and carbon layers respectively and \( n_g \) and \( n_c \) number of glass layers and carbon layers respectively.

- Eq. 3 is replaced by

\[ F = E_g S_g N_g \varepsilon_g + E_c S_c N_c \varepsilon_c \eta \]  

(15)

where as usual all quantities with index \( g \) refer to glass fibres and with index \( c \) refer to carbon fibres. The number of primary yarns (eq. 4) are now different for both fibres

\[ N_g = \frac{\phi}{l_g} n_g \]  

(16)

\[ N_c = \frac{\phi}{l_c} n_c \]  

(17)

\[ N = N_g + N_c \]  

(18)

Finally, eqs. 5 to 11 remain unchanged, \( \varepsilon_0 \) and \( l \) referring to glass fibres.
Analogously to the case of one single fibre, the equation of motion (eq. 1) can be easily integrated step by step up to the time for which \(V\) is zero (penetrator arrest) or when the strain \(\varepsilon_c\) reaches the critical value \(\varepsilon_{c0}/\eta\) (0.0196 for this case). This situation means that the less ductile fibres have failed (the carbon fibres), but the target is not yet fully perforated because the other fibres continue to further reduce the penetrator velocity. The computation can be continued, using the equations set of one single fibre reinforcement, using only the data corresponding to glass fibres. Finally the process ends either by penetrator stopping or by full penetration if the glass fibre strain \(\varepsilon_c\) reaches the critical strain \(\varepsilon_{cg}\).

The residual velocity after full perforation is calculated by mean of eq. 12 introducing values corresponding to glass fibres.

3. Modelisation of high-speed penetration into hybrid glass/carbon epoxy composites

The analytical model was validated by comparing analytical predictions with tests results of a wide experimental programme carried out by Cunniff to determine high-speed performance of aramid fibre reinforced composites.

Now, we will utilise the model to simulate high-speed penetration into hybrid glass/carbon epoxy composites. The experimental programme was described previously [13]. The main features of the firing tests that are relevant for analytical simulation are the following ones:

- The penetrator is a steel ball, 5.56 mm diameter and 7.065 g of mass.
- Balls are launched by means of a light-gas gun, with a 7.62 mm calibre barrel.
- Impact velocities are in the range 200-600 m/s approximately.
- Targets are laminates either of carbon/epoxy or hybrid glass/carbon epoxy with a structure to achieve orthotropic behaviour.

The material data needed to feed the model are summarized in table 1. All data are supplied by the producer or measured directly on the targets.

- Penetrator velocities before and after the impact are measured by means of two infrared windows and a high speed video camera respectively.

Table 1. Target materials data.

| Property                        | Carbon | S2 glass |
|---------------------------------|--------|----------|
| Young’s modulus \(E\) (GPa)     | 230    | 87       |
| Critical strain \(\varepsilon_c\) (%) | 1.1    | 3.3      |
| Fibre density \(r\) (kg/m3)    | 1770   | 2100     |
| Sound velocity \(c\) (m/s)     | 11400  | 6440     |
| Layer’s surface density \(SD\) (g/m2) | 390    | 305      |
| Distance between crossovers \(l\) (mm) | 2.17   | 0.444    |
| Cross sectional area of fibres \(S\) (mm2) | 0.24   | 0.0323   |

Three laminates have been tested, the first one, named C-1610 is carbon fibre reinforced epoxy, while the other two, named H-18/21S and H-20/12S are hybrid glass/carbon epoxy laminates. The characteristics of all laminates are summarized in table 2.

Table 2. Characteristics of laminates.

| Laminate | Thickness (mm) | Number of C layers | Number of glass layers |
|----------|----------------|--------------------|------------------------|
| C-16/0   | 5.64           | 16                 | 0                      |
| H-18/21S | 5.52           | 12                 | 6                      |
| H-20/12S | 6.60           | 16                 | 4                      |

Figures 2, 3 and 4 illustrate the results obtained in terms of residual velocity vs. impact velocity. Dots correspond to experimental results while the solid lines correspond to analytical predictions.
A remarkable agreement is observed between analytical and experimental results, both of ballistic limit V50 (impact velocity for which 50% of the shots perforate the target) as well residual velocities after full perforation, differences observed between analytical and numerical results being lower than the usual scatter of this kind of firing tests.

4. Discussion

Figures 2, 3 and 4 show similar trends. For impact velocities slightly higher than the ballistic limit, a sudden increase of residual velocity is observed. This fact corresponds to an abrupt reduction of energy absorbed by the target. This effect was already explained by the authors [11] and it is observed also for hybrid glass/carbon epoxy composites targets.

There is a small improvement of impact behaviour of hybrid composites as compared with their counterparts carbon fibre composites. The resistance enhancement is explained by the higher critical strain of glass fibres, which
may continue to decelerate the penetrator after failure of the carbon fibres. The improvement achieved is however not significant due to the much lower Young’s modulus of glass fibres than that of carbon fibres.

In the case of H20/12S laminates, the impact resistance enhancement is higher, even though its glass fibre content is lower (12%). This fact is observed both experimentally and analytically. The analytical model gives an explanation of this effect: This laminate has a thickness of 6.6 mm, higher than that of the carbon fibre laminate (5.64 mm) and that of the H-18/21S (5.52 mm) which leads to an increase of the “plug” weight and thus of the ballistic limit.

The position of the glass layers in the laminate has also high importance. The model assumes that all layers have got the same displacement for a certain time, so that glass fibres control the strain, and the carbon fibres may continue to strain until glass fibres strain reaches the critical value ecc/h. This is correct providing the glass fibres layers are placed on the rear of the laminate. If carbon fibres layers were placed on the rear of the laminate, these layers could be strained separately causing delamination and premature failure.

5. Conclusions

The analytical model developed by the authors has been adequately modified to be able for simulation of high-speed penetration into hybrid composite targets.

The model has been used to analyse impact behaviour of glass/carbon epoxy composites, comparing analytical predictions with experimental results of steel balls impacting hybrid laminates previously published.

A good agreement is observed between analytical and experimental results in terms of ballistic limit and residual velocity after perforation.

The model may be a useful tool for primary analysis of hybrid composite targets under high-speed impact, enabling a fast although rough study of many parameters and thus reducing the experimental effort required.

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