A SIMPLE SHELL MODEL FOR SIMULATION OF LOCALIZED IMPACT ON GFRP LAMINATES

A.H. Sheikh, P.H. Bull, J.A. Kepler
***Department of Mechanical Engineering, Aalborg University, Denmark**

Keywords: *High velocity impact, Composite laminates, Finite element modelling, Progressive damage failure, Energy absorption*

Abstract

A numerical model for ballistic impact of GFRP laminated panels has been presented where the panels may consist of one or multiple laminates. For the multiple laminated panel, identical laminates were placed parallel to each other with some gap in between and the impactor velocity was sufficient to penetrate all the laminates. The commercially available code ABAQUS 6.6 (explicit) has been used in the present study where the impactor has been modelled as a rigid body and the laminates have been modelled with a simple shell element. A material model based on a continuum damage mechanics concept for failure mechanism of laminated composites has been implemented through a user subroutine. The numerical model is found to predict the energy absorption reasonably well when compared with the experimental results. Most interestingly, it has clearly demonstrated a feasible phenomenon behind counterintuitive experiment results for the multiple laminated panels.

1 Introduction

The understanding of the behaviour of laminated composite structures subjected to localized impact is an important as well as complex problem, and the degree of complexity increases with the increase of the velocity of the impact [1]. This is primarily due to the dependency of a number of aspects such as material behaviours, failure mechanisms, load transfer mechanisms and others, which are in general complex and associated with numerous uncertainties. As a result of this, the prediction of the impact process leads to an "open problem", where investigations have been carried out in different ways ranging from simple empirical models to extremely sophisticated numerical techniques depending on the importance and severity of the impact. In this context, nonlinear finite element simulation with progressive damage mechanics model is found to be one of the most successful techniques, but it requires considerable computational efforts.

Commercially available finite element codes, having the required capabilities, are commonly used for the simulation of impact problems in order to avoid the major efforts required in implementing the different well-established features including the severe geometric and material nonlinearities found in this problem. Moreover, the impact problem includes a very complex nonlinearity associated with the contact mechanism between the impactor and the structure. In this context, the explicit time integration scheme for solving the nonlinear dynamic equations has been demonstrated to be quite successful. In addition to this, the code should have a proper material model, which can predict the initiation of failure and its propagation in a realistic manner through progressive degradation of material properties. Unfortunately, the problem of progressive damage and failure modelling of laminated composites subjected to ballistic impact is not adequately well established. The significant developments and standardisations of the problem are quite recent and as a result of that, an appropriate material model may not be readily available with a commercially available code. In this context, there is a general trend amongst the researchers to implement a material model in a commercial code.

By this time, a number of studies have been carried out in this direction, but most of them are concerned with low velocity impact [2-11]. For high velocity impact, specifically for the range of impact considered in the present problem where the impactor penetrates the panel completely and exits with a residual velocity, the number of reported study is very few. To the best of author's knowledge, only two papers [12,13] are available on modelling of a fully penetrated impact process of a laminated composite panel where AUTODYN, a commercially available code based on smooth particle hydrodynamics method, is used in both the studies. The present investigation has also addressed impact of multiple laminates where there is no study so far on the modelling of its impact process to the best of authors' knowledge.

In the present investigation, an attempt has been made to implement a material model for laminated composites in the commercially available finite element code ABAQUS Explicit [14] through a user subroutine. The laminates are modelled with shell elements in order to have a simple and computationally efficient technique. The above material model is based on continuum damage mechanics where the in-plane failure criteria proposed by Hashin [5] along with the damage propagation law proposed by Matzenmiller, Lubliner and Taylor [6] have been adopted to predict the initiation and evolution of the failure. Attempts have been made to make the model as simple as possible so as to minimise the number of input data for the material. The methodology has been applied to impact simulation of single and multiple laminate configurations (detail is given in Section 3). The number of laminates considered for the multiple laminated panel is two for the purpose of simulation in the present study. The results obtained in the form of energy absorption or impactor residual velocity is found to be encouraging when compared with those measured in the laboratory experimentally.

From the experimental observations, it appeared that the specific energy absorption (energy absorption/glass fibre mass per unit area) capacity of thin laminates is more that that of thick laminates. This has inspired to use multiple laminated panels consisting of thin laminates placed parallel to each other with some gap in between instead of a single thick laminated panel. Surprisingly, the energy absorption capacity of the multiple laminate configuration has been found to be quite less than the expected value when it was actually tested. It is most interesting that the actual phenomenon behind getting such unexpected results has been clearly demonstrated by the numerical model where the option of retaining the mass for the elements failed in impact process played a major role.

2 Material Model

ABAQUS is a well regarded finite element commercial code and it has a number of material models but all of them are not supported with an appropriate failure model for its progressive damage, which is extremely important in a fully penetrating impact process considered in the present study. The progressive failure model for laminate composites has been recently implemented in its latest version but it is only supported by some specific elements of ABAQUS Standard/Implicit. Unfortunately, the capability has not been extended to ABAQUS Explicit, which is suitable for solving the present problem having severe nonlinearities as mentioned earlier. In this situation, an attempt has been made to implement a user material model for laminate composites where the failure criteria proposed by Hashin [15] are adopted to predict the initiation and subsequent propagation of damage. For this purpose, a user subroutine VUMAT has been written in FORTRAN and it has been attached with ABAQUS Explicit externally. According to the failure criteria proposed by Hashin [15], the failure functions may be expressed as follows.

$$f_1 = \left(\frac{\bar{\sigma}_1}{X_T}\right)^2 + \left(\frac{\bar{\sigma}_{12}}{S_L}\right)^2 \geq r_1^2\text{; If } \bar{\sigma}_1 \geq 0 \qquad (1)$$

$$f_1 = \left(\frac{\bar{\sigma}_1}{X_C}\right)^2 \geq r_1^2\text{; If } \bar{\sigma}_1 < 0 \qquad (2)$$

$$f_2 = \left(\frac{\bar{\sigma}_2}{Y_T}\right)^2 + \left(\frac{\bar{\sigma}_{12}}{S_L}\right)^2 \geq r_2^2\text{; If } \bar{\sigma}_2 \geq 0 \qquad (3)$$

$$f_2 = \left(\frac{\bar{\sigma}_2}{2S_T}\right)^2 + \left(\left(\frac{Y_C}{2S_T}\right)^2 - 1\right)\frac{\bar{\sigma}_2}{Y_C} + \left(\frac{\bar{\sigma}_{12}}{S_L}\right)^2 \geq r_2^2\text{; If } \bar{\sigma}_2 < 0 \qquad (4)$$

In the above equations, the damage threshold (r_i) for any failure mode is taken as unity before the initiation of damage, and it is subsequently upgraded with the propagation of damage in that mode. The damage growth is represented by the continuum damage mechanics model, where the concept of Matzenmiller, Lubliner and Taylor [16] has been used to evaluate the damage variables (d_i) for defining the degradation of the material properties as

$$d_i = 1 - e^{\left(1 - r_i^m\right)/m} \tag{5}$$

where m is a material parameter. With the damage variables, the stress-strain relationship may be expressed as

$$\sigma_1 = \left(\left(1-d_1\right)E_1\varepsilon_1 + \left(1-d_1\right)\left(1-d_2\right)\nu_{21}E_1\varepsilon_2\right)/D \tag{6}$$

$$\sigma_2 = \left(\left(1-d_2\right)E_2\varepsilon_2 + \left(1-d_1\right)\left(1-d_2\right)\nu_{12}E_2\varepsilon_1\right)/D \tag{7}$$

$$\sigma_{12} = \left(1-d_{12}\right)G_{12}\varepsilon_{12} \tag{8}$$

where $D = 1-\left(1-d_1\right)\left(1-d_2\right)\nu_{12}\nu_{21}$ and $d_{12} =$ max $\left(d_1, d_2\right)$. The effective stress components used in equations (1-4) can be simply obtained as $\overline{\sigma}_i = \sigma_i/\left(1-d_i\right)$. A Gauss point is declared dead when the damage variables for all the modes at that point attains a maximum value, which is taken as 0.999. An element is declared dead and removed from the mesh when all the Gauss points of the element become dead. Such an element can not regain its strength in future.

A typical variation of stress with respect to strain has been shown in Fig. 1 for different values of material parameter *m* as reported by Xiao, Gama and Gillespie [17]. In the present study, the value of *m* is always taken as 2.0 for all the modes.

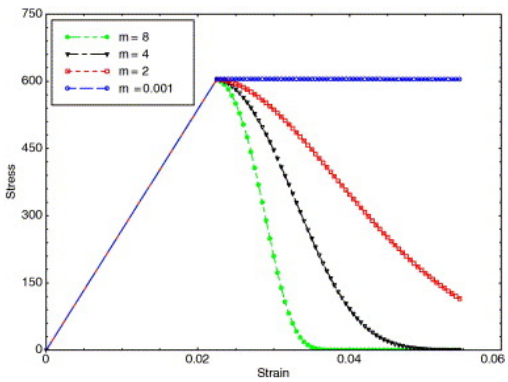

Fig. 1. Stress-strain relationship for different material parameters

Sometimes a strain based failure criteria is preferred for convenience in its implementation compared to stress based failure criterion as mention above. Such an attempt has also been made in the present study where the failure functions may be expressed as follows.

$$f_1 = \left(\frac{E_1\varepsilon_1}{X_T}\right)^2 + \left(\frac{G_{12}\varepsilon_{12}}{S_L}\right)^2 \geq r_1^{\,2}\text{; If } \varepsilon_1 \geq 0 \tag{9}$$

$$f_1 = \left(\frac{E_1\varepsilon_1}{X_C}\right)^2 \geq r_1^{\,2}\text{; If } \varepsilon_1 < 0 \tag{10}$$

$$f_2 = \left(\frac{E_2\varepsilon_2}{Y_T}\right)^2 + \left(\frac{G_{12}\varepsilon_{12}}{S_L}\right)^2 \geq r_2^{\,2}\text{; If } \varepsilon_2 \geq 0 \tag{11}$$

$$f_2 = \left(\frac{E_2\varepsilon_2}{2S_T}\right)^2 + \left(\left(\frac{Y_C}{2S_T}\right)^2 - 1\right)\frac{E_2\varepsilon_2}{Y_C} + \left(\frac{G_{12}\varepsilon_{12}}{S_L}\right)^2 \geq r_2^{\,2}\text{; If } \varepsilon_2 < 0 \tag{12}$$

3 Experimental Setup

A dedicated test chamber has been set up at the basement of a laboratories of the department to have a common experimental facility for ballistic impact test of different structural panels [18]. One of its major equipment is the compressed air gun as shown in Fig. 2. The gun can accommodate different barrels for different impactor size and its velocity. For the present purpose, a 2m long barrel having 20mm caliber has been used. A compressor is used to build-up the air pressure, which can go up to 250 Bars producing an initial velocity of the order of 500m/sec for the impactor used in the present study. A recoil damper is used at the gun muzzle in order to reduce the effect of recoil as well as restrict the pressurised air moving with the impactor. As an additional protection, a blast shield is placed in front of the test specimen (laminated panel) to minimize the effect of the pressurised air blast on the panel. The incidental/initial velocity of the impactor is measured by a speed trap placed between the gun muzzle and the blast shield. A kinetic pendulum, kept behind the test specimen, catches the impactor when it penetrates the specimen completely and exits with an residual velocity. A linear voltage displacement transducer (LVDT) is used to measure the displacement of the pendulum, which is used to estimate the residual velocity of the impactor.

A hemispherical tip cylindrical impactor as shown in Fig. 3 has been used in the present study. The material used is a superior quality aluminium (EN-AW 6082) to have minimum distortion as well as light enough to attain a higher velocity. Some material has been removed from its rear end (Fig. 3) to increase the directional stability. The approximate weight of the impactor is 18.8 g.

Fig. 2. The compressed air gun in the test chamber

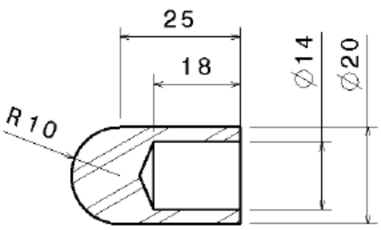

Fig. 3. Cross-sectional view of the impactor

In the present study, the test specimen is always a square panel of 300 mm with a clear square span of 250 mm after fixing it in the testing rig as shown in Fig. 4. Fiber reinforced laminated composite plates have been used for the test panel, which may have one laminate or a number of equispaced identical laminates as shown in Fig. 5. The laminates are made with 650 g/m² non crimp fabric (NCF) glass fiber mat [0/90] and Pro Set 117/229 epoxy having a stacking sequence of $[0/90]_n$, where n may have different values. The vacuum infusion technique has been used for the manufacturing of the laminates, which are post cured at a temperature 50^0C for 24 hours. The resign has been subjected to vacuum of about 99.9% for 30 minutes before the initiation of infusion in order to remove the dissolved air as much as possible. The laminates used in this study are 10 layer $[0/90]_5$ and 20 layer $[0/90]_{10}$ configuration where the 20 layer laminate has an approximate thickness of 4.8 mm and it is 2.4 mm for the 10 layer laminate.

Fig 4. Impacted laminated panel in test rig

Fig 5. Multiple laminated panel

4 Simulation

As it is not easy to get the force exerted by the impactor on the panel during the impact, the impactor has also been modelled like the laminated panel and the two separate bodies have been connected through contact mechanism. In the simulation, the impactor has been idealised as a rigid body, as the deformation of the impactor is always found to be insignificant in the experiment. The impactor has been modelled as 3D rigid surface using the 4-node 3D quadrilateral element R3D4. The movement of the impactor has been restrained in all the directions except translation along its axis. The initial velocity of the impactor has been specified as field at a reference point defined at the centroid of the impactor where its mass has also been assigned. In order to have a simple and computationally efficient model, the fibre reinforced composite laminates have been modelled with the 4-node quadrilateral shell element S4R having the options of reduced integration, hourglass control and finite membrane strains. As the structure has symmetry in both the directions, a quarter part of the panel as well as the impactor have been used in the model. At the beginning, the analysis for a test cases has been carried out with a number of mesh densities in order to assess the adequate mesh density for getting a converged solution. A mesh size of 50x50 for the quarter plate having higher mesh density near the plate centre as shown in Fig. 6 has been found to be sufficient for the present study. For the definition of contact between the impactor and the laminated panel, the general contact algorithm with the option of all exterior surface inclusion has been used. The mass of the free flying dead elements can be retained or removed with a proper option of the nodal erosion facility available with ABAQUS. This has been found to be quite useful for the demonstration of the impact process of multiple laminate panels.

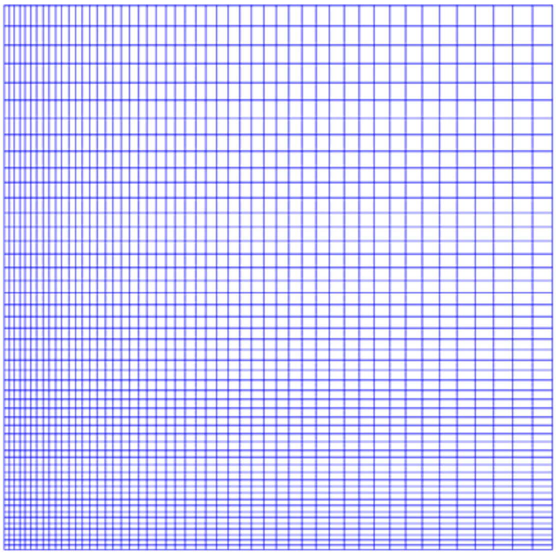

Fig 6. Finite element mesh of the quarter plate

5 Results and Discussion

First of all, the simulation has been done for two single laminated panels ($[0/90]_{10}$, $[0/90]_{10}$) and a double laminated panel ($2x[0/90]_5$) where the distance between the $[0/90]_5$ laminates of the double laminated panel is 20 mm. These panels were tested in the laboratory and the residual velocity of the impactor along with its incidental velocity were measured for the different cases. Based on those, the absorbed specific energy for the panels has been estimated. For the purpose of simulation, the material properties assumed for the laminate [19] are: E_1 = 38.6 GPa, E_2 = 8.3 GPa, ν_{12} = 0.25, G_{12} = 4.2 GPa, X_T = 1062.0 MPa, X_C = 610.0 MPa, Y_T = 31.0 MPa, Y_C = 118.0 MPa, S_L = 72.0 PPa, S_T = 72.0 MPa and ρ = 1850 kg/m^2. The values of impactor residual velocity obtained in the finite element simulation have been presented in Table 1 along with the experimental results. The percentage error for the impactor residual velocity has been evaluated for the different cases and presented in Table 1, which shows a very good predication capability of the proposed numerical model.

Table 1. Simulated residual velocity of the impactor for the different panels

Panels	$[0/90]_{10}$	$[0/90]_5$	2 x $[0/90]_5$
Incidental velocity (m/sec)	506	501	512
Residual velocity (m/sec)	419	449	439.0
Specific energy (J/[kg/m^2])	116.38	142.88	100.40
Residual velocity (m/sec) - FEM	425.64	462.38	447.35
% Error* (Residual velocity)	1.59	2.98	1.90

* (Experimental result-FEM result)/Experimental result

The specific energy absorption capacity of the thin laminate $[0/90]_5$ is found to be more than that of the thick laminate $[0/90]_{10}$. This has inspired to use the double laminated panel ($2x[0/90]_5$) with an expectation that it may have better energy absorption capacity than that of a thick laminate $[0/90]_{10}$. Moreover it was undertaken to develop some understanding, which might be useful in future studies related to impact performance of sandwich panels. Unfortunately, the capability of the double laminated panel has been found to be quite inferior. It appeared to be quite surprising at the time of actual testing in the laboratory, but it has also been observed in the numerical simulation, which has also helped to identify the actual reason behind such an incidence. Actually, some materials are removed from the first laminate in the impact process, which in turn hit the second laminate and reduce its strength significantly. This phenomenon is responsible for less energy release of the impactor and having higher residual velocity, which gives an impression that the double laminated panel has inferior capability. Fig. 7 clearly demonstrates the above phenomenon. The removed materials as mention above are practically the dead elements in the finite element simulation where the stiffness of these elements is practically zero but they are having their mass, which affects the second laminate when they interacts each other. However, ABAQUS has a capability "nodal erosion", which can be used to remove the mass of the dead elements in the simulation. With this option, the simulation of the double laminated panel has been carried out once again where the impactor residual velocity has been found to much lower (436.02 m/sec) as expected. In that case, the impact process is shown in Fig. 8 where the dead elements of the first laminate are not found to cause any degradation of the second laminate.

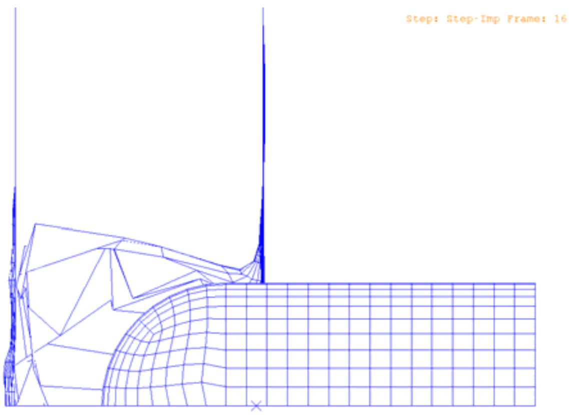

Fig 7. Impact of the double laminated panel without nodal erosion (retaining mass of the dead elements) - thrown out materials of the 1st laminate are rebounded by the 2nd laminate

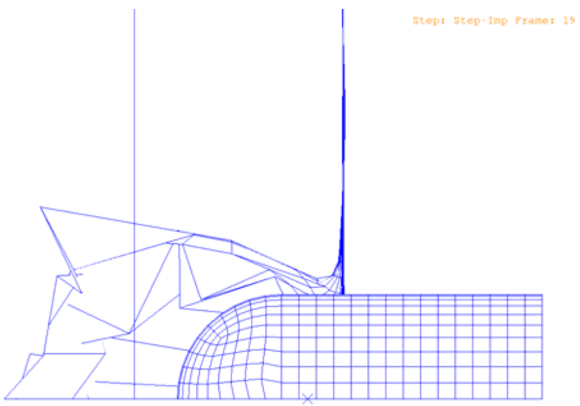

Fig 8. Impact of the double laminated panel with nodal erosion (removing mass of the dead elements)

In order to have more insight of the problem, simulation has been done for the $[0/90]_5$ laminate with incidental velocity of the impactor as 512 m/sec, which may be considered as a representation of the impact process of the first laminate of the double laminated panel. The residual velocity obtained in the simulation is 473.11 m/sec. It has been taken as the impactor incidental velocity and the simulation of the $[0/90]_5$ laminate has been carried out once again in order to represent this as the impact of the second laminate without any effect due to material thrown by the first laminate. The residual velocity obtained in this case is 436.82 m/sec.

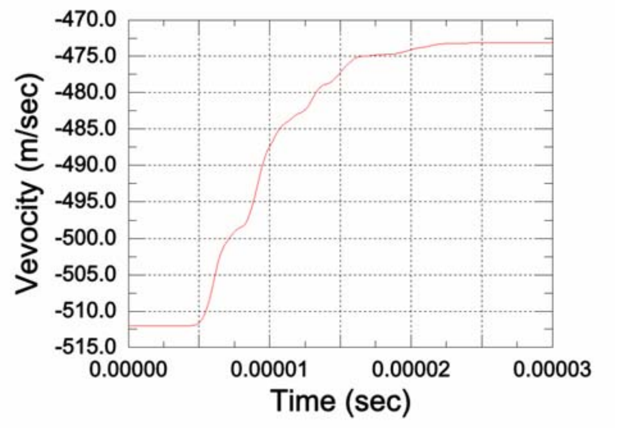

Fig 9. Time history of the impactor velocity for the $[0/90]_5$ laminate impacted with incidental velocity of 512 m/sec (residual velocity: 473.11 m/sec)

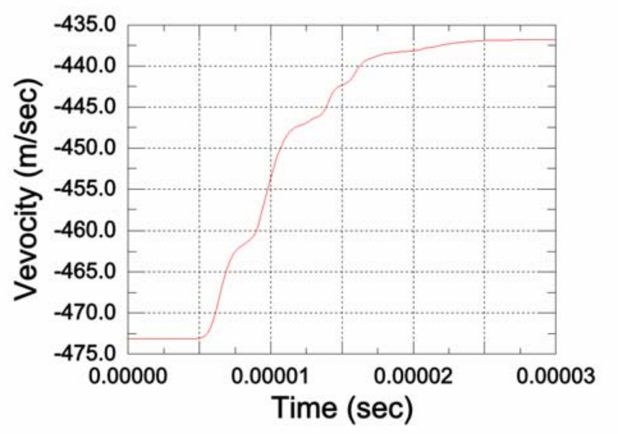

Fig 10. Time history of the impactor velocity for the $[0/90]_5$ laminate impacted with incidental velocity of 473.11 m/sec (residual velocity: 436.82 m/sec)

The time history of the impactor velocity obtained in these two cases as well as in the simulation of the double laminated panel with nodal erosion (removing mass of the dead elements) has been presented in Figs. 9 - 11. The plot in Fig. 11 appears to be simple superimposition of that in Fig.

9 and Fig. 10 as expected. Moreover, the residual velocity in Fig. 10 (436.82 m/sec) is found to be approximately same as that in Fig. 11 (436.02 m/sec), which gives an additional check. For the double laminated panel without nodal erosion i.e., retaining mass of the dead elements, the time history of the impactor velocity has also been presented in Fig. 12. It shows that the thrown out material of the first laminate starts affecting the second laminate after 0.035 msec.

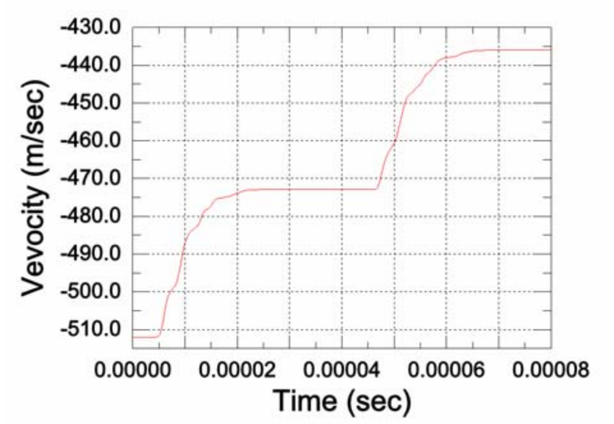

Fig 11. Time history of the impactor velocity for the double laminated panel removing mass of the dead elements (residual velocity: 436.02 m/sec)

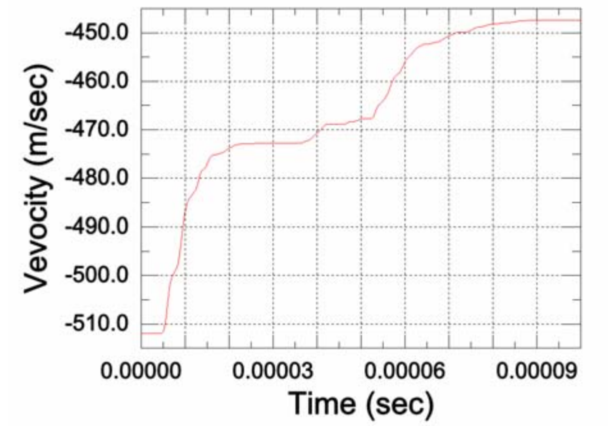

Fig 12. Time history of the impactor velocity for the double laminated panel retaining mass of the dead elements (residual velocity: 447.35 m/sec)

In order to study the effect of the distance/gap between the two laminates of the double laminated panel, a number of simulations have been done with different values of this distance ranging from 5mm to 40mm and the values obtained for the residual velocity of the impactor have been presented in Table 2. It indicates that the thrown out material of the first laminate has a maximum influence on the second laminate when the distance between the two laminates is around 10 mm. So the above influence will be less if the gap between the two laminates becomes too small or too large.

Table 2. Variation of impactor residual velocity with distance between the two laminates (incidental velocity: 512 m/sec)

Distance (mm)	Residual velocity (m/sec)
5	451.68
7.5	453.42
10	456.58
15	454.26
20	447.35
30	443.02
40	442.52

6 Conclusions

An efficient numerical model for the simulation of fully penetrating ballistic impact response of single and multiple laminated panel has been presented. The commercially available finite element code ABAQUS 6.6 has been used for this purpose where an user material model based on a continuum damage mechanics concept for failure mechanism of laminated composites has been implemented through an externally attached user subroutine written in FORTRAN. As ABAQUS Explicit is specifically suitable for high velocity wave propagation problem like the present one, it has been properly exploited in the present study. It has not only helped to avoided the convergence problem in the present analysis having severe nonlinearity but also reduce the solution time effectively. In order to have a simple and computationally efficient model, the laminated composite panels have been modelled with simple layered shell elements. As it is difficult to estimate the load imparted on the laminates by the impactor, it has also been modelled and these separate bodies have been connected with the general contact algorithm of ABAQUS Explicit. The impactor has been idealised as a solid object since it has been found to have a minimum distortion in the actual test. The modelling of the impactor has been done for its external surface to have a simple representation with minimum degrees of freedom. The numerical model has been applied to the simulation of glass fibre reinforced plastic laminates having single and double laminated configuration subjected to a hemispherical tip cylindrical aluminium projectile. The impactor residual velocity predicted in the simulation has been found to be sufficiently close to that measured in the laboratory. Again, the numerical model has clearly identified the actual phenomenon responsible for getting an apparent inferior energy absorption capability of the multiple laminated panels.

Acknowledgement

The work presented was supported by:

- The Innovation Consortium "Integrated Design and Processing of Lightweight Composite and Sandwich Structures" (abbreviated "KOMPOSAND") funded by the Danish Ministry of Science, Technology and Innovation and the industrial partners Composhield A/S, DIAB ApS (DIAB Group), Fiberline Composites A/S, LM Glasfiber A/S and Vestas Wind Systems A/S
- US Navy, Office of Naval Research (ONR), Grant/Award No. N000140710227: "Influence of Local Effects in Sandwich Structures under General Loading Conditions & Ballistic Impact on Advanced Composite and Sandwich Structures". The ONR program manager was Dr. Yapa Rajapakse

The support received is gratefully acknowledged.

References

[1] Abrate S. "*Impact on composite structures*". 1st edition, Cambridge University Press, 1998.

[2] Hou J.P., Petrinic N., Ruiz C. and Hallett S.**R**. "Prediction of impact damage in composite plates". *Composite Science and Technology*, Vol. 60, No. 2, pp 273-281, 2000.

[3] Williams K.V. and Vaziri R**.** "Application of a damage mechanics model for predicting the impact response of composite materials". *Computers and Structures*, Vol. 79, No. 10, pp 997-1011, 2001.

[4] Johnson A.F., Pickett A.K. and Rozycki P**.** "Computational method for predicting impact damage in composite structures". *Composite Science and Technology*, Vol. 61, No. 15, pp 2183-2192, 2001.

[5] Luo R.K., Green E.R. and Morrison C.J. "An approach to evaluate the impact damage initiation and propagation in composite plates". *Composites: Part B*, Vol. 32, No. 6, pp 513-520, 2001.

[6] Guan Z. and Yang C. "Low-velocity impact and impact process of composite laminates". *Journal of Composite Materials*, Vol. 36, No. 7, pp 851-871, 2002.

[7] Lee Y.J. and Huang C.H. "Ultimate strength and failure process of composite laminated plates subjected to low-velocity impact". *Journal of Reinforced Plastics and Composites*, Vol. 22, No. 12, pp 1059-1081, 2003.

[8] de Moura M.F.S.F. and Goncalves J.P.M**.** "Modelling the interaction between matrix cracking and delamination in carbon-epoxy laminates under low velocity impact". *Composite Science and Technology*, Vol. 64, No. 7/8, pp 1021-1027, 2004.

[9] Lua J. and Gregory W**.** "Development of a dynamic failure prediction tool for marine composite structure". *Journal of Applied Mechanics, ASME*, Vol. 256, No. 7, pp 299-308, 2005.

[10] Iannucci L. "Progressive failure modelling of woven carbon composite under impact". *International Journal of Impact Engineering*, Vol. 32, No. 6, pp 1013-1043, 2006.

[11] Zhang Y., Zhu P. and Lai **X**. "Finite element analysis of low-velocity impact damage in composite laminated plates". *Material and Design*, Vol. 27, No. 6, pp 513-519, 2006.

[12] Silva M.A.G., Cismasiu C. and Chiorean C**.G**. "Numerical simulation of ballistic impact on composite laminates". *International Journal of Impact Engineering*, Vol. 31, No. 3, pp 289-306, 2005.

[13] Grujicic M., Pandurangan B., Koudela K.L. and Cheeseman **B.A**. "A computational analysis of the ballistic performance of light-weight hybrid composite armors". *Applied Surface Science*, Vol. 253, No. 2, pp 730-745, 2006.

[14] ABAQUS Analysis User's Manual, Version 6.6, ABAQUS, Inc., USA, 2006.

[15] Hashin Z. "Failure criteria for unidirectional fiber composites". *Journal of Applied Mechanics*, Vol. 47, No. 2, pp 329-335, 1980.

[16] Matzenmiller A., Lubliner J. and Taylor R.L. "A constitutive model for anisotropic damage in fiber-composites". *Mechanics of Materials*, Vol. 20, No. 2, pp 125-152, 1995.

[17] Xiao J.R., Gama B.A. and Gillespie J**.W**. "Progressive damage and delamination in plain weave S-2 glass/SC-15 composite under quasi-static punch-shear loading". *Composite Structures*, Vol. 78, No. 2, pp 182-196, 2007.

[18] Kepler J.A. "*Localized impact on sandwich structures - an experimental study*". Ph.D. dissertation, Special Report No. 46, Institute of Mechanical Engineering, Aalborg University, Denmark, 2001.

[19] Ganesh V.K. and Nail N**.K**. "Some strength studies on FRP laminates". *Composite Structures*, Vol. 24, No. 1, pp 51-58, 1993.