Detailed Modeling of Projectile Impact on Dyneema Composite Using Dynamic Properties*

B.D. Heru UTOMO**** and L.J. ERNST***
**TNO Defence, Security and Safety
Lange Kleiweg 137, 2280 GJ Rijswijk-ZH, the Netherlands
E-mail: Beate.HeruUtomo@TNO.nl
*** Department of Mechanical Engineering, Delft University of Technology
Mekelweg 2, 2628 CD Delft, the Netherlands

Abstract

Dyneema composite panels, which contain high Ultra High Molecular Weight Polyethylene fibers, are used in armor applications. They give good protection against fragments, bullets or other projectiles. In order to be able to study the internal processes in such a composite panel, a new modeling approach is developed and is described in this paper. This approach uses a detailed modeling approach that discretises the fibrous phase in Dyneema composite. In the past, continuum approaches and layer discretisation have been used by other researchers to study the processes in Dyneema composite panels and to predict the ballistic strength of these panels. The aforementioned approaches were however not very successful in predicting the ballistic strength, because fiber sliding, fiber failure and delamination of layers were not taken into account and static properties of the material were used. In addition to this, these models were often too coarse to study the processes in the panel. This often resulted in a calculated ballistic strength that was often too low. In this research, fiber sliding, fiber failure and delamination of layers are taken into account in the proposed model together with dynamically determined material properties. It is expected that studying the physical processes in a Dyneema composite panel and a better ballistic strength prediction should be possible using the aforementioned fiber bundle discretisation approach. The modeling of Dyneema composite is done in ABAQUS/Standard for the quasi-static simulations and in ABAQUS/Explicit for the dynamic simulations.

Key words: Dyneema Composite, Fiber Reinforced Plastic, Strength, Failure, Material Model, Simulations, Dynamic, Constitutive Properties

1. Introduction

Dyneema fiber is the brand name for a special, high-performance grade of Ultra High Molecular Weight Polyethylene (UHMW-PE) fiber. This fiber has the following chemical composition: \(~-[\text{CH}_2-\text{CH}_2]_{n-}\). Dyneema fibers are produced by a patented gel spinning process [1, 2]. They are used in rope-like applications and fiber reinforced composites. Products that contain Dyneema fiber vary from medical applications such as prostheses to leisure articles such as sails to fiber reinforced armor panels that are used in armor applications.

*Received 24 Oct., 2007 (No. 07-0650)
[DOI: 10.1299/jmmp.2.707]
For development purposes, it is important to know what happens inside a Dyneema composite panel that is subjected to impact and to know the ballistic strength of armor panels. The ballistic strength is usually expressed in terms of velocity (see section \textit{2. Ballistic Strength}) and tells us something about the resistance against projectile impact.

Bullets typically have an impact velocity of a few hundred meters per second and therefore possess a very high kinetic energy that is transferred to the Dyneema armor panels within a very short period of time. Especially the area of the panel that is in close vicinity of the impact area (typically twice four times the area of the projectile) is highly affected by the projectile impact.

Delamination, fiber fracture and fiber sliding are the most important phenomena that occur due to projectile impact on Dyneema armor panels. These phenomena and the interaction between these phenomena determine the actual ballistic strength of a composite panel. It is therefore important that both the phenomena themselves and the interaction between the phenomena should be well described by the computer code that is used for simulations in order to obtain a good understanding of these phenomena. In the past, delamination and fiber sliding could not or only partly be described, because mainly continuum formulations were used to model composite armor panels \cite{3, 4}, which give a too coarse discretisation of the problem. In this research, a simulation model is developed that is able to show both delamination and fiber sliding and their interaction. This is done by making a better and more detailed discretisation, namely by discretising fiber bundles, than in case of a continuum model. Using this new model, it is possible to study the effects of projectile impact on Dyneema composite in more detail and it is expected that a more realistic ballistic strength prediction of Dyneema composite should be possible.

\textbf{2. Ballistic Strength}

Phenomena due to ballistic impact are dynamic in nature. Projectile impact occurs within a very small time frame, typically in the order of microseconds for handgun ammunition. It is therefore in general difficult to perform real time measurements, because the data acquisition is often either too slow or too inaccurate. One of the things that can be measured accurately is the velocity of a projectile prior to impact. Therefore, ballistic strength is usually expressed in terms of velocity. There are two velocities that are often used for expressing the ballistic strength, namely the $V_0$ and the $V_{50}$ \cite{5}. These velocities are defined hereafter.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{dyneema.png}
\caption{Dyneema sheet (left) and Dyneema composite (right)}
\end{figure}
2.1. $V_0$

If a projectile impacts on a target, there are two possibilities. The first possibility is that the projectile is stopped by the target, which means that the velocity of the projectile is reduced to zero before it reaches the other side of the panel. The other possibility is that the projectile is slowed down by the target, but flies through the other side of the plate. This means that the projectile will fly out of the other side of the plate with a certain residual velocity. The former case is called a penetration and the latter case is usually called a perforation or in some literature (full) penetration [5].

In this paper, the case in which a projectile is stopped will be called a penetration and the case that a projectile still has a non-zero velocity after impact will be called a perforation (these definitions can differ depending on the country or military division). The $V_0$ depends on the combination of the specific target and projectile. The highest impact velocity that still does not cause a perforation of a target is called the $V_0$. More formally, the $V_0$ is the impact velocity for a specific projectile-target combination at which there is a 0.00 % chance on a perforation case. Determining the $V_0$ therefore usually takes quite a number of experiments.

2.2. $V_{50}$

A more widely used means to express the ballistic strength is the $V_{50}$, which is a more statistical measure. Formally, the $V_{50}$ is defined as the velocity at which there is a 50 % chance on a perforation case and a 50 % chance on a penetration case.

It should be noted that the $V_{50}$ is not an absolute value, but rather an extrapolated one. When comparing simulation results to experimental values, it is difficult to determine how the numerical results should be related to the experimentally determined ballistic strength. The $V_0$ is an easier measure, because the measure is more absolute. On the other hand, a real panel always has a certain number of imperfections, while this is not taken into account in most simulations. Therefore, the statistical nature of the $V_{50}$ may take away the experimental uncertainty to a greater extent.

3. Built up of a Dyneema composite

3.1. Laminate

Dyneema laminates are composed of tens of pressed Dyneema sheets. Dyneema sheet comes from the manufacturer (see figure 1) and is cut in the appropriate size before pressing. The Dyneema sheets are pressed together under elevated pressure and temperature to produce Dyneema composite products such as plates, helmets or panels.

A Dyneema composite plate of 5 mm thickness consists of about 80 sheets. The exact number of sheets that is required for a composite plate depends on the desired thickness of a laminate or rather on the desired performance of the product.

3.2. Sheets

A Dyneema sheet mainly consists of Dyneema filaments that are held together by a small amount of matrix material. The filaments are oriented in alternating orthogonal layers, see figure 2. The finally produced laminate usually has a $0^\circ$-$90^\circ$ orientation, a $45^\circ$-$45^\circ$ orientation is in general rare.

The in-plane strength and stiffness properties of the final laminate are almost exclusively determined by the Dyneema filaments. The matrix material influences the out-of-plane properties of the Dyneema sheet and prevents the Dyneema filaments in the sheet from moving. The number of filament layers and the number of alternating orientations in a sheet depends on the specific type of Dyneema sheet.
4. Dynamic Material Properties

One of the reasons that the ballistic strength from numerical calculations was higher than predicted in earlier work is that material data that has been obtained by quasi-static experiments (especially the tensile modulus of the fibers) has been used as input data. Because the tensile modulus is lower under quasi-static load cases, the energy that is absorbed by the fibers is therefore higher than what one would expect when looking at quasi-static test data.

Usually, one would use Dynamic Mechanical Analysis (DMA) for the determination of the modulus. However, DMA tests typically give good results for frequencies up to 70 Hz, while a frequency of about hundred times as big is felt by the Dyneema composite that is subjected to projectile impact. Therefore, impact on a single Dyneema fiber (consisting of a number of filaments) is used to determine the modulus under more realistic conditions in combination with wave mechanics, see [6].

In this experiment, different projectiles with impact velocities in the range between 150 m/s and 500 m/s are shot at a single fiber, as is shown in figure 3. A camera technique that projects sequential frames in time on top of each other is used to record the impact event on the fiber. What are shown in this figure are impact events on the same fiber type with
different impact velocities. The projectile’s flight trajectory is in all cases from right to left. What happens in the vicinity near the point of impact is shown schematically in figure 4.

From the obtained images from the experiments, the projectile velocity \( V_{pr} \) and the velocity with which the triangle end moves away from the impact point \( C_s \) can be determined. The particle velocity \( W \) can then be determined using:

\[
W = C_s \cdot \left( \sqrt{1 + \left( \frac{V_{pr}}{C_s} \right)^2} - 1 \right)
\]  

(1)

Now that \( W \) is determined, the sound velocity in the fiber \( C_t \) can be calculated by:

\[
C_t = \frac{1}{2} \cdot \left( B + \sqrt{B^2 - 4 \cdot \frac{T_0}{\mu}} \right)
\]  

(2)

with B:

\[
B = \frac{C_s^2}{W} + 2 \cdot C_s \cdot \frac{T_0}{\mu \cdot W}
\]  

(3)

And \( T_0 \) the pretension force of the fiber and \( \mu \) the tenacity of the fiber, which are known in advance of the experiment. Eventually \( E \) can be calculated according to:

\[
E = \rho \cdot C_t^2 = \frac{1}{4} \rho \cdot \left( B + \sqrt{B^2 - 4 \cdot \frac{T_0}{\mu}} \right)^2
\]  

(4)

When the modulus \( E \) is calculated for the same fiber and different impact velocities, it turns out that in the range between 150 m/s and 500 m/s the modulus has a constant value. The modulus in this velocity range is almost 15 % higher than the modulus under quasi-static conditions and its value is about 200 GPa. This means that the energy absorption by the composite may be about 15 % higher than might be expected from quasi-static experiments.
5. Modelling of Dyneema Composite

Besides the improvement of using the dynamic tensile modulus instead of quasi-static data, the numerical model is also altered to allow for more details that were not possible using continuum approaches. In this section, models that were used in earlier research are described. The principle on which the current model is based and the model that is now used for calculations are described thereafter.

5.1. Earlier work

Computer simulations of projectile impact on fiber reinforced composite targets usually use a continuum approach with an orthotropic stiffness definition. In general, these models were too coarse to study the behavior inside e.g. a composite panel. In addition, the ballistic strength of (Dyneema) composites was in general too low using these models. It is believed that this is caused by implementing the (quasi-) static material properties on one hand and that phenomena such as delamination, fiber sliding, fiber fracture and their interactions were therefore not explicitly taken into account on the other hand [7].

In the last decade of the 21st century, the influence of delamination on the ballistic strength was recognized and incorporated in simulations by using either a discrete layered modeling approach [8] or fracture mechanics [9]. Both methods under predict the ballistic strength of a Dyneema composite plate, because fiber sliding and fiber fracture and their interactions with each other are still not taken into account while they take up a portion of the energy of the projectile as well. Using fracture mechanics has the additional drawbacks that the use of it is not well defined for dynamic load cases and that the required properties that should be used as input for the computer simulations are difficult to determine experimentally.

5.2. Fiber bundle discretisation

A numerical model on a filament level gives a very large the problem in terms of model size. This means that in general the computational time of the simulation increases a lot, even when parallelising the computations. It is even expected that current technology does not enable such large computations.

A compromise between a simulation that shows much details (and hence the accompanying increase in required memory and computational time) and a realistic physical model and strength prediction can be achieved by the principle of fiber bundle discretisation. Fiber bundles are projected on rod elements that do not possess any bending degrees of freedom. The fiber bundles in the actual Dyneema composite do almost not possess bending stiffness, so it is assumed that they can be neglected.

By embedding the rod elements in continuum elements that have an orthotropic description (the continuum elements represent the composite without the reinforcing rod elements) the displacements of the rod elements are coupled to the continuum elements. The amount of shear stress that is required to let the fiber bundles slide away from each other is then described by the surrounding continuum elements. Preferably, a couple of continuum elements should be placed between the layers of rod elements. The main reason for this is that the shock waves that are caused by projectile impact are smeared out over more elements. Using this discretisation, fiber sliding and fiber fracture can be taken into account, while the increase in required memory and computational time stays between reasonable bounds.

It should be noted that discretising the fiber bundle properties in this way has the consequence that the continuum part of the model is not a physically correct representation of the composite part without reinforcement. It should be noted that the continuum elements do not purely represent the matrix phase in the composite. The continuum elements still have part of the filament properties as will be explained in section 5.3.
5.3. New composite model

The model that is developed for this research consists of two different elements, namely rod elements and continuum elements. In figure 4, both the rod elements and the continuum elements are shown. The rod elements are embedded in the continuum element and the translational degrees of freedom of the rod elements are coupled to that of the continuum elements.

The new model is used for both static and dynamic simulations. Therefore, care has been taken that the elements in the simulation can be used in both implicit and explicit analysis. The used rod elements are linear, because higher order rod elements were not available for ABAQUS/Explicit. Rod elements in ABAQUS have a constant strain within the element and are suited for finite strain calculations. In reality, the behavior of filaments is linear up to failure. In order to define failure of elements in ABAQUS, their plasticity behavior should also be defined. Because in reality, almost no plasticity occurs prior to failure, a very small amount of plasticity is defined for the rod elements. A softening criterion is used to define the (quick) degradation of the rods. A failure criterion is given in terms of energy and is chosen such that the rod elements fail almost immediately after plasticity occurs. The global behavior of the rod elements that represent the filaments can be seen in figure 5.

The continuum elements (in which the rod elements are embedded) have an orthotropic stiffness definition while they are elastic. The properties of the filaments are projected on the rod elements and therefore in the in plane direction subtracted from the original stiffness matrix $E_{lam}$. The stiffness matrix of the continuum elements looks as follows:

$$
\overline{E}_{new} = \overline{E}_{lam} - \overline{E}_f = \begin{bmatrix}
E_{11} - E_f & E_{12} & E_{13} & 0 & 0 & 0 \\
E_{12} & E_{22} - E_f & E_{23} & 0 & 0 & 0 \\
E_{13} & E_{23} & E_{33} & 0 & 0 & 0 \\
0 & 0 & 0 & G_{12} & 0 & 0 \\
0 & 0 & 0 & 0 & G_{13} & 0 \\
0 & 0 & 0 & 0 & 0 & G_{23}
\end{bmatrix}
$$

Figure 4: Continuum elements (left), rod elements (right)
$E_{\text{new}}$ is the stiffness matrix of the continuum elements in the current model, while $E_{\text{lam}}$ is the stiffness matrix of the laminate if a continuum formulation would be used. Note that the failure criterion of the in-plane shear failure is still equal to the failure criterion of the composite. This discretisation offers the possibility to directly implement fiber bundle failure, fiber bundle sliding and delamination. Since the composite does not so much deform due to in-plane shear, this is not discretised at this moment. $E_f$ is the stiffness of the filaments (rod elements) in matrix form. The out-of-plane properties of the laminate are in reality mostly determined by the fibers. These out-of-plane properties are not discretised and are still integrated in the stiffness definition of the continuum elements. The stiffness matrix of the continuum elements should be seen as the behavior of the laminate on a macro level without the in-plane properties that are determined by the fibers. It should be emphasized that the continuum elements do not solely represent the matrix material in the Dyneema composite.

Damage in the continuum elements is described using an energy criterion. The failure surface is chosen to be elliptical in order to cope with different failure behavior in different material directions. In the thickness direction, the failure behavior is chosen such that the failure energy criterion is the failure energy that is required to cause delamination of the layers in Dyneema composite.

In the out-of-plane direction, the continuum elements suffer from compressive normal stress waves at first. Due to the reflection of the waves, the waves become tensile and mode I delamination will be the result. The composite will also suffer from transverse shear. Since transverse shear is only a function of the interface behavior between the Dyneema layers (and not a function of the fiber bundles), it is the same before (continuum approach) and after making the aforementioned discretisation.

Using this model, it is possible to incorporate simulate fiber sliding and fiber failure and their interaction. Delamination is realized with the removal of elements. When elements are failed and thus removed, gaps will occur and elements have the possibility to move away from each other thus simulating delamination. If an element has failed in a certain direction, it is still able to take up loads in another direction. If the continuum element has completely failed, its mass is transferred to the surrounding elements in order to have no problem with inertia. If a continuum element has completely failed, the connection to the rod element to which it was originally attached to is broken. This means that from that moment on, the rod element is ‘free’ to move and still able to take up loads and eventually fail.

6. Simulations

In order to demonstrate the possibilities of the new developed model, both (quasi-)static and dynamic experiments are done.
6.1. Static simulations

Two (quasi-)static experiments, a tension test and a compression test, are simulated using ABAQUS/Standard in order to study the possibilities of the model. For both the tension and the compression simulation, a quarter of a model has been modeled with symmetry boundary conditions.

The modeling has been done elastically in this case. At the higher end of the sample, a distributed load is applied. The resulting (maximum principle) stresses for the whole model and the fibers in the model are shown in the left side of figure 6. It is seen that the fibers take most of the stresses (highest stress being indicated with a red color). This is also what one would expect, because the tensile modulus of the filaments is about a factor ten higher than the stiffness of the layers. In this model, the stiffness in the load direction of the fiber is the stiffness of the matrix. The filaments that are orientated perpendicular to the load direction only take a small portion of the loads, because they only have to cope with the loads that are present due to the Poisson effect.

The geometry of the part of the compression test is the same as for the tension test and only the load direction is reversed. The results of the compression are similar to the one of the tension test with the stresses reversed. Again, the rod elements take most of the loads, while the perpendicular fibers only take up the small amount of loads that is caused by contraction.

![Figure 6, Tension test](image)

6.2. Dynamic simulations

The main goal of this model is to be able to study the effects of projectile impact within a Dyneema composite panel. Eventually, it should be possible to predict the ballistic strength of the Dyneema laminate that is subjected to projectile impact using the aforementioned developed model.

Because the strength of the Dyneema laminate is different for different geometries and material of the projectile a round-nosed rigid projectile is used. For the simulations, it is assumed that the projectile is a rigid body. In reality, such projectiles are made of a hard-type steel type that is almost non-deformable. The round-nosed projectile is chosen in order to cope with possible problems between sharp-edges and the Dyneema laminate. In first instance, only fibers in close vicinity of the impact point are placed, because that is the area that is most influenced by the projectile.
In figure 7, the absorbed energy is shown due to projectile impact on Dyneema composite. The projectile has a velocity of 500 m/s. It is shown that most of the energy is taken up by the fibers, as might be expected. It is also seen that the laminate has delaminated by the impact of the projectile on it.

7. Conclusions

By making a fiber bundle discretisation in a simulation model, it is possible to study the behavior of Dyneema composite under projectile impact in more detail, because fiber shearing, fiber fracture and delamination of the laminate is shown. The computational time increases only a small amount, because of the embedding of the computationally cheap rod elements in the layers. The results indicate that the processes within a Dyneema composite can be studied very well. The first results are very promising from a qualitative perspective, but the numerical results should however still be quantitatively validated with experimental data.

The prediction of the ballistic strength of Dyneema composite is believed to become more accurate using this model. This is caused by the more correct material data input, since it is determined by impact on a single fiber. At the same time, the new model allows for more detail than if using a continuum approach. Therefore, this model contributes to a more thorough understanding of the phenomena that occur in Dyneema composite due to projectile impact.

8. Recommendations

The model that is described in this paper is still in a preliminary phase. Using this model, it seems to be possible to describe phenomena such as delamination, fiber fracture and fiber sliding. The ballistic strength predictions however still have to be experimentally validated.
The number of filaments that are represented by a single truss is now taken quite arbitrary. A study is required on how many filaments should be integrated in one rod by studying how the amount of integrated filaments influences the results and compare it with experiments. Furthermore, it should also be determined which stiffness the rod elements should get. The stiffness of the filaments itself when not integrated in some kind of matrix material is about ten times higher than the stiffness of a laminate in the direction of the fibers and therefore, the obtained modulus from the fiber impact experiments may need some conversion. It is expected that the stiffness of the rods should have a value between the stiffness of the laminate in the fiber direction and the value of the pure filaments themselves. In addition to this, the fibers should be placed more equally distributed to get a more realistic result.

Also, the geometric influence of the placement of the rod elements should be studied. If we for example have four layers of fiber bundles that are oriented 90 degrees with respect to the previous layer, it would be good to know what the effect of placing two layers in the same direction and then two layers oriented 90 degrees with respect to the previous layers is.

In this model, perfect adhesion between the fiber bundles and the matrix material is assumed (by coupling the degrees of freedom of the rod elements to that of the continuum elements). In reality, there is no perfect adhesion and the influence of this should be studied and perhaps improved in the model using a spring-damper combination.

References

5. J.D. Walker, Constitutive model for fabrics with explicit static solution and ballistic limit, 18th International Symposium on Ballistics, San Antonio, USA (1999)