Two different modelling approaches for fabric composites subjected to ballistic impact

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Abstract. Fabric composites are widely applied in different fields and, in particular, have become a valid option in the realization of protective structures due to their low weight combined with high strength and stiffness. Finite element numerical models are an established method for the assessment and the optimization of the design of engineering structures. Two main approaches for the analysis of impacts on fabric composites are present in the literature. A macro-homogeneous approach considers the materials as an equivalent homogeneous medium with no distinction between the constituents. A meso-heterogenous approach reproduces the material microstructure and therefore its components are considered as different entities. The capacity of these two numerical models to model the ballistic impact of a real bullet against a panel made of plain weave Kevlar® 29 embedded in an epoxy matrix is compared in this study. The outcome of the comparison of the two numerical model is assessed using experimental data from actual ballistic tests. Quantitative results, such as the residual velocity of the bullet, as well as qualitative results, such as the damage morphology, are compared. The latter is especially important in case the impacted structure is multifunctional, aimed to protect as well as to carry load.

1. Introduction

Fabric composites are widely applied in different fields and, in particular, have become a valid option in the realization of protective structures due to their favourable combination of low weight and high strength [1]. The design of protective structures is mainly based on experimental tests and experience. However, the use of simulation tools as a predictive method of the dynamic behaviour of textile-based composites is growing. The impact on protective structures is a complex phenomenon which involves large deformation and failure and for this reason simplified models are not able to catch the whole phenomenon in its complexity. Finite element numerical models are an established method for both the assessment and the optimization of the design of engineering structures. Two main modelling approaches for the analysis of impact on fabric composites are present in the literature. A macro-homogeneous approach considers the materials as an equivalent homogeneous medium with no distinction between its constituents. A meso-heterogeneous approach reproduces the material microstructure and therefore its constituents are considered as different entities. In this approach, not only the material behaviour, but also the interaction between the constituents are fundamental in determining the response to a determined impact. This approach is expected to provide a more detailed description of the problem and therefore should lead to more accurate results, however it requires more computational resources.
In the macro-homogeneous approach, the material behaviour is modelled using the classic orthotropic elasticity. Different failure criteria have been used in the literature, including Chang-Chang [2], [3] and Tsai-Wu [1], [4] which consider the different failure modes of composites. The composite plate can be considered as a uniform body [1], [5] or as a layered body where each layer is considered as a separate part. Zhang et al. [5] compared the two approaches and found that both deliver similar quantitative results such as, ballistic limit velocity and residual velocity in agreement with experimental tests. The layered model was shown to reproduce the damage morphology with higher precision while requiring more computational time [5]. The layered model allows the reproduction of delamination by using a tiebreak interface between the layers [3], [4].

A mesoscale reproduction of the material geometry was adopted for both woven fabrics [6], [7] and fabric composites [8]–[11]. Modelling of fabric composites adds complexity to the problem due to the reproduction of the matrix and its interaction with the yarns. The meso-heterogeneous approach can be used to reproduce all of the target [10], [11], or only in the region directly involved in the impact [4]. In the latter case the surrounding regions of the target are modelled using the macro-homogeneous approach. Different strategies can be adopted in the reproduction of the unit cell geometry. Kudryavtsev and Sapozhnikov used shell elements for the yarns and solid elements for the matrix to reproduce a simplified geometry of the unit cell [10]. Bresciani et al. reproduced an accurate geometry of the unit cell using solid elements for both the yarns and the matrix [4]. For the analysis of aramid fiber different solutions were adopted to characterise the material behaviour of the yarns: isotropic [4] or orthotropic along the central line of the yarn [7]. In both cases the material was considered to be linear elastic until failure which may be based on von Mises [4] or maximum principal [5] stress threshold.

The aim of the present work is to exploit both the macro-homogeneous and meso-heterogeneous approach to develop two numerical models of the ballistic impact on fabric composites. The paper aims also at establishing a methodology of the calibration and validation of the two numerical model by means of characterization based on comparison and further validation with experimental ballistic impact tests on composites made of Kevlar® 29 plain-woven fabrics embedded in an epoxy matrix. The main objective is to compare the accuracy of the two modelling approaches to predict the residual velocity and the damage morphology. The most meaningful mechanical properties of the composite, which are the elastic modulus and the tensile strength in the principal directions, were calibrated by means of simple tensile tests. The static and dynamic mechanical properties were assumed to be identical. This may be an oversimplifying assumption but, it has already been successfully used for the development of a macro-homogeneous model of ballistic impact on aramid fiber-reinforced composites [3]. Furthermore, a dynamic characterization of the dynamic properties of the material is beyond the scope of this study. The developed numerical models were validated considering the highly complex impact conditions of a soft-core projectile subjected to large deformation during the penetration process. Large deformations of the projectile not only increase the complexity of the phenomenon but also require an accurate description of the material behaviour of both the projectile and the target. The outline of the paper is therefore the following: in section 2 the experimental test performed for the calibration and the validation of the numerical models are described; in section 3 the numerical models developed following either the macro-homogeneous and meso-heterogeneous approach are described; in section 4 the results of the experimental tests and the prediction of the numerical models are discussed and the accuracy of the two approaches is compared; finally some conclusion are drawn in section 5.

2. Experimental Tests
Experimental tests for the calibration and the validation of the numerical models were performed on textile-based composites. These composites were manufactured from several layers of plain woven Kevlar® 29 embedded in an epoxy matrix. Kevlar® 29 is an aramid fabric manufactured by DuPont® with a low density and high strength, and is commonly used in ballistic shield design. The elastic modulus of Kevlar® 29 is stated to be 83 GPa and a tensile strength of 3600 MPa by the manufacturer [12]. However, research on the mechanical properties of Kevlar® 29 showed different values depending on the test conditions [13]–[16]. The datasheet of the epoxy used as the matrix states a flexural modulus
of 2.9 GPa and a flexural strength of 120 MPa. Tensile tests were performed according to the ASTM D3039 [17] for the calibration of the numerical models while the ballistic tests were performed according to EN 1522 [18] for validation.

2.1. Tensile Tests
Tensile tests were performed according to the ASTM D3039 [17] which is the standard test method for tensile properties of polymer matrix composite materials. Tensile specimens consisted of 5 fabric layers, had a nominal thickness of 2.5 mm and a dimension of 25x250 mm. The specimens were pulled in displacement control at a constant speed of 2 mm/min until failure. The axial load was measured by the machine load cell. The axial strain was measured using a 50 mm extensometer positioned in the center of the specimen and the strain range for the calculation of the elastic modulus was between 1.8 and 2.2 %. Five specimens were tested to obtain an elastic modulus of $10.06 \pm 0.65$ GPa and a tensile strength of $405.24 \pm 18.03$ MPa.

2.2. Ballistic Tests
Ballistic tests were performed according to the EN 1522 [18] which is the European standard for the classification of bullet resistance for windows, doors, shutters and blinds. Panels for the ballistic test had a nominal thickness of 6.5 mm, a dimension of 270x270 mm and consisted of 14 layers of fabric. The panels were assessed against EN 1522 bullet resistance class FB3 which requires a .357 Magnum bullet with a nominal mass of 10.2 g and a velocity of 430 m/s. The experimental apparatus is shown in Figure 1, including the .357 Magnum bullet which has a conical tip and consists of a soft lead core and a brass jacket. According to the standard requirements, the gun was positioned at a distance of 5 m from the target. The support system consisted of two steel plates with a central square hole of 160x160 mm which were held together with the target by means of four screws. Only one shot with an angle of incidence 90° was fired at the center of the target. Two velocity screens were positioned 2.5 m before and 2.5 m after the target to measure respectively the impact and residual velocity of the target. Two repetitions of the test were performed, and the bullet always completely perforated the panel with high residual velocity.

![Figure 1](image1.png)

**Figure 1.** Experimental apparatus of the ballistic tests (left) and section of .357 Magnum (right).

3. Numerical Model
The two numerical models were based on finite element method and were implemented using the commercial software LS-DYNA. In both the macro-homogeneous and meso-heterogeneous approach a three-dimensional model was implemented, and the double symmetry of the problem was exploited to decrease the computational cost of the analysis. Considering the configuration of the support system, only the material of the panel which is free to deform during the impact, that is the portion of the material in the region of the plate square holes of 160x160 mm, was considered in the numerical model and all the degrees of freedom were constrained in the boundary regions. Symmetry constraint were indeed
applied on the faces cut by symmetry planes. Therefore, the two numerical models implemented are shown in Figure 2. In the case of meso-heterogeneous approach, the yarn and the matrix were only reproduced in the regions near the impact point. The remaining part of the target was modelled using the macro-homogeneous approach.

3.1. Model of the Projectile

The geometry of the lead core and the brass jacket of the projectile was accurately reproduced and meshed with constant-stress solid elements. The Modified Johnson-Cook and Cockcroft-Latham failure criterion (MAT_107) were used for modelling the material behaviour of lead and brass, and the material parameter used are reported in Table 1: E and ν are respectively the elastic modulus and the Poisson’s ratio, A, B and n are the Johnson-Cook strain hardening parameters, C is the strain rate sensitivity parameter and ϵ₀ the reference strain rate, m is the thermal softening parameters and Tₘ is the melting temperature and Wₑ is the Cockcroft-Latham parameter. This is an established approach for metallic material under high-velocity impact [19], [20]. Johnson-Cook is a material model for metals which take into account strain hardening, strain-rate sensitivity and temperature softening [21]. For a detailed description of the material model the reader is referred to the software manual [22].

Table 1. Material parameters for projectile lead core and brass jacket. [23]

| Material | E [MPa] | ν [-] | A [MPa] | B [-] | n [-] | ϵ₀ [s⁻¹] | C [-] | Tₘ | m | Wₑ [MPa] |
|----------|---------|-------|---------|-------|-------|-----------|-------|-----|---|---------|
| Lead     | 16000   | 0.42  | 0       | 36.62 | 0.0987 | 72.108    | 0.1593 | 525 | 1  | 175     |
| Brass    | 115000  | 0.21  | 111.69  | 504.69| 0.42  | 1         | 0.0085 | 1288| 1.68| 914     |

3.2. Macro-Homogeneous Approach

In the macro-homogeneous model each layer of the panel was modelled separately and meshed using constant stress solid elements with a dimension of 0.25x0.25x0.25 mm. This element size was chosen to match as closely as possible the element size of the meso-heterogeneous model which is bound by the geometry of the yarns. The material model used for the composite layers was MAT_054 which is based on orthotropic elasticity and the Chan-Chang failure criterion. The option 2WAY was used so that material have bilinear behaviour in direction 1 and 2, which are the warp and fill direction on the layer. The tensile failure mode in direction 1 is given by Eq. 1
\[ \left( \frac{\sigma_{11}}{X_t} \right)^2 + \beta \left( \frac{\sigma_{12}}{S_c} \right)^2 - 1 \geq 0 \]  \hspace{1cm} (1)

where \( X_t \) is the tensile strength in direction 1 and \( S_c \) is the shear strength on plane 12 and \( \beta \) is the shear weighting factor.

The tensile failure criterion in direction 2 is given by Eq. 2

\[ \left( \frac{\sigma_{22}}{Y_t} \right)^2 + \beta \left( \frac{\sigma_{12}}{S_c} \right)^2 - 1 \geq 0 \]  \hspace{1cm} (2)

where \( Y_t \) is the tensile strength in direction 2.

The compressive failure criterion in direction 1 is given by Eq. 3

\[ \left( \frac{\sigma_{11}}{X_c} \right)^2 - 1 \geq 0 \]  \hspace{1cm} (3)

where \( X_c \) is the compressive strength in direction 1.

The compressive failure criterion in direction 2 is given by Eq. 4

\[ \left( \frac{\sigma_{22}}{Y_c} \right)^2 - 1 \geq 0 \]  \hspace{1cm} (4)

where \( Y_c \) is the compressive strength in direction 2.

The matrix tensile and compressive failure criterion is given by Eq. 5

\[ \frac{\sigma_{22}^2}{Y_c Y_t} + \left( \frac{\sigma_{12}}{S_c} \right)^2 + \frac{(Y_c - Y_t)\sigma_{22}}{Y_c Y_t} - 1 \geq 0 \]  \hspace{1cm} (5)

When one of the failure criterion is met inside an element, the relevant stiffness parameters are degraded (for a detailed description the reader is referred to the software user manual [22]). Element are deleted from the analysis when the tensile failure criterion is met. MAT_054 also allows to consider other strain-based element deletion criteria. Therefore, also a tensile strain threshold equal to the ratio between the tensile strength and the elastic modulus (in direction 1 or 2) was considered. The material parameters for Kevlar29/Epoxy which were mostly obtained from the literature are reported in Table 2. The elastic moduli in warp and fill directions were assumed to be the same and equal to the average elastic modulus obtained in the tensile tests. The tensile strength in the warp and fill direction was obtained by an inverse calibration method as described in section 3.4. The interaction between the layers was modelled using the tiebreak interface: dethatching and sliding of each couple of adjacent layers is inhibited until the interface failure criterion, given by Eq. 6, is met.

\[ \left( \frac{\sigma_{11}}{S_{nt}} \right)^2 + \left( \frac{\tau}{S_{nt}} \right)^2 - 1 \geq 0 \]  \hspace{1cm} (6)
where $S_n$ is the interfacial normal stress threshold and $S_s$ is the interfacial shear stress threshold which were considered respectively to be equal to 34.5 MPa and 9 MPa [4].

### Table 2. Material parameters for Kevlar29/Epoxy (macro-homogeneous approach).

| Symbol | Property                  | Value  |
|--------|---------------------------|--------|
| $\rho$ [kg/m$^3$] | Density                   | 1025   |
| $E_1$ [GPa]         | Elastic modulus 1         | 10.06  |
| $E_2$ [GPa]         | Elastic modulus 2         | 10.06  |
| $E_3$ [GPa]         | Elastic modulus 3         | 6 [4]  |
| $G_{12}$ [GPa]      | Shear modulus 12          | 0.77 [4] |
| $G_{13}$ [GPa]      | Shear modulus 13          | 5.43 [4] |
| $G_{23}$ [GPa]      | Shear modulus 23          | 5.43 [4] |
| $\nu_{12}$ [-]     | Poisson’s ratio 12        | 0.25 [4] |
| $\nu_{13}$ [-]     | Poisson’s ratio 13        | 0.33 [4] |
| $\nu_{23}$ [-]     | Poisson’s ratio 23        | 0.33 [4] |
| $X_1$ [MPa]         | Tensile strength 1        | 425    |
| $Y_1$ [MPa]         | Tensile strength 2        | 425    |
| $X_c$ [MPa]         | Compressive strength 1    | 185 [4] |
| $Y_c$ [MPa]         | Compressive strength 2    | 185 [4] |
| $S_c$ [MPa]         | Shear strength plane 12   | 77 [4] |
| $\beta$             | Shear weighting factor    | 0 [4]  |

3.3. Meso-Heterogeneous Approach

In the meso-heterogeneous approach the yarn unit cell geometry was accurately reproduced using the software TexGen which is a textile geometric modeller developed by the University of Nottingham [24]. The input dimensions for the geometry reproduction were measured by high-resolution pictures of the test specimen. The geometry of the yarn unit cell was subsequently imported in the commercial software Abaqus for the generation of the mesh. TexGen delivers also the geometry of the matrix which however is too complex to generate a mesh. Therefore, a simplified geometry of the matrix was reproduced starting from the geometry of the yarn unit cell. The unit cells were then used to create the whole part for the numerical model and imported in LS-DYNA. The meso-heterogeneous approach was used in the regions surrounding the impact point.

For local meso-heterogeneous modelling of the target two main approaches are used in the literature which are equally valid for the reproduction of the phenomenon. Bresciani et al. reproduced the primary yarns, i.e. the yarns in direct contact with the projectile, in their entire length [4]. Barauskas and Abraitiene [6] reproduced only a squared region in the center of the impact point whose width is approximately three times the diameter of the projectile. The second approach was followed and considering the diameter of the projectile used in this study a square of about 52x52 mm was reproduced with the meso-heterogeneous approach which means 18 unit cells per side. Constant stress solid elements were used for the mesh of both the yarns and the matrix. The size of the element was bound by the geometry of the yarns and was chosen as a trade-off between the accuracy in the reproduction of the geometry and the computational time. The average element size of the macro-homogeneous and meso-heterogeneous model is similar, as visible in Figure 3, in order to compare consistent results. The other regions of the target were modelled using macro-homogeneous approach (described in section 3.2). The connectivity between the two regions of the model was guaranteed by a tied interface.
Both the yarns and the matrix were considered to be isotropic and linear elastic until failure (MAT_001). Maximum principal stress threshold ($\sigma_f$) was defined for the element deletion (MAT_000). The material parameters for Kevlar® 29 yarns and epoxy resin are reported in Table 3. The properties used for epoxy were obtained from the material data sheet while the properties for Kevlar® 29 were obtained by an inverse calibration method as explained in section 3.4. The Poisson’s ratio of the two materials was obtained from the literature.

Table 3. Material parameters for Kevlar® 29 and Epoxy (meso-heterogeneous approach).

| Symbol  | Property     | Kevlar® 29 | Epoxy |
|---------|--------------|------------|-------|
| $\rho$ [kg/m$^3$] | Density      | 1.44       | 1.18  |
| E [GPa] | Elastic modulus | 62         | 2.9   |
| $\nu$ [-]  | Poisson’s ratio | 0.44 [4]   | 0.35 [4] |
| $\sigma_f$ [MPa] | Failure stress | 3000       | 120   |

The definition of the contact in the meso-heterogeneous approach is far more complex than in the macro-homogeneous approach leading to longer computational times. Friction between the yarns is a relevant feature for the capability of the target to absorb the kinetic energy of the bullet. Interaction between the yarns of each layer was modelled using automatic surface to surface contact considering the static friction coefficient, the dynamic friction coefficient and the exponential decay respectively equal to 0.23, 0.19 and $10^8$ [4]. The interaction between the matrix and the yarns was modelled using a tiebreak interface considering $S_n$ and $S_s$ respectively equal to 34.5 MPa and 9 MPa [4].

3.4. Material Parameter Calibration
The Kevlar29/Epoxy tensile strength in direction 1 and 2 (respectively X$_t$ and Y$_t$) for the macro-homogenous approach and the Kevlar® 29 elastic modulus and maximum principal stress threshold (respectively E and $\sigma_f$) for the meso-heterogeneous approach were calibrated using an inverse method. Therefore, numerical models of the tensile test were developed following the same approach used for the model of high velocity impact. The simulations were run iteratively, changing the value of the parameters to be calibrated, until obtaining a match between the experimental and numerical stress-strain curves. The geometry of the specimen was fully reproduced and only the portion of the material outside the apparatus clamps was taken into consideration. Thus, the size of each layer was 25x150 mm with a thickness of 0.5 mm. The meshes used in the model of the tensile test have to be identical to the meshes used in the high-velocity impact model to assure consistency of the material parameters obtained following this procedure. As shown in Figure 4, one side of the specimen was constrained in the longitudinal direction while to the other side a longitudinal displacement was imposed to cause tensile strain inside the specimen. The displacement of the nodes which lie on the extensometer application...
points and the reaction forces were hence calculated to obtain a stress-strain curve which can be compared with the experimental one. The stress-strain curves obtained with the numerical models were compared with the experimental one as shown in Figure 4. The optimized value of $X_t$ and $Y_t$ of Kevlar29/Epoxy was 425 MPa slightly higher than the experimentally measured value of 405 MPa. This mismatch of 5% may be caused by the imperfect uniaxial state of stress inside the specimen and the mesh dependency of the failure criterion. The Kevlar® 29 elastic modulus and maximum principal stress threshold obtained were respectively 62 GPa and 3000 MPa. These values are inside the experimental ranges measured by different authors for Kevlar® 29 elastic modulus and tensile strength [13]–[16]. The stress-strain curve obtained with meso-heterogeneous approach show a noticeable change from the linear behaviour at strain level of 0.02 which corresponds to onset delamination between the yarn and the matrix. This behaviour of the stress-strain curve is also observed for the experimental stress-strain curve but, at a higher level of strain.

![Figure 4. Scheme of the tensile test numerical model (left) and inverse calibration results (right)](image)

### 4. Discussion
The most meaningful result of the ballistic test, in case of complete perforation of the target is the residual velocity of the projectile. The residual velocity of the projectile predicted by the numerical models was compared with the experimental results in Figure 5. The meso-heterogeneous approach predicts the average experimental residual velocity with higher accuracy. Indeed, the percentage error of the macro-homogenous and meso-heterogeneous approaches are respectively 17% and 11%.
This discrepancy may be due to several reasons related to the modelling of the target and of the projectile. First of all, the projectile used in the experimental tests is a soft-core bullet which is subjected to a mushroom deformation during the penetration process. Deformation of the projectile plays an important role in its kinetic energy dissipation and consequently its correct reproduction in the simulation is essential for the accurate prediction of the residual velocity. The projectile material parameters were obtained from the literature, and a complete characterization of the projectile material, which would require resources beyond the scope of this study, would increase the accuracy of the model. These considerations are also valid for the material parameters related to the target which were obtained from the literature. On the other hand, the tensile strength of the material (either Kevlar29/Epoxy tensile strength for the macro-homogeneous approach, or Kevlar® 29 tensile strength for the meso-heterogeneous approach) were calibrated using data from a static test. This parameter is fundamental in the characterization of the ballistic performance of the target. Since high-velocity impact is a phenomenon which involves high strain rates further experimental test should be performed to evaluate the dynamic strength of the target material and the dependence on strain rate of the material response.
The target deformation predicted by the numerical models is shown in Figure 6. The macro-homogeneous approach predicted a higher extension of delamination whereas the meso-heterogeneous approach predicted failure of the tiebreak interface between the yarns and the matrix rather than failure of the matrix itself. Both approaches were able to replicate fiber crushing in the first layers, tensile...
failure in the back layers and delamination. In Figure 7 the target front face damage morphology is compared with the predictions of the numerical models. Both the two approaches correctly predict the size of the hole generated by the projectile. Only meso-heterogeneous approach is capable to reproduce matrix cracking and deboning of the matrix from the yarn even though the size of the predicted damaged area is greater than the experimental. It is thought that more accurate calibration of the matrix material model and of the tiebreak interface criterion would lead to more accurate results. In Figure 8 it is reported the comparison of experimental and numerical back face damage morphology. The macro-homogeneous approach predicted a damage area of elliptical shape which was not observed experimentally. The meso-heterogeneous approach, instead, predict the right damage morphology even if, as in front face damage morphology, it overestimates the area of the region of failed matrix. Therefore, the meso-heterogeneous approach was shown to reproduce the experimental damage morphology more accurately as it simulated the physical phenomenon more precisely due to the more detailed modelling of the material. The higher accuracy of the meso-heterogeneous approach was however obtained at three times higher computational time which is due to the higher number of contact interfaces of the model.

5. Conclusions
The macro-homogeneous and meso-heterogeneous approaches were exploited to develop two numerical models of a ballistic impact against fabric composites. The accuracy of the two models in predicting the projectile residual velocity and the damage morphology was compared. For this reason, ballistic tests according to the EN 1522 standard were performed on panels manufactured from Kevlar 29 plain weave fabrics embedded in epoxy matrix. The bullet used for these tests was a .357 Magnum with an impact velocity of 430 m/s. Tensile tests were also performed to calibrate the tensile properties both for the macro-homogeneous and meso-heterogeneous approach. This calibration was performed using an inverse method and thus numerical models of the tensile tests were developed. Both two approaches were shown to be capable of reproducing the fundamental features of composite failure: fiber tensile failure, fiber crushing and delamination. The meso-heterogeneous approach delivers more accurate results both in terms of prediction of the residual velocity and reproduction of the damage morphology. On the other hand, the advantage of the macro-homogeneous approach was a three times lower computational time required to complete the simulation.

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