Numerical Modelling of Multilayer Woven Para-aramid Fabrics

M. M. Moure[1], J. Aranda-Ruiz[2], F.J. Galán-Ortega[1], M. Rodriguez-Millán[4]

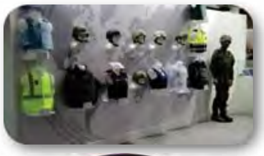
[1] Bioengineering and Aerospace Engineering Department, University Carlos III of Madrid, Spain
[2] Continuum Mechanics and Structural Analysis Department, University Carlos III of Madrid, Spain
[4] Mechanical Engineering Department, University Carlos III of Madrid, Spain

ABSTRACT

In this work, a mesoscopic 3D numerical model, able to predict the ballistic limit and the damaged area of woven aramid fabrics, has been developed. Two different types of fabrics based on para-aramid yarns with different interlacing geometries have been characterized and analyzed from yarn level to weave level. Mechanical properties such as maximum stress, failure strain, and elastic modulus have been obtained from uniaxial tensile tests, while the inter-yarn friction coefficients (static and kinetic) have been obtained by a combination of single yarn pull-out tests and an analytical model. The numerical model has been validate through ballistic impact tests in terms of ballistic limit and damaged area. Additionally, the model has been used to study the impact response of multilayer fabrics, obtaining the influence of the number of layer in the ballistic limit.

1. INTRODUCCTION AND MOTIVATION

High-performance aramid fabrics have increased their demand in recent years in applications where high levels of energy absorption are required, as in the case of structures and personal protections under impact loadings. This increase has been mainly driven by their desired engineering properties, such as high elastic modulus, high strength, low density, good chemical resistance and thermal stability *[1]*.



- Friction between yarns plays an important role in the impact behavior of aramid fabrics, increasing the energy dissipation of the fabric when the yarns begin to move one concerning the other, and also is reflected in the way the loads are transferred and redistributed between neighbor yarns *[2]*.
- The ballistic limit (known as V50), the deformation shape of the woven or the influence of the inter-yarn friction can be studied using the Finite Element Method.

2. OBJECTIVE

The main objective of this work is to implement a 3D mesoscopic models based on Finite Elements Analysis which allow to study the impact behavior of multilayer para-aramid fabrics. An intensive experimental campaign, based on uniaxial tensile tests and yarn pull-out tests, has been developed in order to obtain the necessary properties of the yarns to use them as inputs in the numerical model.

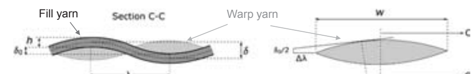
3. EXPERIMENTAL PROCEDURE (inputs for numerical model)

3.1. Geometrical Characterization of the Material

Two woven aramid fabrics with different areal densities are analyzed.

Aramid Kevlar®K129

Fabric - Yarn orientation	*w* (mm)	*h* (mm)	*λ* (mm)	*Cross Yarn Section (mm²)*	*δ (mm)*	*δ₀ (mm)*	*θ/2 (°)*
A-Fill	1.1420	0.1753	1.1520	0.0647	0.1650	0.0610	5.22
B-Fill	0.8985	0.1825	0.9545	0.0549	0.1510	0.0400	9.81
A-Warp	1.0950	0.1753	1.1650	0.0687	0.1760	0.0773	6.43
B-Warp	0.9050	0.1825	0.9305	0.0527	0.1830	0.0473	10.30



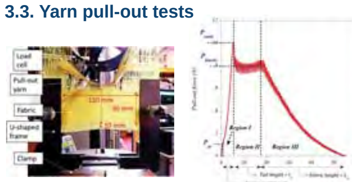
3.2. Yarn uniaxial tensile tests

Mechanical properties in both orientations for fabrics A and B

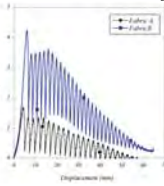
Fabric - Yarn orientation	*F (N)*	*E (GPa)*	*σ_{max} (GPa)*	*ε_{max}*
A-Fill	158.612 ± 14.249	101.740 ± 2.596	2.451 ± 0.220	0.029 ± 0.001
B-Fill	140.036 ± 9.237	103.205 ± 1.669	2.549 ± 0.168	0.029 ± 0.001
A-Warp	166.065 ± 4.334	99.898 ± 1.868	2.416 ± 0.063	0.029 ± 0.002
B-Warp	132.984 ± 0.092	106.126 ± 3.119	2.523 ± 0.002	0.029 ± 0.001

← *INSTRON 8516 universal testing machine*

3.3. Yarn pull-out tests



Static and kinetic inter-yarn friction coefficients are obtained by means of the pull-out force vs displacement curves and the analytical model of Das et al. described in *[3]*:



Das et al. *[3]*

$$\mu_S = \frac{Ln\left[\frac{P_{static}}{(P_{in}/n)}\right]}{n \cdot \theta}$$

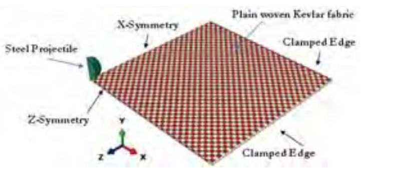
$$\mu_k = \frac{Ln\left[\frac{P_{kinetic}}{(P_{in}/n)}\right]}{n \cdot \theta}$$

Fabric - Yarn orientation	*P_{in} (N)*	*P_{static} (N)*	*$P_{kinetic}$ (N)*	*μ_s*	*μ_k*	*μs/ μk*
A-Fill	1.23	7.85	5.64	0.63	0.54	1.17
B-Fill	0.22	1.81	0.91	0.34	0.31	1.10
A-Warp	0.90	11.73	8.54	0.62	0.53	1.17
B- Warp	0.18	1.94	0.82	0.34	0.30	1.13

4. NUMERICAL MODEL DESCRIPTION (Abaqus/Explicit commercial code)

- **Plain woven fabric: Mesoscopic 3D deformable body** (Fill and warp yarns/ 100x100 mm²)
- **Projectile: 3D Rigid Body**
- **Materials: Aramid Fabrics** (orthotropic behavior)
  Tempered Steel for projectile
- **Quarter Symmetry**
- **General Contact interaction using static-kinetic exponential decay contact law:**

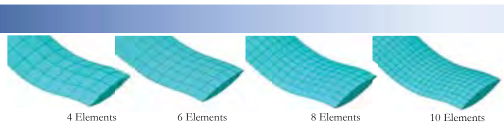
$$\mu = \mu_k + (\mu_S - \mu_k)e^{-\alpha \cdot |V_{rel}|}$$

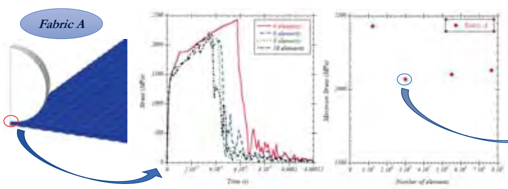


Element types: 299025 C3D6R and C3D8R nodes

5. MESH SENSIBILITY

A mesh sensibility study has been conducted modifying the number of elements in the yarn width cross section.

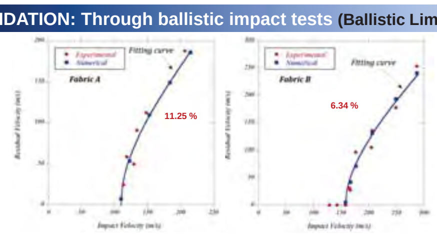




Mesh selected
6 Elements in yarn width cross section

6. VALIDATION: Through ballistic impact tests (Ballistic Limit and Damaged Area)

Ballistic Limit (V50) validation

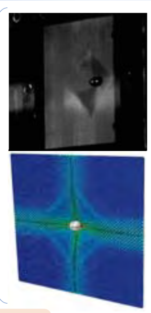


	Fabric	*Ballistic limit (m/s)*	*κ*
Experimental		110	2.31
Numerical	A	110	2.05
Error (%)		0.00	11.25
Experimental		162	2.05
Numerical	B	158	1.92
Error (%)		2.47	6.34

Recht and Ipson *[4]*

$$V_r = (V_0^\kappa - V_{bl}^\kappa)^{1/\kappa}$$

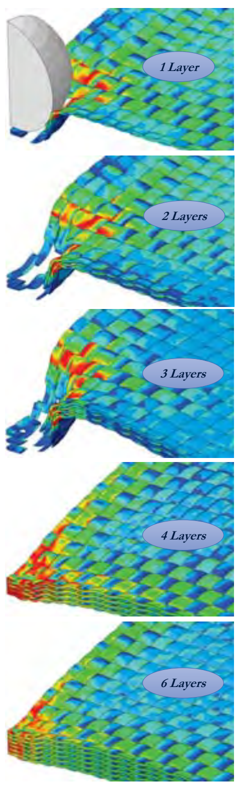
Damaged area validation

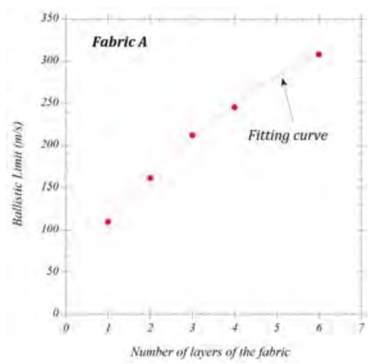


The model is capable of accurately reproducing the impact-velocity curves and the damaged area obtained experimentally

7. RESULTS

Several ballistic impact simulations have been carried out at different impact velocities and over a total of five different multilayer fabrics (1, 2, 3, 4 and 6 layers) both for fabrics A and B; with the intention of obtaining the ballistic limit in each case. The results obtained for fabrics A and B present the same trend, therefore, only the results for fabric A are presented as an example. In the figures of the left, the contour plots of fabric A at an impact velocity of 215 m/s and for the five cases of multilayer fabrics are presented.





By increasing the number of layers:

- The ballistic limit increases
- The damaged area decreases
- The stress concentration at the impact point decreases
- The energy is transferred to the crossing yarns.

By means of the FEM model developed

The ballistic limit at a certain velocity can be predicted for fabrics with different number of layers defining a fitting curve and without performing additional experimental tests.

CONCLUSIONS

A 3D mesoscopic numerical model has been developed using the experimental results obtained from the yarn uniaxial tensile tests and the yarn pull-out tests, using those results as inputs for the FEM model. Several conclusions have been obtained:

- The FEM model has been validated. The model is capable of accurately reproducing the impact-velocity curves (V50) and the damaged area obtained experimentally.
- The ballistic limit of the fabric increases with the number of layers of which it is composed.
- By increasing the number of layers of a fabric the stress concentration at the impact point decreases and the energy is transferred to the crossing yarns.
- The ballistic limit at a certain velocity can be predicted for fabrics with different number of layers by defining a fitting curve and without performing additional experimental tests.

References

[1] Dong Z, Sun CT. Testing and modeling of yarn pull-out in plain woven Kevlar fabrics. Compos Part A Appl Sci Manuf 2009;40:1863–9.
[2] Nilakantan G, Gillespie JW. Yarn pull-out behavior of plain woven Kevlar fabrics: Effect of yarn sizing, pullout rate, and fabric pre-tension. Compos Struct 2013;101:215–24.
[3] Das S, Jagan S, Shaw A, Pal A. Determination of inter-yarn friction and its effect on ballistic response of para-aramid woven fabric under low velocity impact. Compos Struct 2015;120:129–40.
[4] Recht RF, Ipson TW. Ballistic Perforation Dynamics. J Appl Mech 1963;30:384–90.