Virtual testing of composite armour probabilistic penetration

For the first time ever, a fully validated and predictive virtual testing capability can predict the V0-V100 probabilistic penetration behaviour of advanced composite material-based soldier and vehicle armour. The case of Kevlar fabrics used in body armour is considered.

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For decades, the design and ballistic impact performance evaluation of soft armour (e.g. aramid fabrics) and hard armour (e.g. S2-glass, UHMWPE composites) has relied on prototyping and destructive testing based on iterative trial-and-error, build-and-shoot approaches with reliance on empirical databases.

Let us consider Kevlar fabric-based body armour. Prototyping and testing each fabric armour design iteration is both time-consuming and costly based on the material (fibre spool), weaving loom (setup and drawing), touch labour (target preparation, fixturing), and infrastructure (range equipment). Ballistic impact tests proceed sequentially using a single barrel or gas gun.

The cost and time aspects are greatly exacerbated given that dozens to hundreds of test shots are needed to characterize the probabilistic penetration response of the armour system, which is represented by the V0-V100 curve where VX represents the probability X% that a projectile with an impact velocity V will completely penetrate though the target. This probabilistic penetration response is a consequence of various intrinsic (material related), extrinsic (testing related), and extraneous (unwanted error related) sources of stochastic variability; for example, the statistical yarn tensile strength. In turn, this stochasticity results in the well-known zone of mixed results (ZMR) during testing, where the lowest penetrating test shot velocity (VP) is actually lower than the highest non-penetrating test shot velocity (VNP), i.e. VP < VNP. This would be counter-intuitive from a deterministic sense.

The opportunity – Virtual testing

Real-world prototyping and testing can be conducted in a fully virtual environment, which is referred to as virtual prototyping and virtual testing (VP-VT). This process involves developing a computer model representation of the fabric target with the associated impact physics, typically based on finite element analysis (FEA).
The advantages of VP-VT are tremendous. Leveraging supercomputing, multiple virtual tests (ballistic impact simulations) can be conducted in parallel leading to a faster determination of the V0-V100 curve than by experiments carried out one at a time.

Generating virtual targets (fabric FEA mesh with individually modelled 3D yarns) is relatively straightforward using available textile software pre-processors as opposed to actually weaving a fabric. Running of the impact simulations is a relatively routine task once all the associated models and computer scripts have been set up the first time, unlike actual testing where the same set of repetitive, labour-intensive tasks need to be conducted each time. VP-VT enables in-depth parametric studies and sensitivity analyses to elucidate critical mechanisms that influence performance.

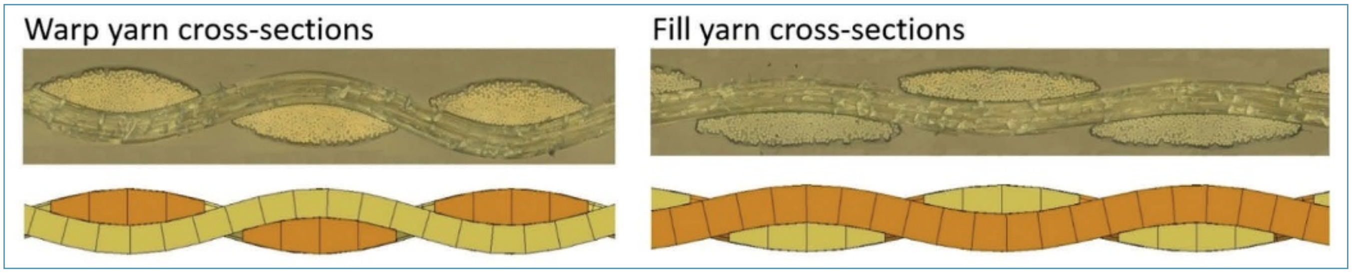

Fig. 1: Fabric material and virtual cross-sections

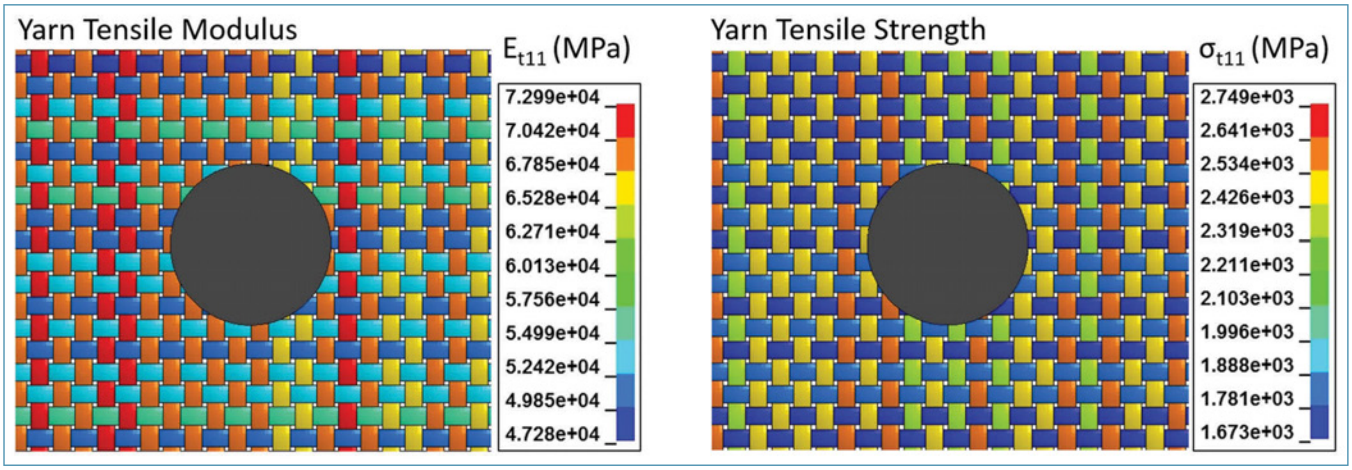

Fig. 2: Mapping of stochastic yarn material properties into the fabric FEA model

Most importantly, VP-VT enables the rapid exploration of conceptual weave architectures, geometries, and constituent materials including hybridized variants. In summary, VP-VT can (i) enable the exploration of vast material-design spaces amenable to optimization studies; (ii) lower the barrier to early-stage inception of new weaves, materials, and processes into soldier protection platforms; (iii) mitigate risk; and (iv) reduce lead times and compress material maturation cycle times.

The barrier – Deterministic calibrated models

The biggest barrier to the widespread adoption of VP-VT stems from the current state of the art in FEA simulations of ballistic impact on composite armour.

The near entirety of relevant works in the literature are deterministic and calibrated.

Obviously, deterministic models cannot capture sources of stochastic variability that are critical in evaluating the probabilistic penetration behaviour of composite armour, therefore they have limited practical relevance.

Whilst some FEA model calibration may be unavoidable, the widespread practice of "turning knobs" in models to match some already-available experimental test data implies the model is not fully predictive in nature and cannot be used to explore new materials and impact scenarios with confidence.

The solution – Probabilistic virtual testing framework

Teledyne Scientific Company developed a virtual testing framework that can exactly recreate the environment and workflow of the experimental testing framework.

A Kevlar S706 plain-weave fabric (34 yarns/in., 600 den KM2 yarns) is considered as a demonstration. The ballistic test target comprises a fully-clamped 4 in. x 4 in. single ply. Two 0.22 cal projectiles are considered: an 11-gr stainless steel sphere and a 17-gr alloy steel FSP (fragment simulating projectile). For each projectile case, approximately 40 targets are shot once each at their centre over a range of projectile impact velocities (Vi), and the outcome in terms of a non-penetration (=0) or penetration (=1) is recorded.

At the end of testing, the V0-V100 curve is generated using a statistical analysis. This involves using MLE (maximum likelihood estimation) to fit a normal distribution to the test data; thus, the mean (μ) represents the well-known V50 velocity parameter. The computational modelling framework within the virtual testing framework is capable of simultaneously mapping in several sources of stochastic variability into the FEA model and, in turn, generating probabilistic outcomes.

The following are considered: (i) statistical yarn tensile strength, (ii) statistical yarn tensile modulus, (iii) statistical inter-yarn friction, (iv) random projectile impact location, and (v) random projectile rotation (for the FSP projectile

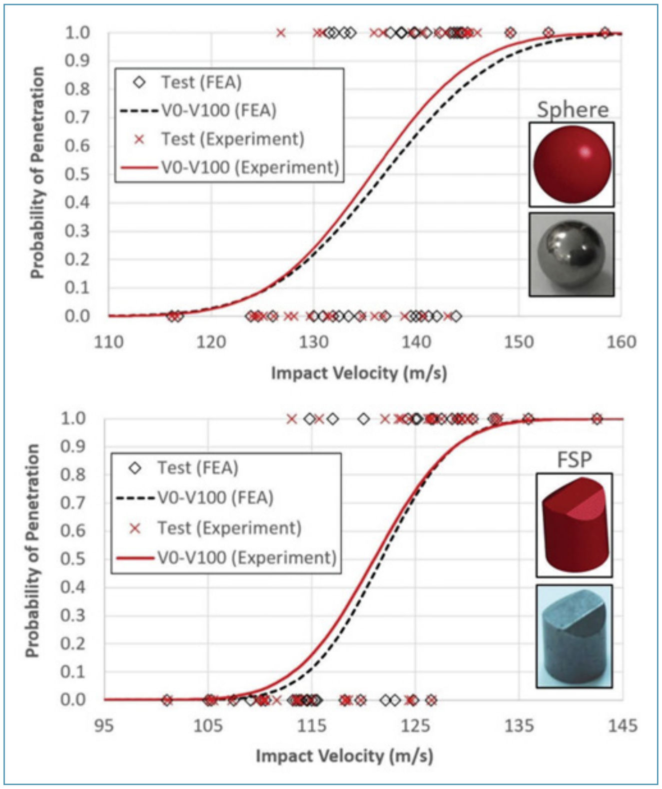

Fig. 3: Experimental validation of the virtual test predictions (V0-V100 curves)

only). Previous extensive experimental testing such as single-yarn tensile testing and single-yarn frictional pullout testing has generated all the required statistical input data for the fabric FEA models.

Figure 1 displays the fabric virtual microstructure that is quantitatively validated using image analysis of 2D opticals of the fabric cross-section. Figure 2 displays an exemplary mapping of the statistical yarn tensile moduli (Et11) and tensile strengths (σt11) onto the individual 3D yarns of the fabric FEA model. A MATLAB-based script is used to generate the mapping. There are separate mappings for each of the fabric targets. Similarly, each warp-to-fill yarn contact pair has a stochastic inter-yarn friction coefficient.

The precise projectile impact location relative to the fabric dead centre is also randomly varied within a small window in accordance with experimental observations where it is impossible to precisely strike the exact same spot during each test shot. For the FSP projectile only, random projectile rotation (yaw) is also considered a source of variability because of the non-symmetric strike face.

Figure 3 shows the experimental validation of the virtual testing. For the first time ever, an FEA model was able to successfully predict the entire experimental V0-V100 curve, with excellent agreement for both the spherical and FSP projectile impact scenarios. The raw test shot data is also shown in Figure 3 with the non-penetrations at y=0 and penetrations at y=1. Again, the FEA model was able to successfully capture the lowest penetrations and highest non-penetrations (i.e. bounds of the ZMR).

Although not shown here, the FEA model was even able to capture some variability in the projectile exit trajectories which were sometimes oblique to the gun barrel axis, and for the FSP projectile case also showed projectile tumbling. For complete details on the FEA model implementation, methodology, and experimental validation, the reader is referred to the works of Nilakantan [1-4].

Conclusions

Key to the success of this work was the generation of a comprehensive experimental test database (microstructure, material, performance) and a tightly integrated set of experiments and models, ensuring a consistent, seamless flow of data and insights back-and-forth between models and experiments.

This virtual testing framework can readily be extended to include other weave architectures, fibre materials, projectiles and bullets.
A fully predictive computational tool for composite armour will provide a disruptive capability that will open up the material design space and lead to improved, lightweight armour while minimizing the need for costly destructive testing. Obviously, other structural composite applications in the automotive and aerospace sectors can also greatly benefit from the computational methods developed in this work. □

More information:
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References

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