COMPUTATIONAL MODELING OF THE IMPACT OF 2D AND 3D FABRICS INCORPORATING MULTISCALE AND PROBABILISTIC SIMULATION TECHNIQUES

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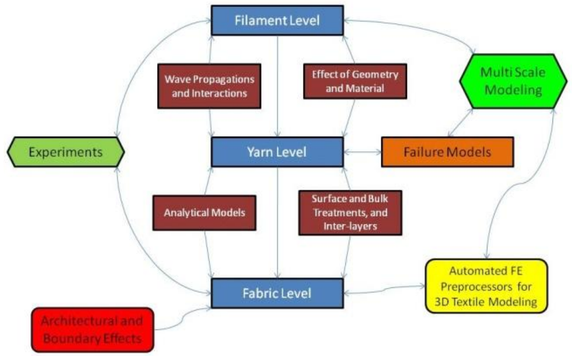
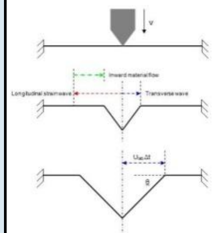
RESEARCH SUMMARY

- Analytical modeling of yarn and fabric impact
- Finite element (***FE***) modeling of the impact of dry 2D and 3D fabrics using LS-DYNA
- Investigating the role of materials and architecture on the impact response of 2D and 3D fabrics
- Experimental characterization of the strength of high modulus yarns and through-thickness compression response under quasi-static and high rates
- Advanced material modeling of high strength continuous filament tows / yarns including viscoelasticity, length scale effects, and statistical strength distributions
- Implementation of material models (***UMAT***) in LS-DYNA
- Probabilistic techniques to computationally study the V_0 to V_{100} response of fabrics
- Multi scale modeling of 2D fabrics using the Hybrid Element Analysis (***HEA***)

METHODOLOGY



SIMPLE ANALYTICAL MODEL - YARN TRANSVERSE IMPACT



$$c = \sqrt{\frac{E(1-\upsilon)}{(1+\upsilon)(1-2\upsilon)\rho}} \qquad W = c.\varepsilon$$

$$U_{lag} = c\sqrt{\frac{SJF.\varepsilon}{1+SJF.\varepsilon}} \qquad SJF = NR+1$$

$$SE_{yarn} = \int_0^L E(\dot{\varepsilon})\varepsilon^2 A dx$$

$$KE_{yarn}^{smeared} = \frac{1}{2} m_{yarn\_inst} v_{(n)}^2 = 2\int_0^{L^{(n)}} \frac{1}{2}\rho A dx \left(\frac{v^{(n)}x}{L^{(n)}}\right)^2$$

$$KE_{yarn}^{interpolated} = \frac{1}{4}\rho A L^{(n)}\left(v^{(n)} + v^{(n-1)}\right)^2 \qquad \Delta t \le \alpha \frac{(m_{projectile} - m_{yarn})c}{EA}\sqrt{\frac{1+\varepsilon_{fail}}{\varepsilon_{fail}}}$$

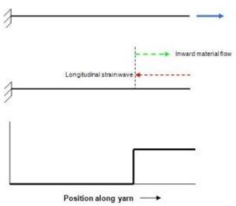
$$v = \sqrt{(1+SJF.\varepsilon)^2 U_{lag}^2 - \left[(1+SJF.\varepsilon)U_{lag} - W\right]^2}$$

$$v^{(n)} = v^{(n-1)}\left(\frac{1-\chi}{1+\chi}\right)$$

where

$$\chi = \frac{E.A.\Delta t}{c(m_{projectile} - m_{yarn\_inst})}\sqrt{\frac{SJF.\varepsilon}{1+SJF.\varepsilon}}$$

SIMPLE ANALYTICAL MODEL - YARN TENSILE TESTING



$$\frac{\partial^2 u}{\partial t^2} = c^2 \frac{\partial^2 u}{\partial x^2}$$

$$u(t) = at^1 + bt^2 + ct^3 + \ldots$$

$$\varepsilon = \frac{\partial u}{\partial x} \qquad \varepsilon_y = -\upsilon_{xy}\varepsilon_x$$

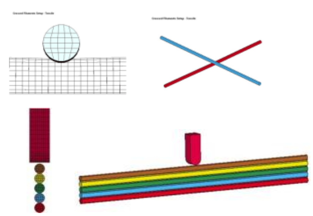
$$\sigma_x = \frac{E}{c}\frac{\partial u}{\partial t}$$

$$SE_{yarn} = \frac{1}{2}\int_0^L E(\dot{\varepsilon})\varepsilon^2 A dx \qquad F = \frac{2EA}{c}\frac{\partial u}{\partial t}$$

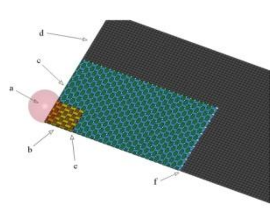
$$KE_{yarn} = \frac{1}{2}mv^2 = \frac{1}{2}(\rho A l)(c\varepsilon)^2$$

FILAMENT INTERACTIONS

- Study wave propagations and interactions between filaments in various configurations: Parallel, Stacked, and Crossed
- Parametric studies on effect of material properties and interfacial treatments on interactions



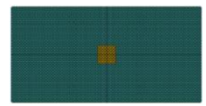
MULTI SCALE MODELING – HYBRID ELEMENT ANALYSIS



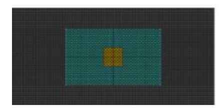
a	Projectile
b	Local region, solid element yarns
c	Local region, shell element yarns
d	Global region, homogenized shell elements
e	Interface #1
f	Interface #2

Hybrid Element Analysis (HEA) is defined as '*the finite element analysis of a structure by combining different finite element formulations at both a single and multiple scales of modeling*'

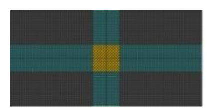
SAMPLE HEA MODELS



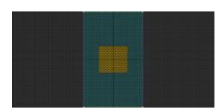
Single Scale HEA



Central Patch HEA



Center Strip HEA



Center Cross HEA

Impedances matched across all interfaces to prevent interfacial reflections of the longitudinal strain wave

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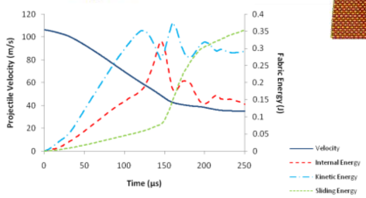
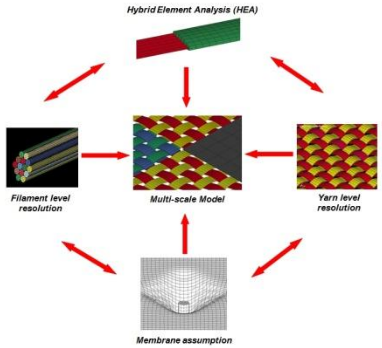
CONTINUED

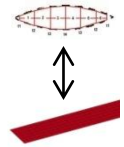
IMPACT TESTING OF FABRICS -BASELINE MODELS

Single layer Kevlar S706 fabric held on the two shorter sides and impacted at the center by a rigid spherical projectile, explicit yarn architecture modeled using solid elements



IMPACT TESTING OF FABRICS - MULTI SCALE MODELS

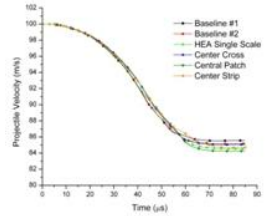




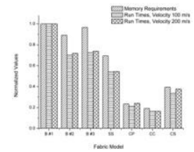
New method of modeling yarns with shell elements

- Massive savings in computational expense
- Enables simulation of large dimensioned fabric targets
- Degree of resolution decreases away from impact zone
- Shell element yarns utilize non-uniform nodal thicknesses

SAMPLE SIMULATION RESULTS BASELINE Vs. HEA

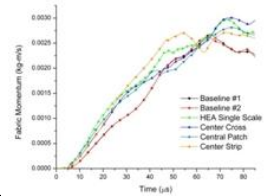


Projectile velocity

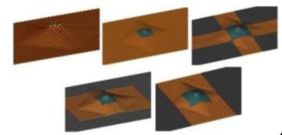


Computational savings

Time instant of 40 μs



Fabric momentum

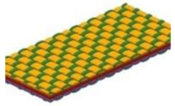


Time instant of 55 μs

ROLE OF ARCHITECTURE AND MATERIALS IN 2D AND 3D FABRICS

- Investigate benefits of 3D architecture over 2D architecture
- Effect of stitching yarns in 2D fabrics and z-tows in 3D fabrics
- Effect of material properties (ρ, E, σ_{fail}) on performance
- Effect of yarn/tow geometry variables such as cross sectional shape, span, and undulations
- Effect of z-tow inclination (θ_z) on dynamic deflection, energy dissipation, impact resistance, and structural integrity
- Case study involves 2D fabric models with and without through thickness stitching, and 3D fabric models with varying z-tow inclinations, all fabric models equivalent in areal density and material properties

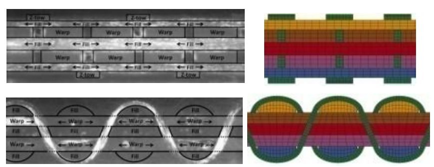
2D Fabric with Stitching

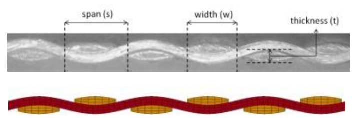


3D Fabric with θ_z=90°

SETUP OF 2D AND 3D FABRIC FINITE ELEMENT MODELS

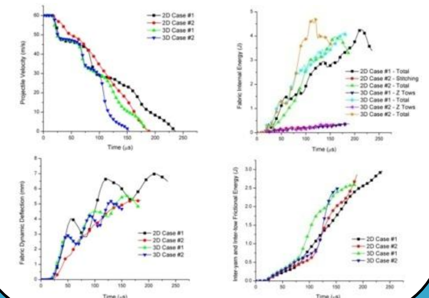
- Dimensions obtained from micrographs serve as geometrical input to the preprocessor DYNAFAB





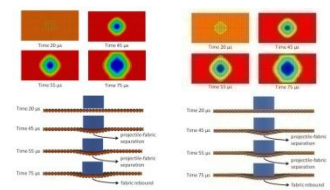
SAMPLE SIMULATION RESULTS 2D Vs. 3D FABRIC

Non penetrating impact by rigid RCC projectile at 60 m/s of 4x2 in. equivalent 2D and 3D fabrics gripped on all four sides



RESULTS… contd.

Case #1

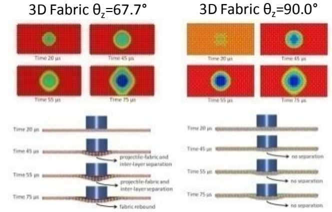


Case #2

3D Fabric θ_z=67.7°

3D Fabric θ_z=90.0°

Case #1



Case #2

2D Fabric w/o Stitching

2D Fabric with Stitching

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CONTINUED

STATISTICAL NATURE OF YARN STRENGTH – PROBABILISTIC SIMULATION TECHNIQUES

- Statistical nature of yarn strength arises from the existence and nature of defect distribution within the filament
- Strength decreases with length as the probability of finding a critical defect increases

- Four stages to the study:

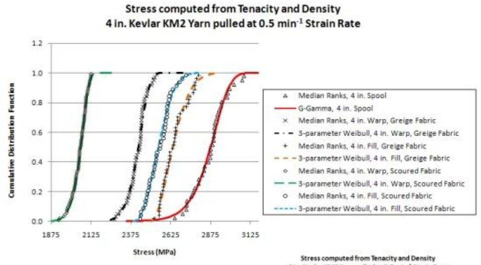
(1) Use of experimental testing to generate strength data of yarns from a spool and extracted from a fabric
(2) Use of statistical distributions (E.g. Weibull) to characterize the data
(3) Assess weaving process induced strength degradations
(4) Incorporation of statistical distributions into FE code through custom material models and implementation as a Monte Carlo approach

- Some benefits of the study

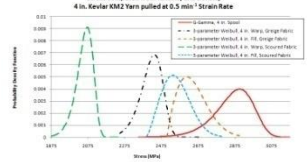
(1) Assess effect of statistical variability in material properties on fabric performance under impact
(2) Generate V_0-V_{100} curves computationally
(3) Study degradation due to the weaving processes on fabric performance
(4) Assess V_{50} values of fabrics comprised of hybrid or new materials and architectures before resorting to experimental testing

EXPERIMENTAL CHARACTERIZATION OF YARN STRENGTH – WEAVING EFFECTS

600 denier Kevlar KM2 Yarns extracted from Spool, Greige S706 fabric, and Scoured S706 Fabric

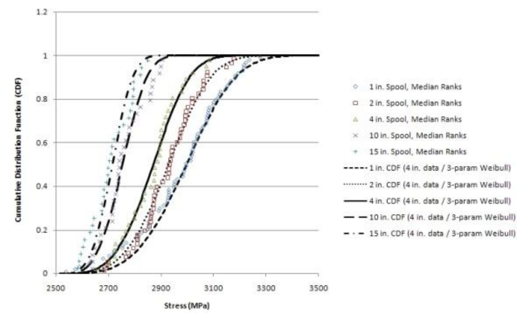


3-parameter Weibull and G-Gamma distributions used for CDF (on top) and PDF (on right)



EXPERIMENTAL CHARACTERIZATION OF YARN STRENGTH –LENGTH SCALE EFFECTS

600 denier Kevlar KM2 yarn



$$F(\sigma) = 1 - \exp\left(-\left(\frac{L}{L_0}\right)^{\alpha}\left(\frac{(\sigma - x)}{\sigma_0}\right)^{m}\right)$$

Cumulative Distribution Function (CDF) for a 3-parameter Weibull distribution with parameters $\boldsymbol{\sigma_o}$ (scale), $\boldsymbol{m}$ (shape), $\boldsymbol{x}$ (threshold), length scale parameter $\boldsymbol{\alpha}$ (α_1 for $L < L_0$; and α_2 for $L > L_0$)

MAPPING THE STATISTICAL STRENGTH DISTRIBUTIONS

- Two current methods available to map the statistical strength distributions on to the FE model

METHOD I

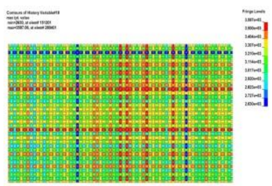
- Each yarn (and all elements within it) assigned a to unique strength such that the histogram of all yarn strengths recreates the experimentally generated statistical distribution

METHOD II

- Each element assigned to a unique strength such that the histogram of all element strengths recreates the experimentally generated statistical distribution
- Homogenization of defect distributions to eliminate mesh sensitivity

PROBABILISTIC FINITE ELEMENT MODELS

METHOD I

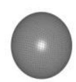


METHOD II

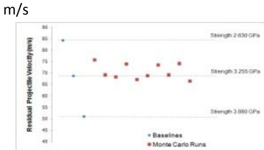
SAMPLE SIMULATION RESULTS

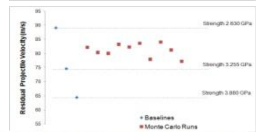
V_{strike} Vs. $V_{residual}$

Single layer plain weave Kevlar fabric held on four sides, impacted in the center at 100 m/s



projectile type





Model	Projectile	V_s (m/s)	V_r (m/s)	σ (m/s)
Method I	Spherical	100	70.635	3.312
	Cylindrical	100	81.150	2.323
Method II	Spherical	100	72.232	3.920

ACKNOWLEDGEMENTS

This work is supported by the Army Research Laboratory through the Composite Materials Research (CMR) program