Novel Multi-scale Modeling of Woven Fabric Composites for use in Impact Studies

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Abstract

A novel approach to the multi scale modeling of the impact of woven fabrics using LS-DYNA® has been presented. This new technique entitled 'Hybrid Element Analysis (HEA)' incorporates the use of different finite elements at both a single and multiple level of modeling. A yarn level resolution is maintained around the impact zone or local region, while a homogenized resolution has been used for the far field or global region. The central patch of yarn level resolution uses a combination of solid and shell elements. A new method for modeling individual yarns using shell elements is discussed, which more accurately captures the geometrical contours of the yarn cross section. The surrounding homogenized zone uses shell elements. Interfaces using various types of tie-constraints are created between the different finite elements at the various scales of modeling. The acoustic impedances have been matched across the interfaces. A systematic approach is presented to determine the geometric and material parameters of the homogenized zone. The HEA approach maintains the accuracy of using a fabric model comprised entirely with yarn level resolution utilizing solid elements, but at a fraction of the computational expense. This enables the finite element simulation of multi layered fabric systems with very large domains, which was previously very difficult because of the impractical computational requirements of such an exceedingly large model. Compared to previous numerical multi-scale models, the finite element model using the HEA approach presented in this paper more accurately captures the entire impact event at a lower computational expense, making it a very useful tool for future studies.

Keywords: impact, plain weave fabric, multi scale modeling, finite element analysis (FEA), LS-DYNA

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Introduction

Woven fabrics composed of light weight and high strength continuous filaments are especially useful in a wide-range of applications such as protective materials for military and law enforcement personnel and as well as structural containment of turbine fragments. The attractive energy dissipating and penetration resistance capability of these fabrics coupled with their highly intricate architecture and multi scale nature have made them the focus of considerable research for the past few decades. Various approaches have been employed to model these fabrics and are outlined in the comprehensive reviews recently by Tabiei and Nilakantan [1], and earlier by Cheeseman and Bogetti [2].

With the advent of high speed computing, the option of using numerical analyses to simulate fabric impact has become popular. Different modeling techniques include representing the fabric as a homogenous continuum using 2-d elements [3, 4], and explicitly modeling individual yarns using 2-d and 3-d elements [5-7]. While the former approach is computationally efficient, it cannot be used to visualize yarn sliding and yarn failure and cannot capture frictional effects which have been shown to have an important effect on the fabric response to high speed impact [8]. The latter approach of modeling individual yarns is computationally very expensive, but it can accurately capture frictional effects and individual yarn interactions.

Recently, multi scale modeling techniques have emerged that combine the benefits of the previous approaches by balancing accuracy and the detail of modeling with computational efficiency. Barauskas and Abraitiene [9] developed a combined mezzo- and macro- mechanical model where thin shells were used to model individual yarns around the impact zone and roughly meshed membrane elements were used in the surrounding regions. Rao et al. [10] developed two multi scale models where the shape of the local region viz. with yarn level architecture, varied between the shape of a rectangle and a cross.

It is apparent that this field of multi scale modeling of fabric systems is fairly recent. In this paper, we present a new technique entitled the *Hybrid Element Analysis* (HEA) that is able to capture the behavior of the fabric system at a much lower computational expense. This is demonstrated by comparing results against a baseline numerical model, which comprises of a plain weave textile composite modeled entirely using a yarn level architecture with solid elements. All fabric finite element (FE) models in this research have been created using automated in-house preprocessors, further detailed in the appendix.

HEA Applied to a Single Yarn

When modeling yarns, there is a tradeoff between accuracy and computational expense when choosing between solid and shell elements. A good approach would be to combine the benefits of both finite elements into the yarn model. At the impact zone, a higher level of accuracy is needed due to projectile-yarn interactions. At locations outside of this impact zone, the main mode of yarn deformation is tensile in nature which can be modeled using a lower level of resolution. In this region the emphasis is therefore on computational efficiency. A useful approach then would be to use solid elements to model the yarns at the impact zone and shell elements at regions away from the impact zone. We call this approach a '*Hybrid Element Analysis*' and define it as '*the finite element analysis of a structure by combining different finite element formulations at both a single and multiple scales of modeling*'. Figure (1) displays HEA applied to a single yarn.

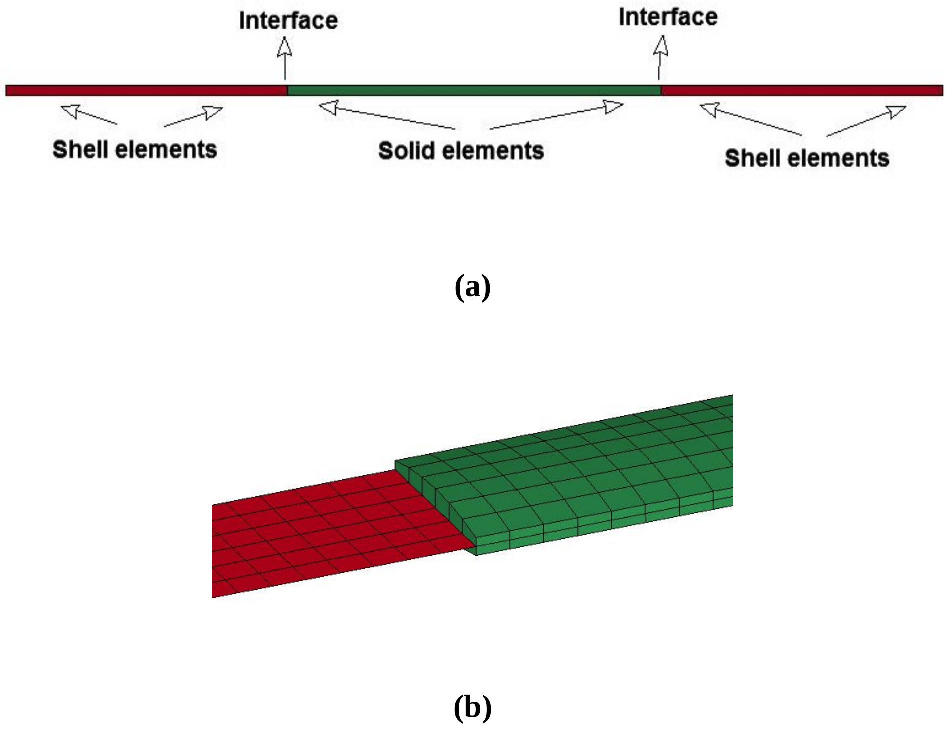
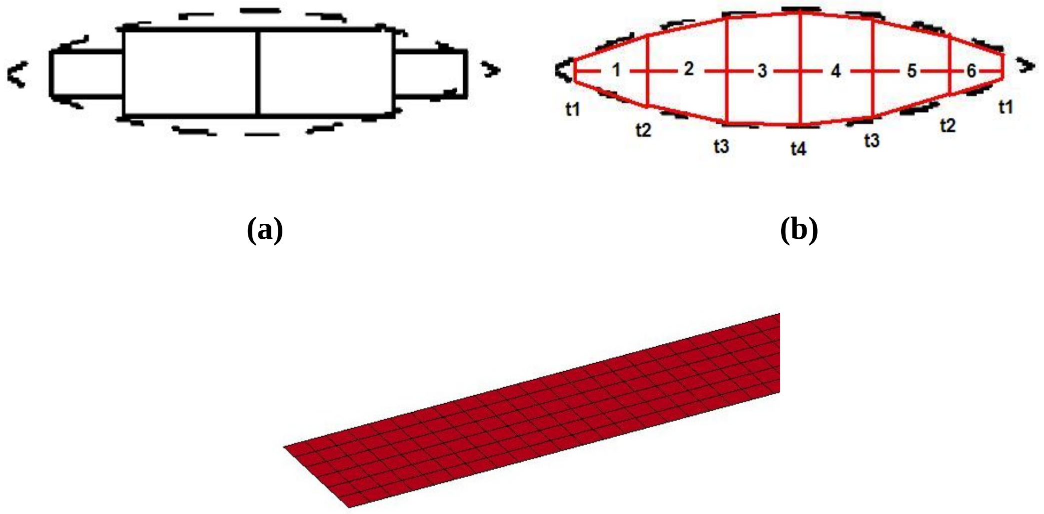


Fig. 1. (a) HEA of a yarn using shells and solids (top view) (b) Close up at the interface

A tied interface is used between the shell and solid elements, using the keyword *CONSTRAINED_SHELL_TO_SOLID*. Since the material properties used in the material models for both the shell and solid elements are the same, and the yarn cross sectional area is the same by virtue of our new modeling approach, discussed below, for yarns modeled using shell elements, there is an impedance match across the interface. This is very important as it ensures that there are no reflections of the longitudinal wave at the interface, and that the transverse displacement or bending wave propagates properly across the interface.

Previous approaches [6, 11] to modeling yarns using shell elements are shown in Figure (2a). As can be observed, the cross sectional shape is not well approximated leading to thickness jumps at the shell element boundaries [6]. This makes it difficult to accurately capture inter-yarn sliding interactions. An improved modeling approach is illustrated in Figure (2b), where a yarn has been modeled using 6 shell elements across the width, with non-uniform nodal thicknesses *t1* to *t4*. These non-uniform nodal thicknesses have been specified for each shell element, so that it closely approximates the cross section of a yarn. Such a modeling approach leads to a more accurate representation of the yarn geometry and consequently improved contact interactions between yarns. A special in-house preprocessor *DYNAYarn* (see Appendix A) was used to create the FE mesh and automatically assign the non-uniform nodal thicknesses to each shell element.



(a) **(b)**

(c)

Fig. 2.Yarn cross section using shell elements with
a) Uniform nodal thicknesses (b) Non-uniform nodal thicknesses
(c) FE mesh of a yarn modeled using shell elements

HEA Applied to Fabric Models

Figure (3) illustrates the various regions of a typical HEA model. Figure (4) displays three of the many possible models using the HEA approach. Figure (4a) displays a single scale HEA model with explicit yarn architecture used everywhere. Solid elements have been used around the impact zone and shell elements have been used everywhere else. Figure (4b) displays a multi scale '*Central-Patch*' HEA model with yarn level resolution around the impact zone and a membrane-type homogenization at far field regions. The yarn level resolution zone uses both solid and shell elements. Tied interfaces are created to couple the various elements at different scales. Failure is incorporated only for the central patch containing the solid elements in accordance with experimental observations. Figure (4c) displays a multi scale '*Center-Cross*' HEA model where the local yarn architecture is maintained within a cross that extends all the way to the fabric boundaries, and a membrane-type homogenization everywhere else.

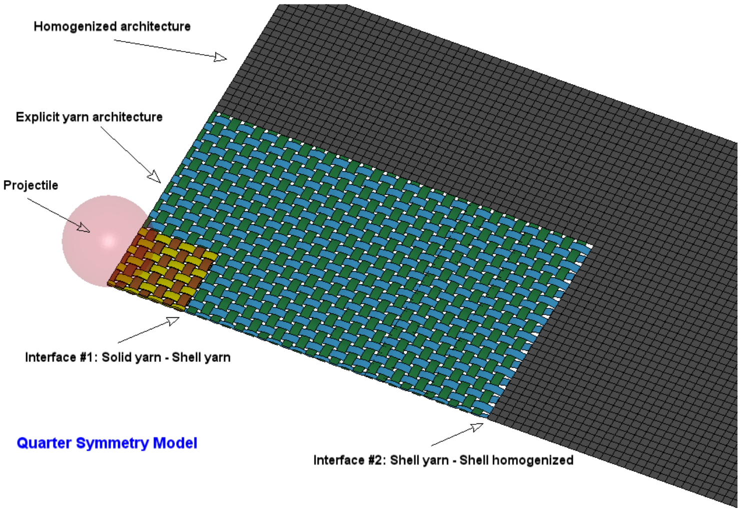
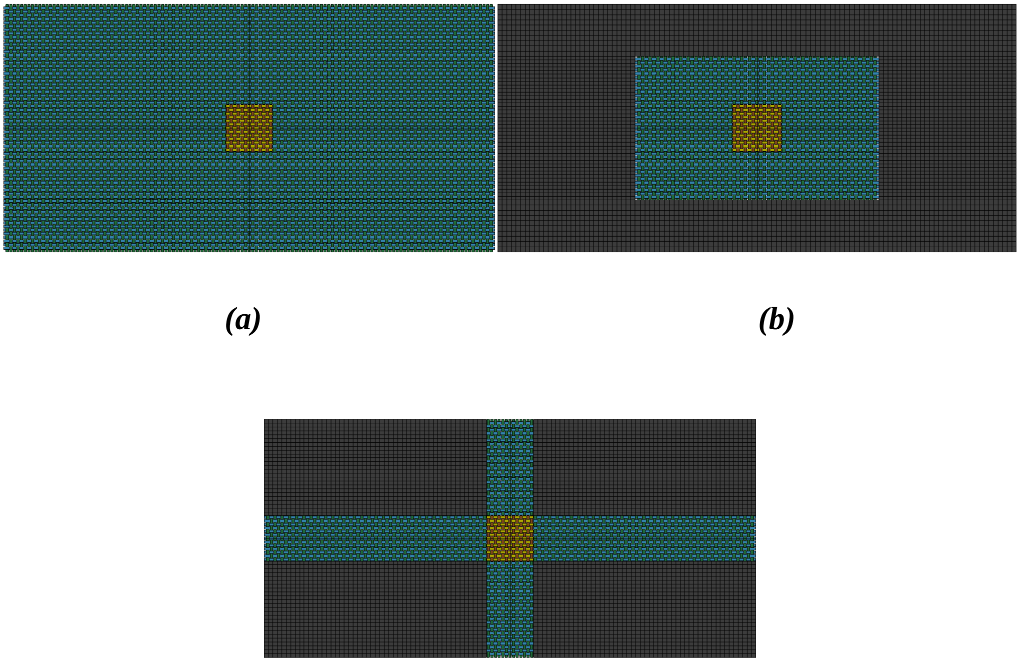


Fig. 3. Setup of a fabric model using the HEA approach



(a) *(b)*

(c)

Fig. 4. Possible HEA configurations (a) single scale (b) multi scale 'Central-Patch' (c) multi scale 'Center-Cross'

By using shell elements to model yarns, it becomes feasible to model yarns that extend all the way to the fabric boundaries, such as in the single scale HEA and Center-Cross HEA. The HEA approach always ensures that the propagation of the longitudinal strain wave and transverse displacement wave across the solid-shell yarn interface is unaffected. In order to ensure this also occurs at the shell-shell interface between the local and global region, the geometrical and material parameters for the global region must be properly determined and this is discussed in the next section.

Estimation of Global Region Parameters

Terminology

E	Elastic modulus of the global region
ρ	Material density of the global region
t	Thickness of the global region
L	Length of the global region
W	Width of the global region
c	Longitudinal wave velocity in a yarn
A	Yarn cross sectional area

So far the procedure to model a fabric entirely at the local level, viz. by capturing its architecture at the yarn level has been well developed in the literature. However, the procedure to model the homogenized fabric at the global level or far field region is not well developed. Some multi scale approaches such as those in Barauskas [9], and Rao et al. [10], rely on arbitrarily selecting material properties and a trial-and-error approach for estimating the global region parameters until numerical results converge with experimental data. This is an inefficient approach in terms of time taken to set up the model, and the numerical model is not predictive in nature but rather plays catch up with baseline or experimental data. This section provides an outline of a more consistent approach used to estimate the global region geometric and material parameters. The three main conditions to satisfy while modeling the global region are (a) maintain the same areal density in the global region or conservation of mass (b) maintain unaffected longitudinal wave propagation in the global region (c) match impedance across the local-global interface. If the impedance is not matched, there will be reflections of the longitudinal wave at the local-global interface causing premature failure within the local region or at the local-global interface.

The unknowns to be determined for the isotropic global region are E, ρ, and t. The thickness of the global region is set as the total thickness of the fabric yarns at the cross over points. Consider the width of the global region to be the same as that of the local region, for the sake of the following calculations. The length of the global region will depend on what ratio of local to global size has been chosen by the user for the model and does not affect these calculations. Generally, it is sufficient that the size of the local region be at least three times the size of the projectile's presented area.

The density of the global region can be determined from the first condition.

$$\rho = \text{areal density} / t \qquad (1)$$

This leaves the determination of the longitudinal modulus of elasticity. For a fabric, because of the effective doubling of the lineal density at the cross over points, the effective theoretical longitudinal wave velocity is obtained by dividing *c* by a factor of the square root of 2. Here *c* is given by

$$c=\sqrt{\frac{E}{\rho}} \tag{2}$$

However a more reliable approach would be to numerically simulate a fabric patch subjected to a high rate tensile test and measure the time it takes for the stress wave to propagate from the pulled to the fixed end. Then the effective longitudinal wave speed is simply the length of the fabric patch divided by the time taken. This is the final longitudinal wave speed that needs to be incorporated into the global region to satisfy the second condition. We will then use this in the third condition. The total impedance is given by the relation

$$Z=\rho c A \tag{3}$$

Then the third condition requires that

$$\sqrt{E_{global}\rho_{global}}A_{global}=\rho_{local}c_{local}A_{local} \tag{4a}$$

where A_{global} is given by *Wt*, and the subscript *global* refers to the homogenized region while the subscript *local* refers to the region modeled with a yarn level resolution. Equation (4a) simplifies to the following final expression for the longitudinal modulus in the global region

$$E_{global}=\frac{E_{local}\rho_{local}A_{local}^2}{\rho_{global}A_{global}^2} \tag{4b}$$

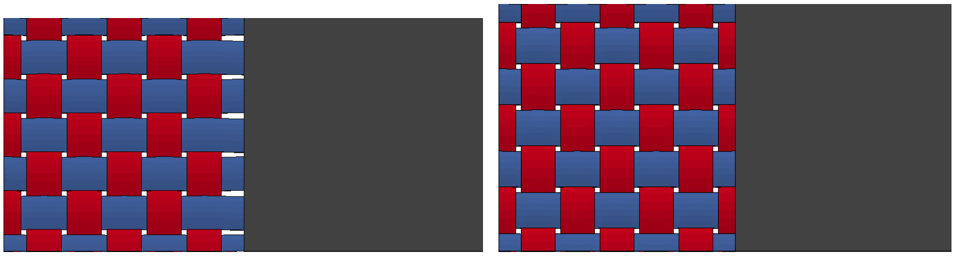
Two types of interfaces at the local-global interface are possible. A *Type-1* interface is when only one set of yarns are coupled to the global region, as illustrated in Figure (5a). A *Type-2* interface is when both sets of yarns are coupled to the global region, as illustrated in Figure (5b). For a *Type-2* interface, A_{local} is the sum of two components: the cross sectional area of a yarn multiplied by the number of yarns across the face of the global region (component 1), and, the continuous area of the vertical mid-section of the orthogonal yarn that runs parallel to the face of the global region (component 2). The area is given by

$$A_{local}=A_1+A_2 \tag{5}$$

where

$$A_1=A_{yarn}n_{warp/fill} \tag{6}$$

For a *Type-1* interface, the total area would be just A_1. Equation (4b) pertains to the *Type-1* interface.



(a) *(b)*

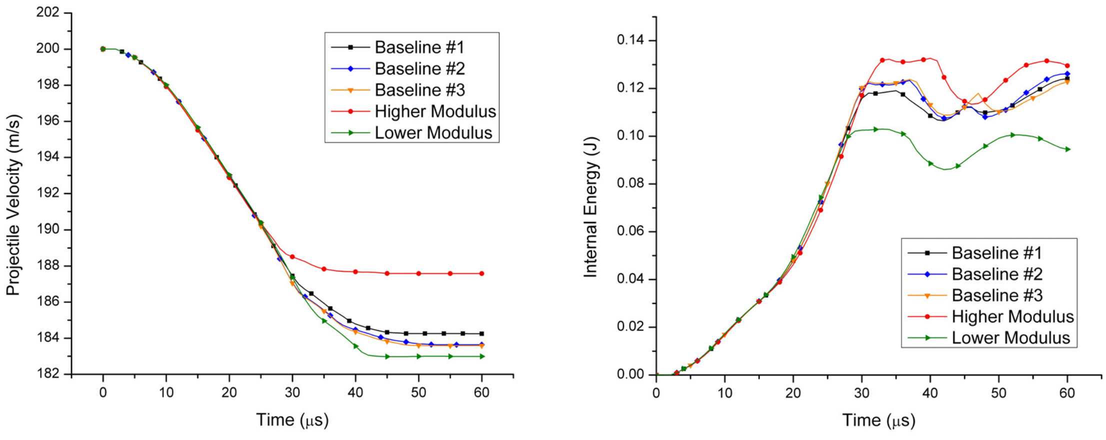
Fig. 5. Local-Global interfaces used in HEA (a) Type-1 (b) Type-2

The parameters calculated by using this consistent approach are near-optimal. This approach prevents the need to run multiple time consuming simulations while trying to fit the global region parameters to match experimental or baseline numerical observations.

Results and Discussion

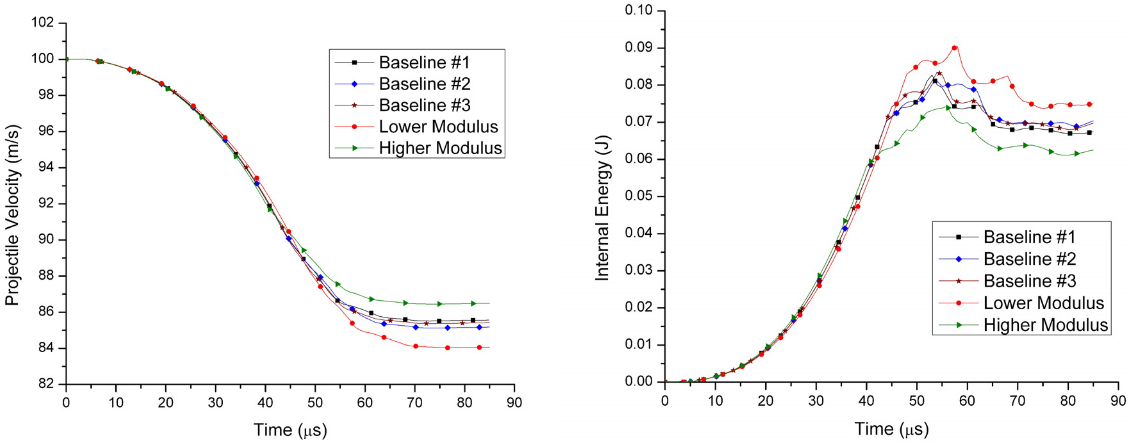
Consider the case of a 0.63 gm rigid spherical projectile impacting a 101.6 mm x 50.8 mm fabric at the center. The fabric is comprised of Kevlar KM2 yarns with areal density of 180 g/m^2. The material properties of the orthotropic yarn are chosen as follows: longitudinal elastic modulus ($E_{longitudinal}$) of 62 GPa, transverse elastic moduli ($E_{transverse}$) of 620 MPa, shear modulus (G) of 3280 MPa, zero Poisson ratios, density (ρ) of 1310 kg/m^3, and a maximum principal stress to failure of 3400 MPa. The yarns are modeled using single integration point solid elements and the projectile is modeled using fully integrated shell elements. A static frictional coefficient of 0.18 is specified for the yarn to yarn contact algorithms and 0.18 for the projectile to yarn contact algorithms While experimentally determining the longitudinal modulus of the Kevlar KM2 yarns, it is common for a scatter of up to 10% in the measured data for the modulus. In order to quantify this effect on the system response, viz. projectile velocity history and fabric internal energy history, two special baseline cases are run where the longitudinal modulus is varied by 10% about the mean while keeping the all other material properties including the failure stress constant, resulting in an $E_{longitudinal}$ of 55.8 GPa and 68.2 GPa respectively. Two case studies with differing boundary conditions have been studied (i) the fabric is gripped only on the two shorter sides and impacted at 200 m/s, and (ii) the fabric is gripped on all four sides and impacted at 100 m/s. Due to symmetry only one quarter of the fabric has been modeled. The FE model is created using the in-house preprocessor *DYNAFab* (see Appendix A).

Figures (6) and (7) display the projectile velocity history and fabric internal energy history responses of the baseline simulations for the two aforementioned cases. In the first baseline, contact between the yarns is specified using the keyword *CONTACT_AUTOMATIC_GENERAL*, in the second baseline, *CONTACT_AUTOMATIC_SURFACE_TO_SURFACE* has been used, while in the third baseline, the keyword *CONTACT_AUTOMATIC_SINGLE_SURFACE* has been used. An eroding type contact is used between the projectile and yarns. The first baseline uses a more robust contact algorithm which is computationally more expensive but ensures that two parallel yarns will not inter-penetrate since all yarn part definitions are placed in the slave definition. The special baseline cases with the lower and higher longitudinal elastic moduli provide a set of lower and upper limits within which the results obtained from the HEA models can be considered acceptable.



(a) *(b)*

Fig. 6. Fabric with two sides gripped and impacted at 200 m/s (a) projectile velocity history (b) fabric internal energy history



(a) *(b)*

Fig. 7. Fabric with four sides gripped and impacted at 100 m/s (a) projectile velocity history (b) fabric internal energy history

Two HEA models are set up to compare results against the baseline numerical models described before. For the HEA Central-Patch model, the dimensions of the central square patch with local yarn architecture modeled using solid elements are 9.64 mm x 9.64 mm. The outer dimensions of the surrounding rectangular patch with local yarn architecture modeled using shell elements are 47.6 mm x 29.4 mm. The ratio of total local area to the entire fabric area is 0.27 and ratio of total local area to total global area is 0.37. For the HEA Center-Cross model, the dimensions of the central square patch with local yarn architecture modeled using solid elements are 14.4 mm x

14.4 mm. The outer width of the cross with local yarn architecture modeled using shell elements is 14.4 mm and extends all the way to the fabric boundaries. The dimensions of each of the four disjoint homogenized regions are 43.6 mm x 18.20 mm. The ratio of total local area to the entire fabric area is 0.385 and ratio of total local area to total global area is 0.626. The global region parameters are determined using the approach outlined in an earlier section. Table (1) lists the material properties used in the multi-scale HEA models. A *Type-1* tie-constraint interface is used between the shells in the yarn and the shells in the far field homogenized region. A special in-house preprocessor *DYNA-HEA* (see Appendix A) is used to automatically create the FE mesh and all interface definitions of the HEA model.

Local region (Yarn architecture with Solids and Shells) Orthotropic Elastic				
$E_{longitudinal}$ **(MPa)**	$E_{transverse}$ **(MPa)**	ρ **(kg/m^3)**	**G (MPa)**	γ
62000	620	1310	3280	0.0

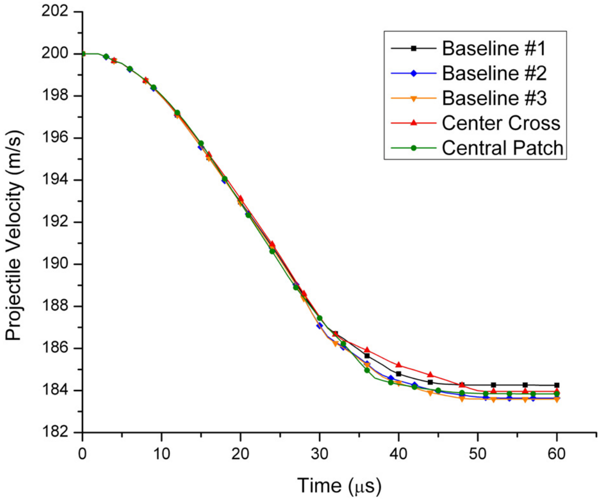
Maximum Principal Stress Failure Criterion ($\sigma_{failure}$)				
Two/Four sides held	**Two sides held**		**Four sides held**	
Baseline (MPa)	**Center Cross (MPa)**	**Central Patch (MPa)**	**Center Cross (MPa)**	**Central Patch (MPa)**
3400	3400	3400	3325	3450

Global region (Shells) Isotropic Elastic			**Global region (Shells) Orthotropic Elastic only for the Central-Patch case, with 2 sides held**			
E (MPa)	ρ **(kg/m^3)**	γ	**E (MPa)**	ρ **(kg/m^3)**	**G (MPa)**	γ
9008.61	745.04	0.0	9008.61	745.04	250	0.0

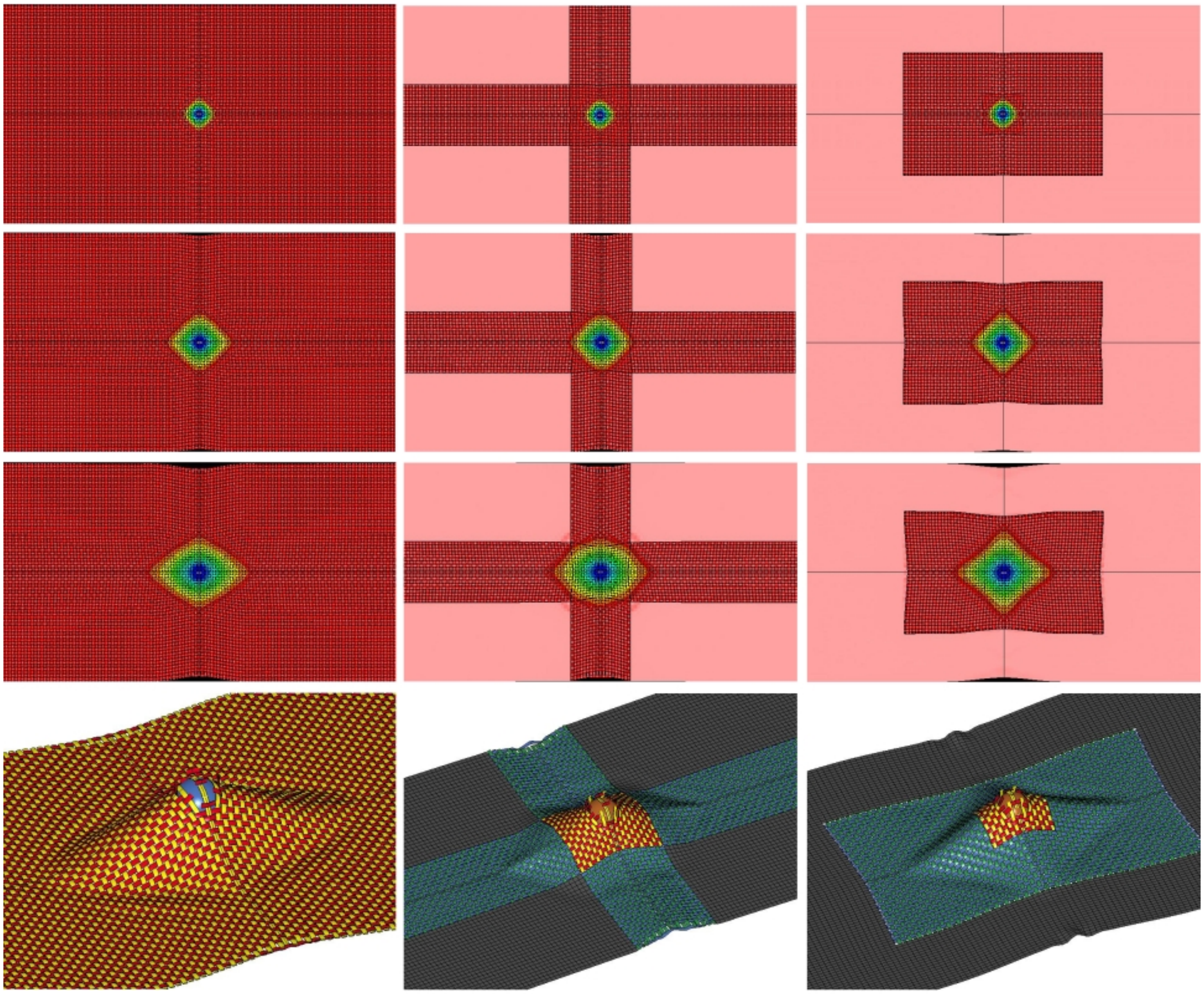
Table 1. Material properties of the local and global regions

The local region comprising the solid and shell element yarns use the material model *MAT_ORTHOTROPIC_ELASTIC*. The keyword used to set up the global region is *PART_COMPOSITE*. The material model used for the global region is *MAT_ELASTIC*. Only for the Central Patch HEA model with two sides held, the global region material model was switched to *MAT_ORTHOTROPIC_ELASTIC* with a lower shear modulus. The element formulation for the solid elements is *ELFORM 1* while for the shell elements it is *ELFORM 16* with two through thickness integration points. The tied interface between the solid and shell yarns is through the keyword *CONSTRAINED_SHELL_TO_SOLID*, while for the shell yarns to the shell global region, the keyword *CONSTRAINED_TIE-BREAK* is used.

Figures (8) and (9) compare the results between the baseline and HEA models. As can be seen from both cases, there is a very good agreement between the results. It is interesting to observe from the contour plots of the vertical displacement that the sides of the deformation pyramid are straight for the baselines, while they are slightly concave for the Center-Cross HEA and slightly convex for the Central-Patch HEA models in both case studies. This is a direct result of slightly constraining the relative sliding motion of the yarns in the far field regions of the fabric due to the homogenizing assumption of the global region. This also made it necessary to reduce the in plane shear modulus of the global region for the Central-Patch HEA model that was gripped on two ends. For this model we also can observe the two shell warp yarns at the free ends separating from the shell fill yarns that have free ends, as they get pulled inwards. While this makes no significant difference to the overall response, it can be avoided by making the size of the central cross with local yarns bigger, but at the cost of computational expense. In a future study, the authors will investigate the effect the relative size of the local region to global region has on the response, as well as the relative amount of shell to solid yarns within the local region, by which the optimal configuration of the HEA model can be determined. This will result in the maximum computational efficiency while still maintaining the accuracy of the model predictions. By comparing the projectile velocity response of the HEA models to the baseline models, we see a very good agreement and that they lie within the bounds set by the special baseline cases with varying elastic moduli.

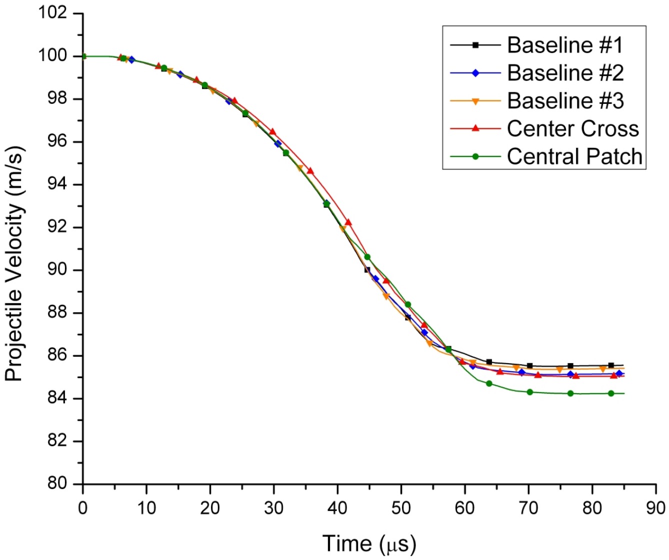


(a)

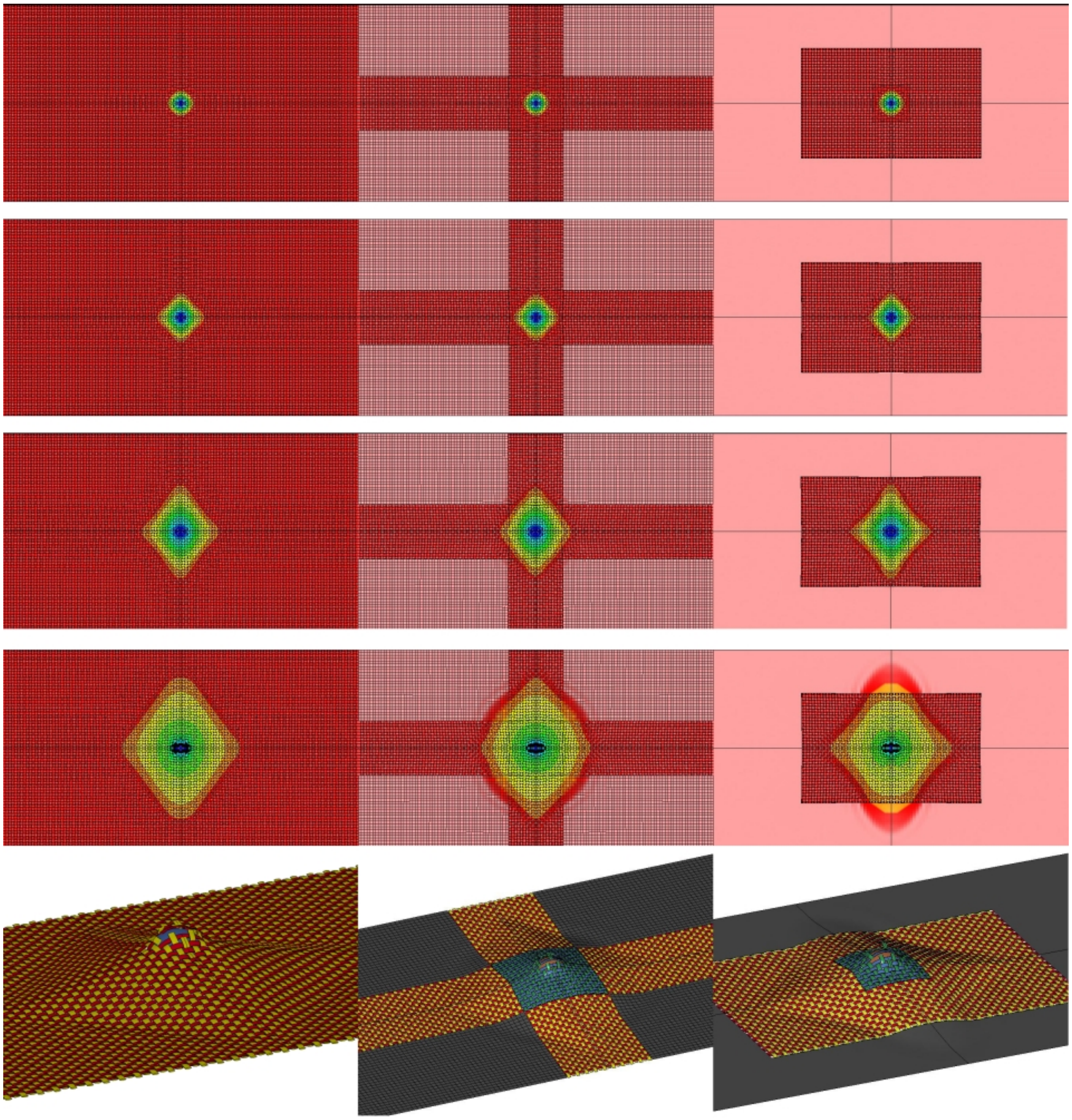


(b)

Fig. 8. Fabric with two sides gripped and impacted at 200 m/s (a) projectile velocity history (b) deformation profiles at the time instants of (row 1) 10 µs, (row 2) 20 µs, (row 3) 30 µs, and (row 4) 40 µs


Projectile Velocity (m/s)
102
100
98
96
94
92
90
88
86
84
82
80
0
10
20
30
40
50
60
70
80
90
Time (μs)
Baseline #1
Baseline #2
Baseline #3
Center Cross
Central Patch

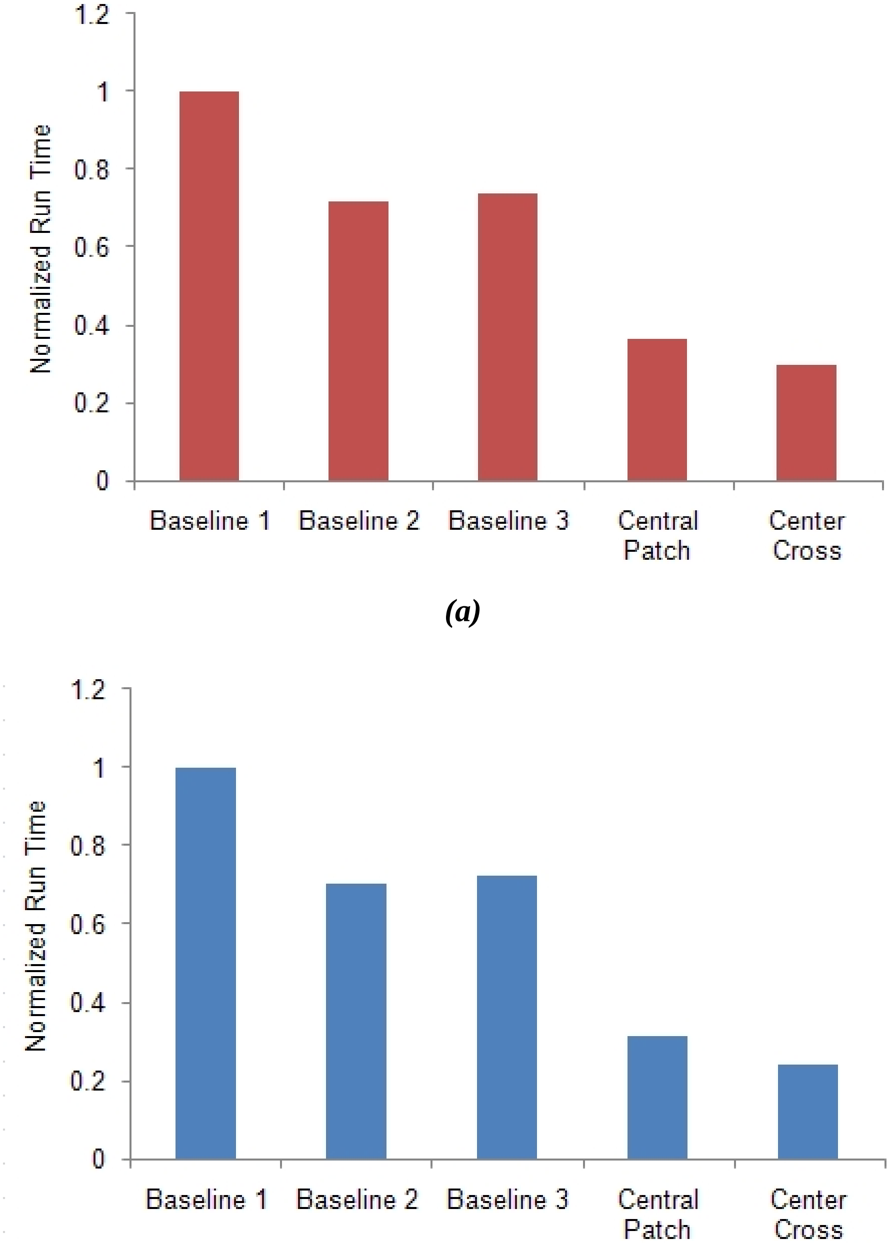
(a)



(b)

Fig. 9. Fabric with four sides gripped and impacted at 100 m/s (a) projectile velocity history (b) deformation profiles at the time instants of (row 1) 15 µs, (row 2) 25 µs, (row 3) 40 µs, (row 4) 60 µs, and (row 5) 55 µs

Figure (10) compares the run times for both cases. The simulations were run using LSDYNA SMP Version 971 on a 64-bit Dell Precision 690 Workstation with four Intel Xeon 3.00 GHz processors. The Center-Cross HEA approach was about 4 times faster than the first baseline. Even when using a computationally cheaper contact algorithm for the baseline, the Center-Cross HEA was still 3 times faster. The Central-Patch HEA model was about 3 times faster than the first baseline. This large savings in computational expense while still reproducing the accuracy of the baseline simulations demonstrates the usefulness of the HEA approach. As the dimensions of the model and the simulation termination time increase, these savings become even larger. Further, if the relative size of the local to global region is reduced and a coarser mesh is used for the global region, further savings in computational expense can be realized and this will be investigated in future work.



(a)

(b)

Fig. 10. Simulation run times (a) fabric gripped on two sides and impacted at 200 m/s (b) fabric gripped on four sides and impacted at 100 m/s

9. Conclusions

A novel approach, the Hybrid Element Analysis, was presented that incorporated using different finite element formulations at both single and multiple levels of modeling for simulating the impact of textile composites. A consistent approach to determining the global region material parameters was presented that eliminates the need to run time consuming trial-and-error simulations. A suite of in-house FE preprocessors, *DYNAYarn* and *DYNAFab*, were presented, that are capable of rapidly setting up models of yarns and fabrics for FE simulations. This allows for rapidly setting up models to study architectural effects, mesh sensitivity, and parametric effects of material properties on the fabric response. The manual method of creating the interface definitions between the local and global regions with shell elements is very demanding and time consuming, however the preprocessor *DYNA-HEA* automates the entire procedure.

The HEA approach was able to accurately reproduce the baseline simulation results but at a fraction of the computational expense, proving it to be an invaluable tool in the modeling and simulation of the impact of fabric systems. Initial results from our research have shown to be very promising. Through this novel approach, it is envisioned that realistic dimensions of multi-layer fabric panels could be accurately simulated within the framework of currently available computational resources.

10. Acknowledgements

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Appendix A

Automated Finite Element Modeling of Plain Weave Textile Structures using a Preprocessor: *DYNAYarn, DYNAFab, DYNA-HEA*

The yarn centerline equation for a plain weave balanced fabric is given as

$$y = \left(\frac{t}{2}\right)\cos\left(\frac{\pi x}{s}\right) \tag{B.1}$$

where the yarn thickness '*t*' is along the y-direction and the length is along the x-direction. The span '*s*' is governed by the tightness of the weave. The use of the cosine trigonometric function is interchangeable with the sine function depending on the starting position of the yarn.

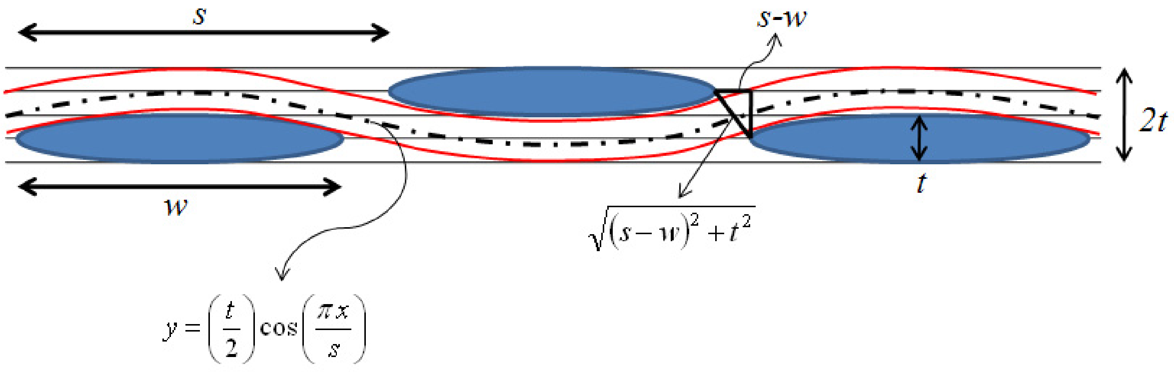


Fig. B1. Schematic of the balanced plain weave fabric geometry

The equation defining the elliptical cross sectional shape of the yarn is also given by the centerline equation. This ensures that the surfaces of orthogonal yarns are just touching each other without any initial penetrations, which is a very important requirement of the FE model. The user inputs data into an easy to use graphical user interface (GUI) which acts as a front end to the preprocessor. The input data to the preprocessor consists of the fabric length (l) and breadth (b), and for each set of warp and fill yarns: yarn width (w), thickness (t), span (s), and desired mesh density (n_w, n_t, n_l), where the subscripts stand for width, thickness, and length respectively. The algorithm of the preprocessor for creating a fabric model with yarn level architecture is shown below. The preprocessor is coded using the high level language MATLAB®. Three versions of the preprocessor are available: *DYNAYarn* is capable of modeling straight and crimped yarns with solid and shell elements; *DYNAFab* is capable of modeling balanced plain weave fabrics with yarn level architecture using solid elements; and *DYNA-HEA* is capable of creating the Central-Patch and Center-Cross multi-scale models including all the tied interface definitions. A screenshot of the front-end GUI for *DYNA-HEA* is also shown below.

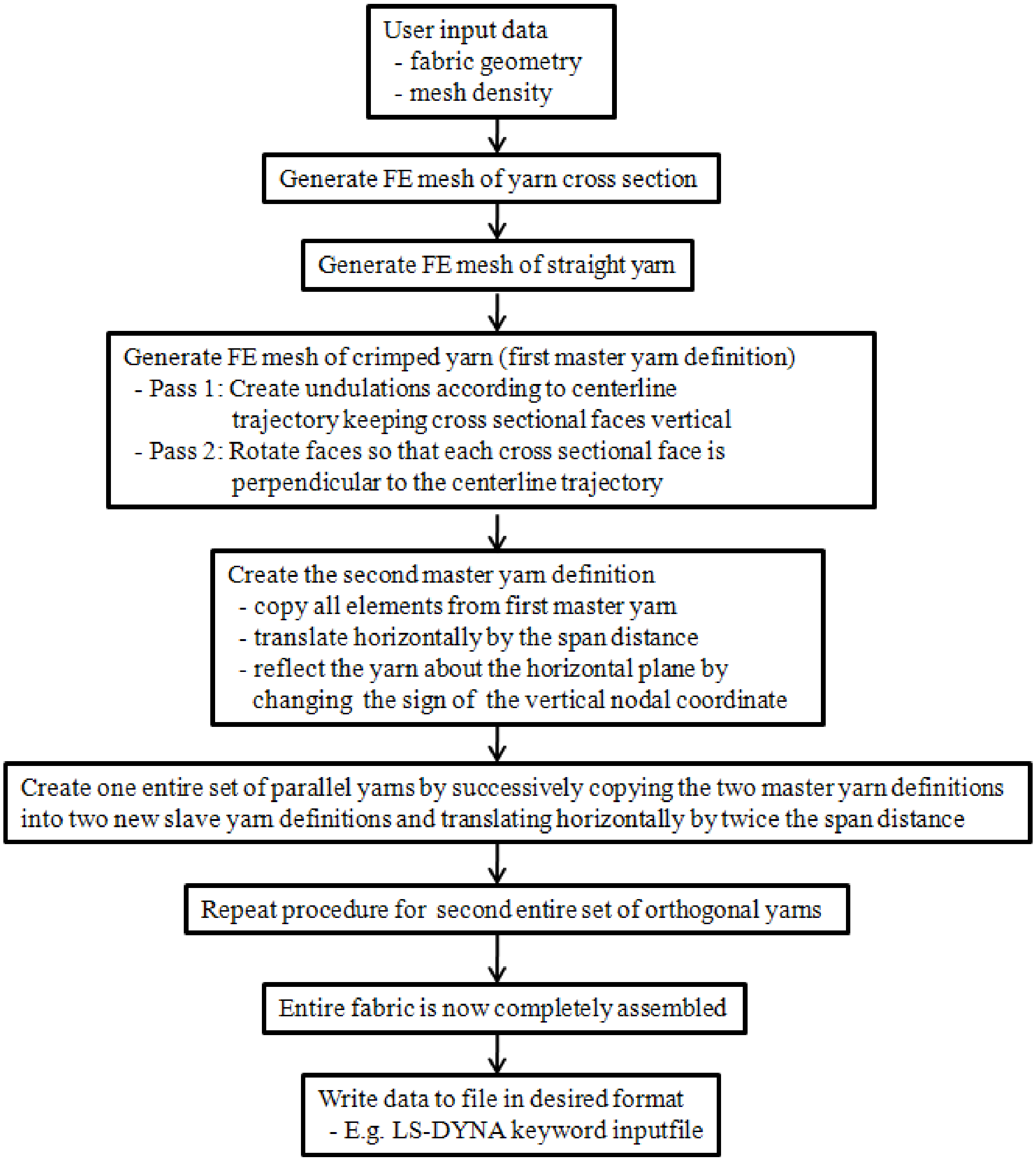
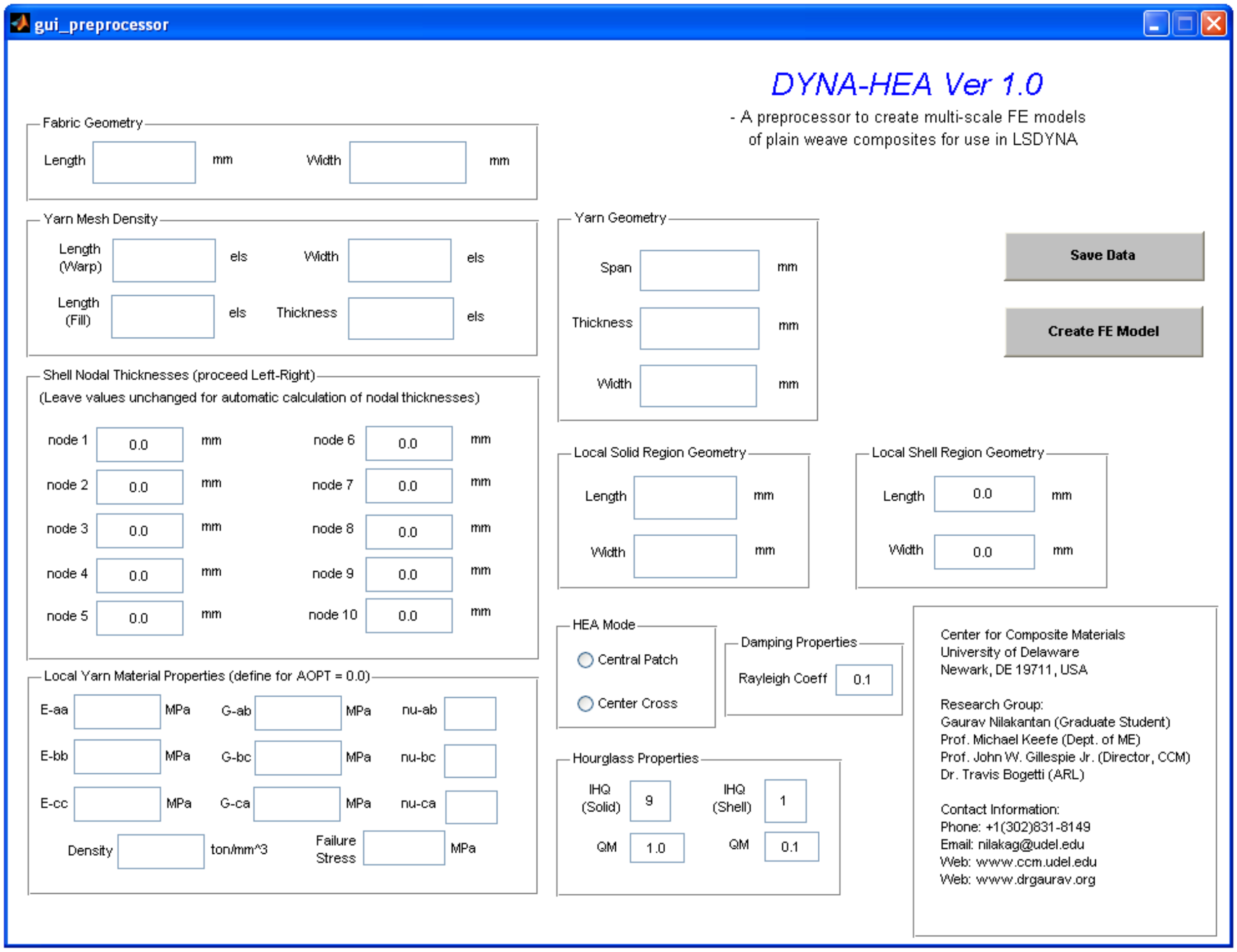


Fig. B2. Flow chart of the preprocessor algorithm for DYNAFab



DYNA-HEA Ver 1.0

- A preprocessor to create multi-scale FE models
of plain weave composites for use in LSDYNA

Fabric Geometry
Length mm Width mm

Yarn Mesh Density
Length (Warp) els Width els
Length (Fill) els Thickness els

Shell Nodal Thicknesses (proceed Left-Right)
(Leave values unchanged for automatic calculation of nodal thicknesses)
node 1 0.0 mm node 6 0.0 mm
node 2 0.0 mm node 7 0.0 mm
node 3 0.0 mm node 8 0.0 mm
node 4 0.0 mm node 9 0.0 mm
node 5 0.0 mm node 10 0.0 mm

Local Yarn Material Properties (define for AOPT = 0.0)
E-aa MPa G-ab MPa nu-ab
E-bb MPa G-bc MPa nu-bc
E-cc MPa G-ca MPa nu-ca
Density ton/mm^3 Failure Stress MPa

Yarn Geometry
Span mm
Thickness mm
Width mm

Local Solid Region Geometry
Length mm
Width mm

Local Shell Region Geometry
Length 0.0 mm
Width 0.0 mm

HEA Mode
○ Central Patch
○ Center Cross

Damping Properties
Rayleigh Coeff 0.1

Hourglass Properties
IHQ (Solid) 9 IHQ (Shell) 1
QM 1.0 QM 0.1

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Fig. B3. Screenshot of the preprocessor DYNA-HEA

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