NUMERICAL MODELING OF DYNAMIC RESPONSE OF FABRIC MATERIALS SUBJECTED TO IMPACT LOADING

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Abstract

The present work investigates the dynamic response of fabric materials subjected to impact loading. The major purpose of study is the implementation, calibration and validation of meso-scale approach and material model for fabrics modeling in order to predict their dynamic response accurately. Furthermore, the current research targets to access which of the examined para-aramid fabrics is the best in terms of energy absorption and to rank, from the analysis view, the parameters which influence the fabric behavior. It was found that the yarn level modeling technique is capable of capturing accurately both the dynamic response of fabrics and the main energy redistribution mechanisms of the impact energy. The analytical results showed that yarn-strain energy is the main energy carrying mechanism, the kinetic energy represents an additional significant mechanism whereas the frictional energy is ranged from 2% to 8.2% of overall transfered energy. Moreover, the parameters sensitivity analysis of yarn material model revealed that the elastic modulus in yarn direction constitutes the most important factor on fabric deformation. The results of current study can serve as reference guide for the prediction of dynamic response of textile structures subjected to impact loading and promote the minimization of required number of experimental runs.

1. Introduction

Various threats have become a growing problem all over the world, therefore the protection of people and structures is essential. The para-aramid fabric materials are widely-known for their application in blast and ballistic protection [1]. They are often used in protection systems, such as body armor, combat helmet, vehicle armor and security aircraft systems, to resist high-velocity penetration. All these protection systems should be designed properly in order to ensure the safety of people and the integrity of structures. Therefore, the important issue here is the effective design of textile systems which should be capable of absorbing the maximum possible energy against ballistic impact. The above prerequisite and the continuing effort to reduce the cost of experimental campaigns have motivated the researchers to further elaboration using computational-based engineering analyses.

Several numerical studies concerning the dynamic response of fabric materials subjected to impact loading have been conducted. M.Grujicic et al. [2] have investigated the fabric deformation and fracture behavior under different combinations of fixed and free boundary conditions. G.Nilakantan et al. [3] have carried a study about the woven fabric impact using multi-scale modeling techniques. D.Zheng et al. [4] have investigated the friction effects of single ply tri-axial braided fabric on ballistic impact. It was concluded that frictional effects play an important role in the energy absorption of fabrics. Y.Duan et al. [5] have also conducted a study about the frictional effects on the ballistic

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impact behavior of a single-ply high-strength fabric. They inferred that the fabric with high friction absorbs more energy than the fabric with no friction. However, a complete study of calibration and validation of yarn-level modeling technique and yarn material model with experimental tensile tests and high velocity impact tests is missing from the literature. Also, the sensitivity analysis of model's parameters and the comparison between different fabric configurations are still limited.

In the present work, an extensive investigation of response of plain weave fabrics and tri-axial braided fabrics using explicit finite element analysis was executed and correlated with experimental quasi-static tensile tests and high-velocity impact tests. In particular, it was attempted to implement yarn level modeling techniques, to calibrate the material model's parameters which are required for fabric material characterization, to correlate the experimental and numerical absorbed energy for failure criterion calibration and finally to compare the different fabric configurations.

2. Methodology

In order to evaluate the impact behavior of each fabric accurately, the presented methodology of Figure 1 has been followed. Three calibration steps for material characterization and one verification step of numerical model were required. In the first step, an optimization algorithm using Mode Frontier suite was designed to determine the best combination of model's parameters in order to fit the experimental tensile load-strain curve with the corresponding numerical curve. The above approach of problem was emerged by the fact that the use of typical yarn properties (Table 1) did not provide reasonable results during the initial effort to predict the amount of absorbed energy without the calibration of material model. The second step was similar to the first one but the fitting of experimental and numerical fabric deformation values was the target of algorithm. Whereas the third step addressed the yarn failure stress calibration taking into account the experimental pre-impact and after-impact velocity of projectile. In final step, a comparison procedure between experimental and numerical residual velocity of projectile was used as a verification criterion of numerical code and material model. This methodology was individually applied for each of the used fabric materials.

3. Materials

Two plain weave para-aramid type A fabrics with areal density 200 gr/m^2 and 400 gr/m^2 respectively, one tri-axial para-aramid type A fabric with areal density 200 gr/m^2 and two tri-axial braided para-aramid type B fabrics with areal density 200 gr/m^2 and 260 gr/m^2 supplied by Triaxial Structures,Inc. were investigated. The geometry and material properties of fabrics are described in Table 1.

4. Experiments

4.1 Tensile tests

A typical testing machine was used for fabrics characterization to quasi-static loading. In particular, the standard EN ISO 13934-1, which is valid for textiles, was followed. The procedure of standard is capable of defining the maximum force and elongation at maximum force using strip method. According to the standard, this method is applicable to both woven fabrics and fabrics produced by other techniques. In strip method, the full width of the test specimen is gripped in the jaws of the testing machine. The specimen was extended at a constant rate 100 mm/min until its rupture. The specimen length and width was 200 and 50 mm respectively, whereas two test specimens were tested for each material configuration. The Figure 2 presents the testing machine.

4.2 Impact tests

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Three impact runs were conducted during the present research. The target of first impact run was the measurement of plasteline footprint to the rear of impacted fabric when the projectile velocity (37.5 m/sec) is not enough to cause fabric penetration.

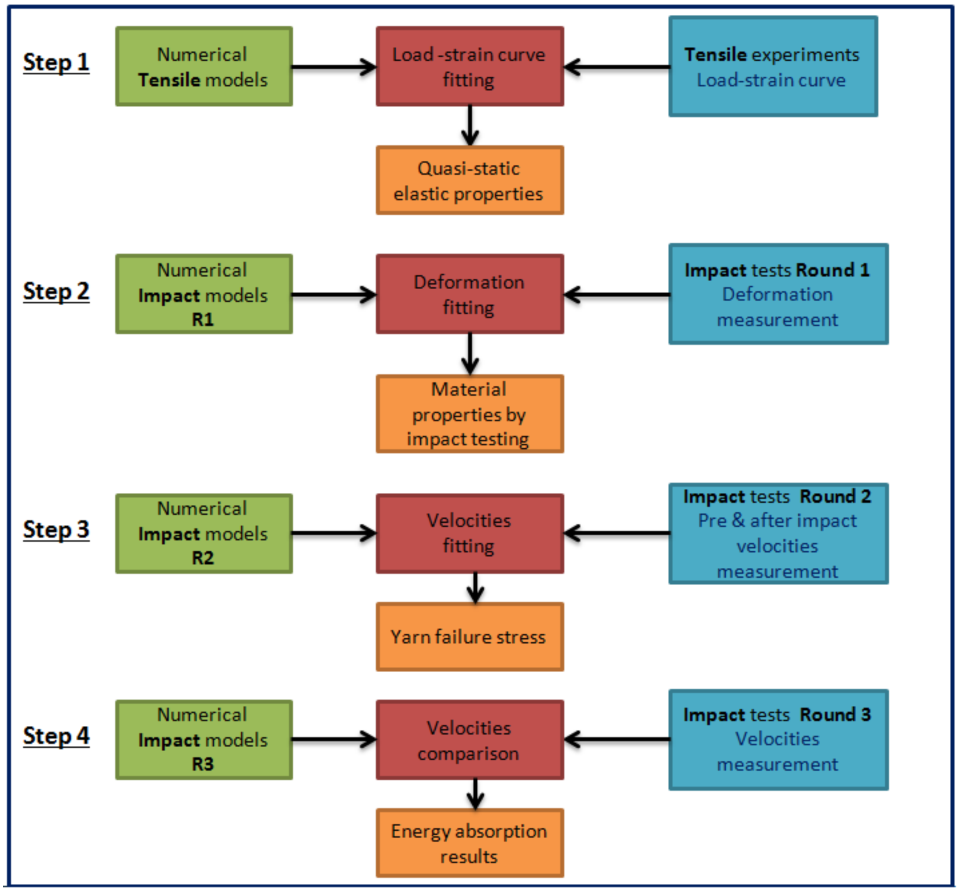

Figure 1. Methodology diagram.

Table 1. Geometry and typical physical properties of fabrics.

Fabric Architecture	Areal density (gr/m^2)	Yarn width (mm)	Yarn thickness (mm)	Distance between yarns (mm)	Fiber material	Tensile Modulus (GPa)	Elongation at break (%)
Plain Weave	200	1	0.1	0.05	Para-aramid type A	70.5	3.6
	400	1.5	0.2	0.05			
Tri-axial Braided	200	0.92	0.2	1.8			
	200	0.92	0.2	1.8	type B	91.0	3.45
	260	0.92	0.2	0.42			

The goal of second and third run was the velocity recording during the event. In particular, air-gun apparatus was used for the impact testing of fabrics in all cases. The steel projectile was selected to be spherical with diameter 12.7 mm and 8.4 grams mass.

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Figure 2. Tensile testing machine.

The impact test specimens were chosen to be of circular geometry, having a diameter of 150 mm. In order to measure the projectile velocity before and after impact accurately, a high-speed camera Fastcam SA4 manufactured by Photron was installed at 1300 mm far away from the trajectory. The camera's lens was located at 900 mm height from the ground, which corresponds to the height value of projectile track. The high-speed camera recorded the event at rate 120,000 frames per second. A dimensional grid was placed behind the trajectory as reference for the position of the projectile. Figure 4 shows the air-gun apparatus and its fixture for the test sample placement.

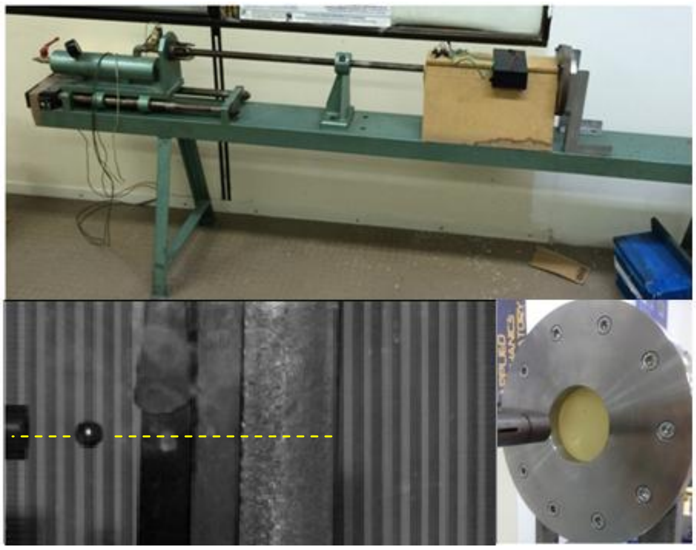

Figure 3. Air-gun apparatus, tubular fixture and sphere trajectory.

5. Numerical modeling

The finite element modeling of fabrics was performed utilizing the LS-DYNA code. Yarn level modeling technique was adopted for tensile and impact cases as it approaches the real weave architecture of fabric perfectly. Therefore both the projectile-yarn and yarn-yarn level interactions were captured. After the vital mesh sensitivity analysis, six shell elements with variable thickness were applied through the yarn width whereas eight elements modeled the unit representative yarn length. In case of impact modeling, the tri-axial fabrics were modeled thoroughly as they do not show clear-cut

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geometrical symmetries in contrast to plain weave fabrics. On the grounds of computational time, in case of plain weave fabrics, only one quarter of coupon geometry has been modeled, once no discrepancies were found with full model (Fig.5).

The yarns making up both plain weave and tri-axial fabrics have much less stiffness in all other directions except for the fiber directions. Therefore, the transverse moduli Ey and Ez and shear moduli Gxy, Gxz, Gyz are small compared the modulus in fiber direction (Ex), whereas the Poisson's ratios were set equal to zero as no interaction between normal and transverse moduli exist in a yarn. The failure of yarn was implemented using the tensile strength in fiber direction (x-axis). The above stiffness and failure parameters of material model together with coefficients of friction are set as variables in optimization algorithms. The numerical models of plain weave architecture for tensile and impact cases are shown in below figures (Fig.4-5).

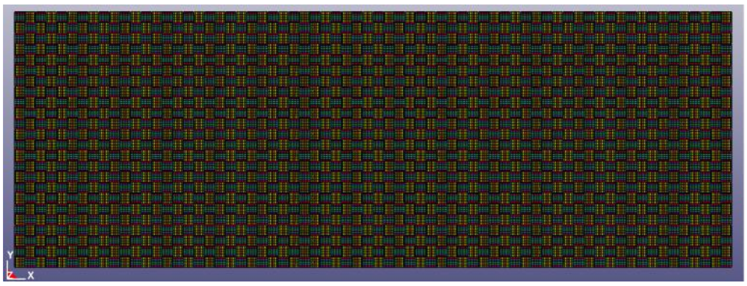

Figure 4. Tensile model of 200 gr/m^2 plain weave fabric.

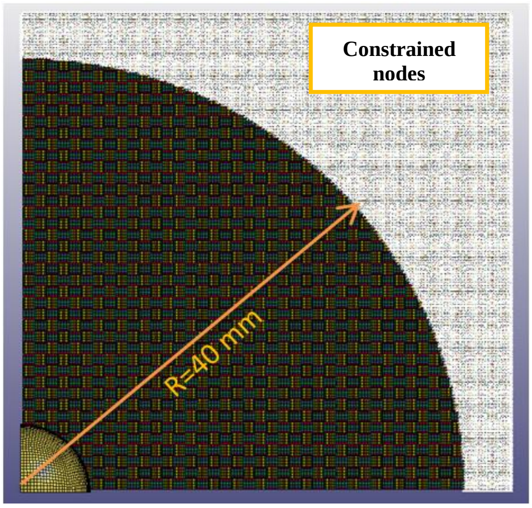

Figure 5. One quarter of impact model of 200 gr/m^2 plain weave fabric.

6. Results - Discussion

6.1 Model's parameters by experimental and numerical load-strain curve fitting (step 1)

In step 1, the experimental and numerical load-strain curves were fitted. The combination of model's parameters for each fabric material, when the maximum error between the two curves is minimized, is presented in Table 2. Comparing the table's values, the below conclusions are drawn:

- The elastic modulus in x direction is significantly higher than the other stiffness parameters.

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- The modulus in fiber direction was being expected not to vary in fabrics with same material type.
- The elastic modulus in x direction of plain weave fabric 200 gr/m^2 and tri-axial 200 gr/m^2 (Type A) are in line, whereas the x-axis modulus of other fabrics is lower.

It is inferred that the implementation of curve fitting method was vital for the definition of material model's parameters as the initial effort using the typical physical properties of yarns (Table 1) was proved unsuccessful.

Table 2. Model's parameters combination for each fabric derived by tensile testing.

Fabric Type	Material (para-aramid)	Friction coefficient	Ex (GPa)	Ey, Ez (GPa)	Gxy (GPa)	Gxz, Gyz (GPa)
Plain weave 200	Type A	0.5	50.0	1.0	0.1	1.0
Plain weave 400	Type A	0.5	35.0	1.0	0.1	1.0
Tri-axial 200	Type A	0.5	50.0	1.0	0.1	1.0
Tri-axial 200	Type B	0.5	45.0	1.0	1.0	1.0
Tri-axial 260	Type B	0.5	28.0	1.0	1.0	1.0

6.2 Model's parameters by experimental and numerical deformation comparison (step 2)

As mentioned above, the second algorithm correlates the experimental and numerical deformation of fabric when subjected to 5.9 J impact loading (37.5m/sec) keeping the x-axis modulus constant and varying the other moduli. The results of comparison proved that the elastic and shear moduli as well as the friction coefficient are in line with the values which emerged by the tensile load-strain curve fitting. Therefore, the values of Table 2 are capable of describing the dynamic behavior of fabrics. The experimental and numerical deformations for each fabric are presented in Figure 6. The maximum discrepancy between numerical and experimental value is observed in tri-axial braided para-aramid type B fabric with areal density 200 gr/m^2 and it is close to 9.2 %. By parameters sensitivity analysis, it was provided that the model's highest sensitivity parameter is elastic modulus of yarn material in x-direction (fiber). The second important factor was showed to be the friction coefficient between yarn and yarn, whereas the influence of moduli in other directions and friction coefficient between projectile and yarn on fabric deformation is negligible. For instance, a 22% increase in elastic modulus in x-direction implies a decrease of 3.26% in fabric deformation.

6.3 Yarn failure strength (step 3)

The table 3 shows the yarn failure strength in MPa which was calculated in step 3 of the study. It is observed that not only the elastic modulus in x-axis but also the yarn failure strength changes to fabrics with same material type due to the filaments misalignment by manufacturing. This conclusion reveals the necessity of yarn failure calibration. If the failure strength value had been assumed constant in different fabrics in terms of geometry while they have been produced by the same material type, again the numerical estimation of energy absorption would be misguided.

6.4 Comparison of experimental and numerical energy absorption (Impact loading 23.62J)

In final step of current investigation, a comparison between numerical and experimental results in terms of absorbed energy was conducted in order to check the validity of numerical approach. The numerical energy absorption results are showed to estimate accurately the experimental values in cases of fabrics with yarn material type A (PW400-A, PW200-A, TR200-A) in contrast to fabrics with type B (TR200-B, TR260-B). This discrepancy may be observed due to the fact that the material model is

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not capable of incorporating the effect of strain rates by modifying the appropriate strength parameter during impact. Additionally, in figure 8, the main absorbing mechanism of the impact energy is clearly shown to be the yarn strain energy whereas the sliding energy is the minor mechanism. The first mechanism value is close to 62-75% and the second one is ranged from 2% to 8.2% of overall absorbed energy. Furthermore, it is concluded that the plain weave fabric with areal density 400 gr/m^2 presents the higher absorbed energy for 75 m/sec impact loading in relation to other fabric configurations, whereas the 260 gr/m^2 tri-axial braided fabric is the second in ranking.

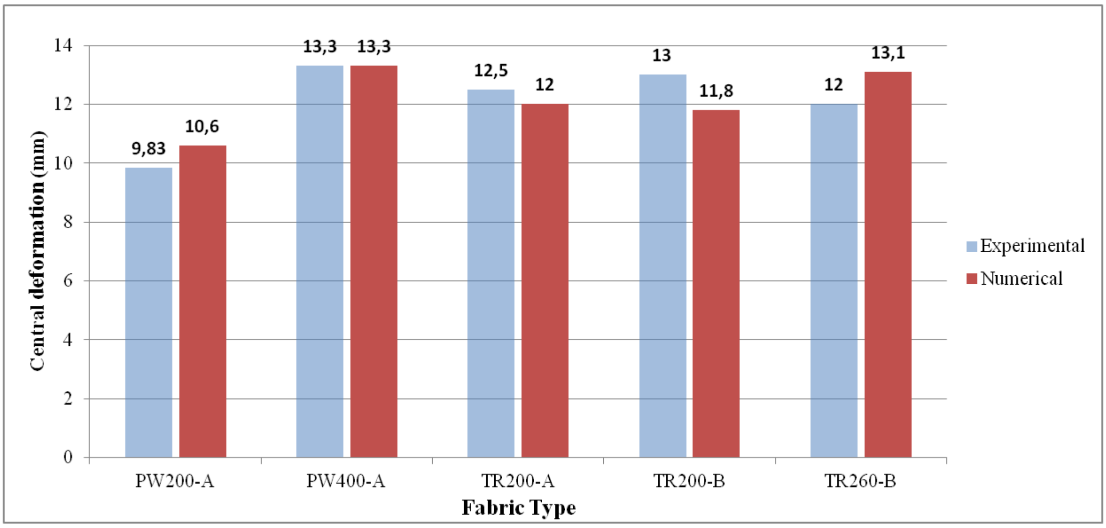

Figure 6. Experimental and numerical deformation of fabrics (37.5 m/sec projectile velocity or 5.9J).

Table 3. Yarn failure strength for each fabric material (60 m/sec projectile velocity or 14.8J).

Fabric Type	PW400-A	PW200-A	TR200-A	TR200-B	TR260-B
Yarn failure strength (MPa)	4250	4750	4750	4200	3500

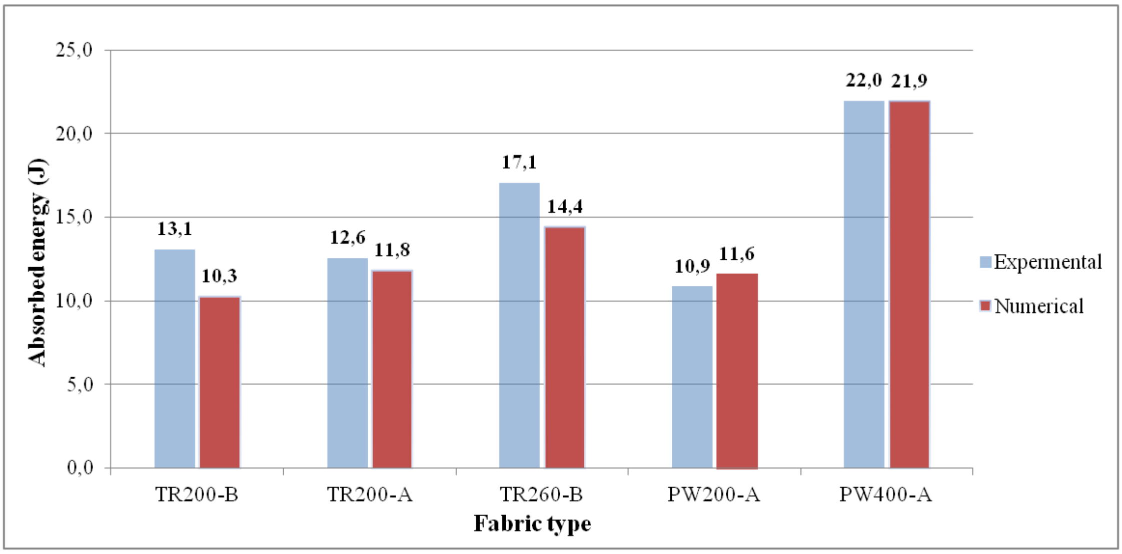

Figure 7. Experimental and numerical energy absorption (75 m/sec projectile velocity or 23.6 J).

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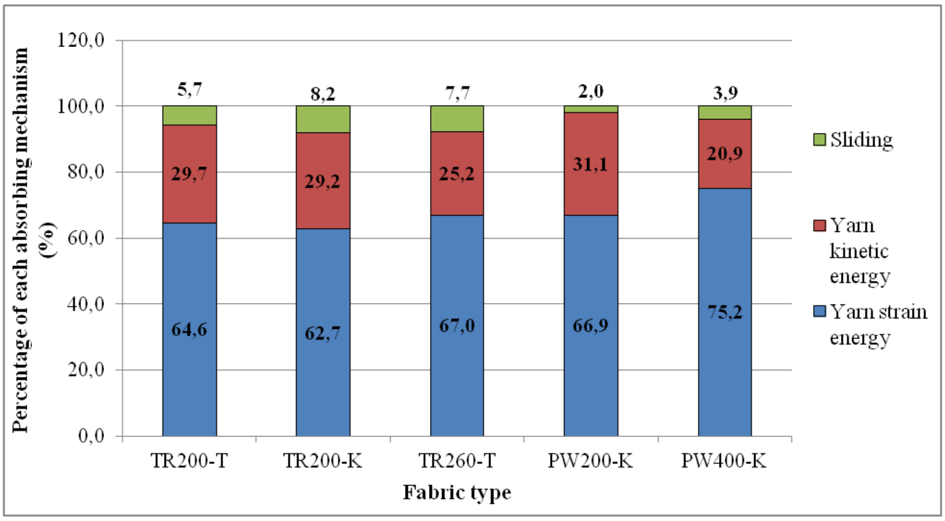

Figure 8. Different absorbing mechanisms (Case of 75 m/sec projectile velocity).

7. Conclusions

By the results comparison, it was proved that the numerical modeling approach has the capacity to predict to a great extent both dynamic response and overall energy absorption of fabrics materials subjected to impact loading. Therefore, this technique and results can serve as reference guide for the prediction of fabrics dynamic response in structure level. For future work, additional experimental tests could be performed to evaluate the efficiency of modeling technique to higher velocity impacts.

Acknowledgments

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References

[1] L.Wang , S. Kanesalingam, R. Nayak, and R. Padhye. Recent trends in Ballistic Protection. *Textiles and Light Industrial Science and Technology*, Vol. 3, 2014.

[2] M. Grujicic, W.C. Bell, G. Arakere, and T. He. A meso scale unit-cell material model for the single-ply flexible-fabric armor. *Journal of Materials and Design*, 30:3690-3704, 2009.

[3] G. Nilakantan, M. Keefe, T. A. Bogetti, R. Adkinson, and J. W. Gillespie. On the finite element analysis of woven fabric impact using multi-scale modeling techniques. *International Journal of Solid and Structures*, 47:2300-2315, 2010.

[4] D.Zheng, W. Binienda, J. Cheng, and M. Staniszewski. Numerical modeling of friction effects on the ballistic impact response of single-ply tri-axial braided fabric. *Proceedings of the 9th International LS-DYNA Users Conference, Manchester, UK*, June 2-4 2013.

[5] Y. Dyan, M. Keefe, T.A. Bogetti, and B.A. Cheeseman. Modeling friction effects on the ballistic impact behavior of a single-ply high-strength fabric. *International Journal of Impact Engineering*, 31:996-1012, 2005.

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