Proceedings of the Canadian Society for Mechanical Engineering International Congress 2022
CSME Congress 2022
June 5-8, 2022, Edmonton, AB, Canada

Numerical Simulation of Ballistic Impact of 20 mm Fragment Simulating Projectiles (FSPs) into Ultra-High Molecular Weight Polyethylene (UHMW-PE) Targets

Kshitiz Khanna[1], Morten Rikard Jensen[2]
[1]CertaSIM CANADA ULC, Toronto, ON, Canada
[2]CertaSIM, LLC, Saratoga, CA, USA

Abstract— Composite materials are widely used in the defense and aerospace industry because of their light weight and high strength properties. Ultra-high molecular weight polyethylene (UHMW-PE) is commonly used in the design of various types of armor from vehicle applications to personal protective clothing. Understanding the ballistic characteristics of this material is essential to designing safe armor systems. A numerical analysis of the ballistic impact of fragment simulating projectiles (FSPs) on UHMW-PE is presented in this paper using the IMPETUS Afea Solver Suite. The material model for UHMW-PE under high strain rates has not been discussed in the available literature. In this study, the IMPETUS fabric material model is used to define the UHMW-PE properties, along with a cohesive failure criteria to capture delamination. Several simulations were conducted with projectile impact velocities ranging from 464 m/sec to 1058 m/sec, and thickness variations of UHMW-PE of 10 mm, 20 mm, and 36.2 mm. The numerical results, which include ballistic limit and residual velocity, are verified against experimental data present in the literature. The collective findings can be applied to future work to accelerate the design process by minimizing the time and cost of performing experiments.

Keywords: Fragment Simulating Projectiles; Ultra-High Molecular Weight Polyethylene; Numerical Analysis; Terminal Ballistics; The IMPETUS Afea Solver®

I. INTRODUCTION

The danger to our warfighters from ballistic weaponry is and will be an ongoing concern for the future. The use of high-strength and lightweight armor keeps them safe from these advanced threats. Various materials are available, but Ultra-high molecular weight polyethylene (UHMW-PE) fiber is the world's strongest fiber. It is also known as Dyneema®, and DSM commercially develops it [1]. Dyneema® has various applications but is not limited to protective armor such as soft armor, hard armor, helmets.

Experimental work that investigates ballistic impact of threats on ultra-high molecular weight polyethylene (UHMW-PE) has been performed [2], [3]. A wide array of experiments was published by Nguyen et al. [2] in which 10 mm and 20 mm fragment simulating projectiles (FSPs) are shot at the various thicknesses of UHMW-PE plates. Reddy et al. [3] conducted experimental ballistic research with hybrid composites with variable carbon percentage composites (C100, C75, C50, C25, D100). These composites were prepared with carbon/epoxy and Dyneema® laminates. However, experiments are expensive and time consuming and the cost is increased by the process required to create the composite panels. As with all engineering applications today, simulation is the key to reducing experiment and development cost.

The material properties of UHMW-PE are characterized as a continuum non-linear orthotropic model, and this assumption is validated for thin composite (~15 mm) plates under hypervelocity impact application [4][5]. Nguyen et al. [6] proposed a model of Dyneema® composites with a continuum non-linear orthotropic model and an erosion model that takes care of directional dependent failure. This study validates the numerical results of thick composites against the experimental work performed by Nguyen et al. [2].

To determine the protection level of armored vehicles for KE and artillery shell fragments, the threats to be considered are small and medium caliber projectiles, fragment simulating projectiles. The common fragment simulator used by NATO is the fragment simulating projectile (FSP). The acceptance procedure is defined in [7].

In this paper, a reinforced composite model is applied for Dyneema® with fibers that can be defined in different directions. The interlaminar failure is defined by a failure stress criterion. The in-plane compressive stiffness in the fiber direction and the out-of-plane non-linear compressive stiffness are used in thickness direction. The FSPs are modeled with a Johnson-Cook strength model. The model is validated against the experimental work conducted and published by Nguyen et al. [2]. The 20 mm FSPs are impacted on UHMW-PE plates of

10 mm and 20 mm thickness, and the ballistic limit and residual velocities are validated. The base for the presented work is the documentation published in [8].

II. NUMENERICAL MODELING OF BALLISTIC IMPACT

The numerical model was developed in The IMPETUS Afea Solver®. It is a general purpose Non-linear Explicit Transient Dynamic Finite Element Package. The material models used in this study for FSP and UHMW-PE, and the detailed numerical model setup information are provided in this section.

A. Fragment Simulating Projectiles (FSP) Material Model

The material of FSP is steel, grade 4340, and the material model of the FSP is considered as the Johnson-cook model. The details of the material model, along with von Mises flow stress equation are given in [9]. The calibration is performed by IMPETUS [10]. Strain rate and thermal softening parameters are also included in the model.

The detailed material properties for UHMW-PE are presented in Table I.

TABLE I. FSPs MATERIAL PROPERTIES [10]

Parameter	***Values***	***Units***
Density	7837.9	Kg/m3
Young’s modulus	207	GPa
Poisson’s ratio	0.33	-
Initial yield strength, A	1.03	GPa
Hardening parameter, B	0.477	GPa
Hardening parameter, n	0.18	-
Strain rate hardening parameter, C	0.012	-
Thermal softening parameter, m	1.0	-
Ambient temperature	293	K
Melting temperature	1763	K
Strain rate parameter	1.0	-
Heat Capacity	477	J/K

B. Ultra-High Molecular Weight Polyethylene (UHMW-PE) Material Model

UHMW-PE is modeled as the composite consists of unidirectional sheets cross plied at 90° to each other. The constitutive model includes fiber stress, damage and failure which is computed individually for each fiber direction. The details of the material model are given in [10]. It also includes stress-based failure criteria between layers. The density of the composite is 980 kg/m3. SK76 yarns are used to manufacture the composite. The tensile strength and failure strain are considered as 3.6 GPa and 3.7% respectively [11]. The young modulus of 500 MPa and yield limit of 20 MPa is assumed. The interlaminar tensile failure stress and shear failure stress is considered as 5.35 MPa and 7.85 MPa respectively [6]. The detailed calibration documentation of the model is available in the object store of the IMPETUS Afea Solver® [12].

The detailed material properties for UHMW-PE are presented in Table II.

TABLE II. UHMW-PE MATERIAL PROPERTIES [10]

Parameter	***Values***	***Units***
Density	980	Kg/m3
Young’s modulus (Matrix)	500	MPa
Poisson’s ratio (Matrix)	0.45	-
Fiber stiffness	110	GPa
Fiber locking strain	0	-
Strain (element erosion)	1.0	-
Matrix yield stress	20	MPa
Non-linear bulk stiffness parameter	400	GPa
Initial Stiffness (fraction of fiber stiffness)	0.125	-
Strain rate parameter	0.05	-
Reference strain rate	100	-
Fiber fill fraction	0.415	-
Optional non-linear bulk stiffness exponent	1.5	-

C. Model Set-Up

A numerical model is developed and shown in Fig 1. A quarter model is considered for this study because the FSP and UHMW-PE target geometry and the physics of the problem. Zhang et. al. [13] showed that the difference in numerical analysis of time history back face deformation is 0.8% when using quarter model in comparison to full model applying LS-DYNA® [14]. The quarter dimensions of the target plate are 0.15 m by 0.15 m, and the thickness varies as 10 mm and 20 mm. The FSP used for this study is 20 mm.

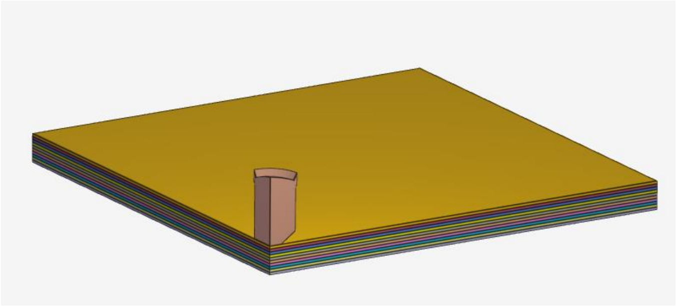

Figure 1. Model Setup.

Quadratic hexahedron elements (27 nodes and 27 integration points) are used to model 20 mm FSPs and UHMW-PE targets. The FSP model has 448 quadratic hexahedron elements, and UHMW-PE elements count changes according to the plate thickness. One quadratic element is used through the thickness for each layer shown in Fig 2. There are two sets of simulations; one with 1 mm layers and the other with 2 mm layers; for instance, 10 mm target plate simulation is modeled validated with 10 layers of 1 mm each and 5 layers of 2 mm each thickness.

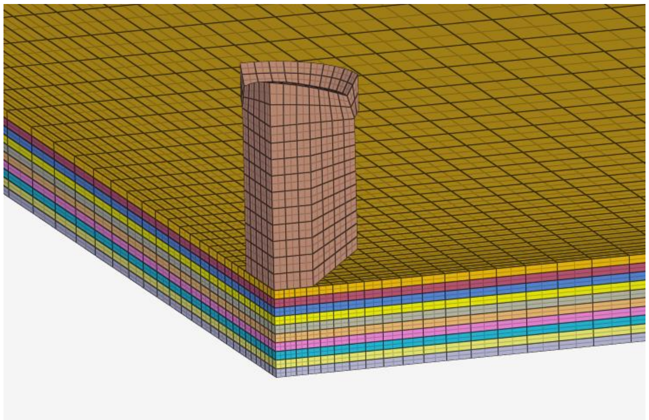

Figure 2. Meshing

The FSPs are modeled using Johnson-Cook material model, *MAT_JC and *PROP_THERMAL input commands. The composite UHMW-PE target plates are modeled with *MAT_FABRIC. The adhesive properties between layers are specified with *MERGE and *MERGE_FAILURE_COHESIVE. The surface normal in the X and Y directions are free both directions but fixed in the Z direction. The FSP impact velocity is defined by *INITIAL_VELOCITY.

The simulations were run on the NVIDIA RTX 8000 GPU. The model built is validated against the experimental data presented in [2]. In this study, three things are validated: (1) Ballistic Limit, (2) Residual velocity, (3) Apex displacement. The different sets of datasets are mentioned in Table III and Table IV.

TABLE III. IMPACT VELOCITY DATASET [2]

Impact Velocity (m/sec)	***Target Thickness***
464	10 mm
643	10 mm
984	10 mm
683	20 mm
899	20 mm
1058	20 mm

TABLE IV. BALLISTIC LIMIT DATASET [2]

Ballistic Limit (m/sec)	***Target Thickness***
394	10 mm
620	20 mm

III. RESULTS AND DISCUSSION

Altogether approximately 14 simulations were performed, and the simulation results are compared with the experimental data presented in [2]. This section is divided into three different result subsections.

A. Ballistic Limit Results

For evaluating the ballistic limits when 20 mm FSP is shot into 10 mm and 20 mm UHMW-PE target plate, material parameter values were used as shown in Table I and Table II. For comparison with experimental results, a couple of simulations are conducted: one with 0.9 time the experimental ballistic limit and the other one with 1.1 times the ballistic limit. Each layer of composite is modeled with 2 mm thickness. As shown Fig. 3 and Fig 4, FSP is with 0.9 times the ballistic limit is not penetrating but penetrating with 1.1 times the ballistic limit. The complete results are shown in Table V below, and it successfully matches the experimental results, i.e., FSPs with 0.9 scaling parameter are not fully penetrating whereas FSPs with 1.1 scaling parameter are fully penetrating.

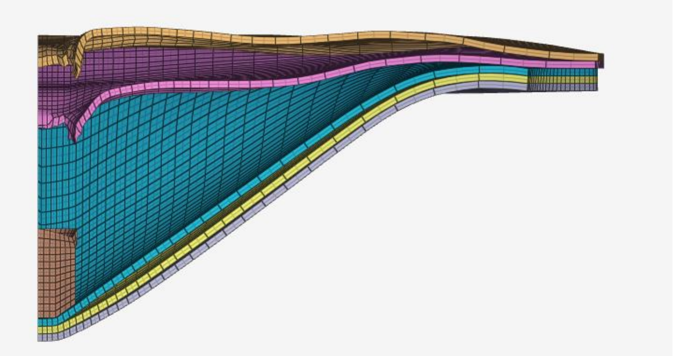

Figure 3. 20 mm FSP on 10 mm UHMW-PE target with 0.9 times Ballistic Limit Velocity

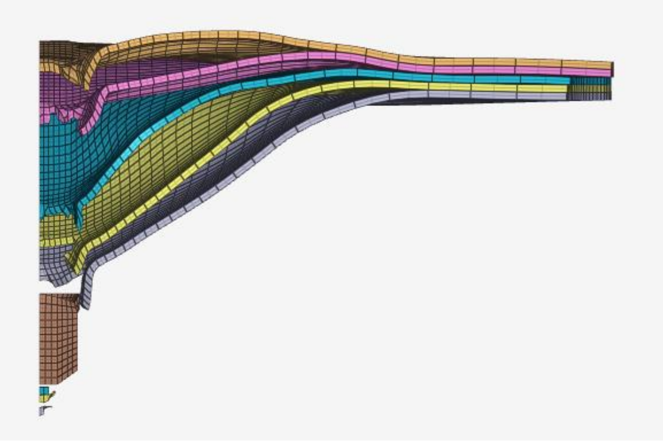

Figure 4. 20 mm FSP on 10 mm UHMW-PE target with 1.1 times Ballistic Limit Velocity

Table V. Ballistic Limit Results

Experimental Ballistic Limit (m/sec)	***Velocity Scaling Parameter***	***Target Thickness***	***Each Layer Size***	***Full Penetration***
394	0.9	10 mm	2 mm	No
394	1.1	10 mm	2 mm	Yes
620	0.9	20 mm	2 mm	No
620	1.1	20 mm	2 mm	Yes

B. Impact Velocity vs Residual Velocity

The residual velocity of the 20 m FSP is the attribute of interest in this work as well. Preliminary simulation of impact velocity of FSP into the 10 mm plate with 2 mm layer thickness is performed. The residual velocity of the projectile came out to be 0.8% off as compared to the experiments, as shown in Fig. 5. In the figure, the blue line indicates time history of FSP velocity, and the gray horizontal line is the experimental value of the residual velocity.

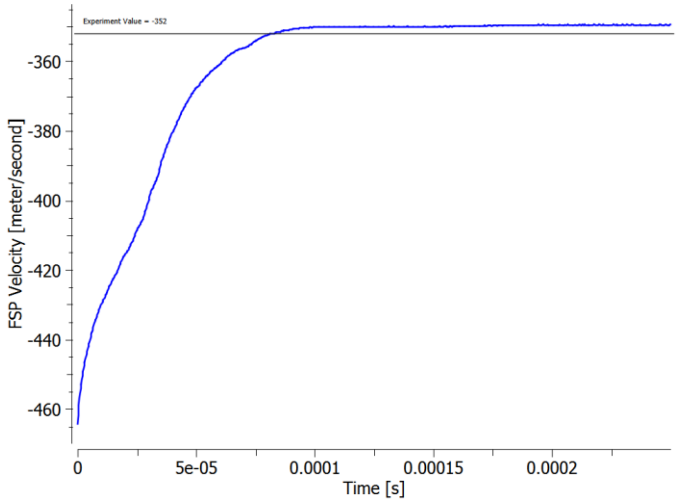

Figure 5. Time History Plot for FSP Velocity with impact speed of 464 m/sec on 10 mm UHMW-PE Target.

After validating the model with the preliminary simulation, the residual velocity response for 643 m/sec and 984 m/sec FSP impact velocity is simulated. The numerical studies were performed for 10 mm UHMW-PE target plates. The detailed study results are listed in Table VI. The results have a great agreement with the experiments. The maximum error is 3.6% for 984 m/sec impact velocity. The maximum simulation runtime is around 34 minutes for the analysis of 464 m/sec impact velocity and each target layer size of 1 mm. And the minimum simulation runtime is around 4 minutes for the analysis 984 m/sec and each target layer size of 2 mm. The target layer size of 2 mm took lower runtime because of the number of elements used. As one element is considered through the thickness for each layer, modeling 2 mm layer in comparison with 1 mm layers reduce the number of target plate elements to half.

Table VI. Comparison of simulation residual velocities with experiments at different impact velocities for 10 mm target plate.

Impact Velocity, V_{50} (m/sec)	***Experimental Residual Velocity (m/sec)***	***Each Layer Size***	***Simulation Residual Velocity (m/sec)***	***Error (%)***
464	352	1 mm	343.5	2.4
464	352	2 mm	349.2	0.8
643	583	1 mm	568.3	2.5
643	583	2 mm	562.6	3.5
984	952	1 mm	920.9	3.2
984	952	2 mm	917.3	3.6

The study is extended to the impact analysis onto the 20 mm UHMW-PE target plates. In this specific dataset, the residual velocity response for 683 m/sec, 899 m/sec and 1058 m/sec FSP impact velocity is simulated. There is good agreement of results as compared to the experimental data. The error percentage are within 10% range, as listed in Table VII. The maximum simulation runtime is around 1 hour 50 minutes for the analysis of 683 m/sec impact velocity and each target layer size of 1 mm. And the minimum simulation runtime is around 10 minutes for the analysis 1058 m/sec and each target layer size of 2 mm.

Table VII. Comparison of simulation residual velocities with experiments at different impact velocities for 20 mm target plate.

Impact Velocity, V_{50} (m/sec)	***Experimental Residual Velocity (m/sec)***	***Each Layer Size***	***Simulation Residual Velocity (m/sec)***	***Error (%)***
683	447	1 mm	489.9	-9.6
683	447	2 mm	489.5	-9.5
899	737	1 mm	760.6	3.2
899	737	2 mm	751.9	2.0
1058	866	1 mm	915.1	5.6
1058	866	2 mm	921.2	6.3

C. Apex Position

Rear end of the UHMW-PE composite plate develops a pyramid shape bulge under a ballistic impact. The velocity-based bulge propagation for UHMW-PE plates was studied Chocron et al. [15]. Apex position is defined as the history of the displacement from the last plate of the composite to the tip of the bulge, as shown in Fig. 6. The numerical results were compared to the experiments presented in [2]. The numerical model was set up for 10 mm and 20 mm UHMW-PE composite target plate. The location of the output node center location of the back target plate. The impact velocities for this numerical study are 365 m/sec for 10 mm UHMW-PE target plate simulation and 615 m/sec for 20 mm UHMW-PE target plate simulation. Numerical results are in great agreement for 10 mm target plate, as shown in Fig. 7, and for 20 mm plate, numerical results show good agreement till halfway before starting to over predict. However, the maximum difference between simulation and experiment for 20 mm plate simulation is around 13%. One should notice that nowhere in the experimental reporting is it mentioned what the accuracy is nor what the is the level of repeatability.

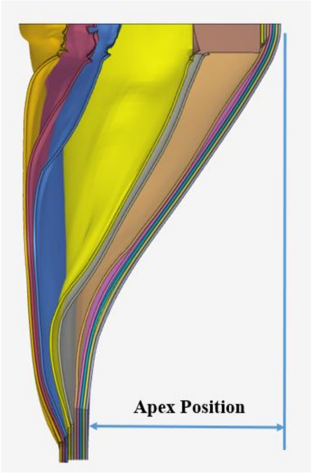

Figure 6. Apex Position Defînetion

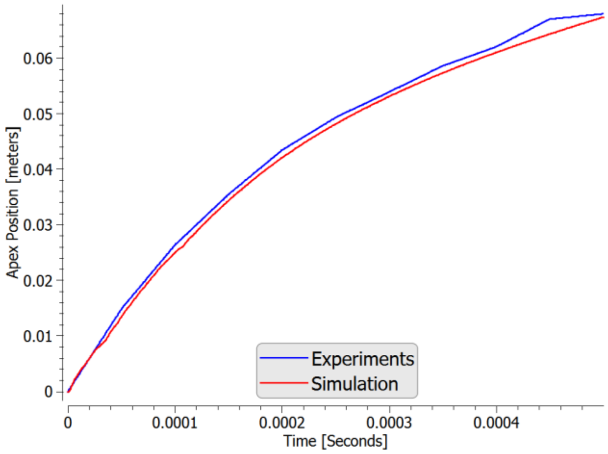

Figure 7. Apex position time history plot for 10 mm plate

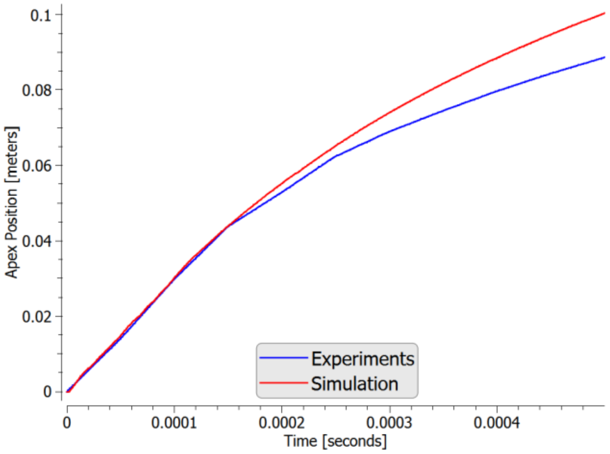

Figure 8. Apex position time history plot for 20 mm plate

IV. CONCLUSION

A numerical model is investigated using the IMPETUS Afea Solver suite for the ballistic impact of 20 mm FSP into the Ultra-high molecular weight polyethylene (UHMW-PE) composite target plates. The *MAT_FABRIC constitutive model command is introduced, and the methodology was validated against experimental data available in the literature. The FSPs are shot at different impact velocities onto the 10 mm and 20 mm targets. Ballistic limit, residual velocity and apex position were in good agreement with experiments.

The ballistic limit numerical study predicted full penetration with the impact velocity of 1.1 times the ballistic limit values, and no-go penetration with 0.9 times the ballistic limit values. The predicted residual velocities were within 4% for 10 mm plate and 10% for 20 mm plate as compared to the experiments. And at the end, apex position time history was within 13% of the experiments. The error percentage for residual velocity study and apex position is slightly more when FSP is impacted on the thicker plate (20 mm). The simulation results provide a good understanding of the ballistic impact of FSP onto the UHMW-PE target plates. Through different studies, it provides a confidence in the material properties used.

V. FUTURE WORK

Based on the presented validated numerical model, the future work will expand this study to higher thicknesses of UHMW-PE plates (36.2 mm, 75.6 mm, and 101.7 mm). Moreover, there is planning to validate the current model with 12.7 mm FSPs against 9.1 mm, 20 mm, 25.2 mm, 35.1 mm, and 50.4 mm thick UHMW-PE target plates. Further it will be of interest to perform a sensitivity study of the material and process parameters as well as do mesh convergency study.

ACKNOWLEDGMENT

The authors are thankful for the input and support from Marcus Menchawi, Senior Engineer and QA Manager at IMPETUS Afea AB, Sweden

REFERENCES

[1] DSM, “Dyneema®,” Updated March 16 2020. [Website]. Available: https://www.dsm.com/dyneema/en_GB/home.html, Accessed on: February 9, 2022.

[2] L. H. Nguyen, S. Ryan, S. J. Cimpoeru, A. P. Mouritz and A. C. Orifici, “The effect of target thickness on the ballistic performance of ultra high molecular weight polyethylene composite.” *Int J Impact Eng*, vol. 75, pp.174–183, 2015.

[3] T. S. Reddy, P. R. S. Reddy and V. Madhu, “Dynamic behaviour of carbon/ultra high molecular weight polyethylene (UHMWPE) hybrid composite lamiates under ballistic impact.” *J. Dyn. Behav. Mater.*, vol. 7, pp. 403-413, September 2021.

[4] L. H. Nguyen, T. R. Lässig, S. Ryan, W. Riedel, A. P. Mouritz and A. C. Orifici, “Numerical moodeling of ultra-high molecular weight polyethylene composite under impact loading.” *Proc Eng*, vol. 103, pp.436-443, 2015.

[5] T. R. Lässig, L. H. Nguyen, M May, W. Riedel, U Heisserer and H Van der Werff “A non-linear orthotropic hydrocode model for ultra-high molecular weight polyethylene in impact simulations.” *Int J Impact Eng*, vol. 75, pp.110-112, 2015.

[6] L. H. Nguyen, T. R. Lässig, S. Ryan, W. Riedel, A. P. Mouritz and A. C. Orifici, "A methodology for hydrocode analysis of ultra-high molecular weight polyethylene composite under ballistic impact," *Compos. Part A Appl.*, vol. 84, pp.224–235, 2016.

[7] NATO AEP-55, "Procedures for evaluating the protection level of armoured vehicles", AEP-55, Volume 1, Edition 2, August 2011.

[8] IMPETUS, "Validation - Terminal Ballistics", The IMPETUS Afea Solver®, October 2021.

[9] G. Johnson, R. Gordon and W. H. Cook, "A constitutive model and data for metals subjected to large strains, high strain rates, and high temperatures." *in proc. 7th international symposium on Ballistics*, 1983, pp. 541-547.

[10] IMPETUS, "Documenatation built into the IMPETUS Material Object Library", Available at the IMPETUS AFea Solver® GUI Interface", Accessed on: February 9, 2022

[11] M. R. O'Masta, "Mechanisms of Dynamic Deformation and Failure in Ultra-High Molecular Weight Polyethylene Fiber-Polymer Matrix Composites." Ph.D dissertation, School of Engineering and Applied Science, University of Virginia, Charlottesville , 2014. [Online]. Available: https://libraetd.lib.virginia.edu/public_view/k930bx37g, Accessed on: Februrary 9, 2022.

[12] IMPETUS Afea, "The IMPETUS Afea Solver®". [Online]. Available: https://www.impetus.no/, Accessed: 09-Feb-2022.

[13] T. G. Zhang, S. S. Satapathy, L. R. Vargas-Gonzalez and S. M. Walsh, "Modelling ballistic response of ultra-high molecular weight polyethylene (UHMWPE)," US Army Research Laboratory, Maryland, USA, Rep. no. ARL-TR-7723, July 2016.

[14] LS-DYNA, "LS DYNA® Keyword User's Manual, R13.0. Livermore (CA): Livermore Software Technology (LST), An Ansys Company, 2021 Accesse on: Februrary 11, 2022.

[15] S. Chocron, N. King, R. Bigger and J. D. Walker, "Impacts and waves in Dyneema® HB80 strips and laminates," *J Appl Mech*, vol. 80, May 2013.