

IMPROVING THE BALLISTIC IMPACT RESISTANCE OF SOFT BODY ARMOUR

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SEPTEMBER 2021

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SOFT BODY ARMOUR**

by

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Submitted

in fulfilment of the requirements for the degree of Doctor of Philosophy

to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI

September 2021

Dedicated to the heroes of all countries

CERTIFICATE

This is to certify that the thesis titled '**Improving the Ballistic Impact Resistance of Soft Body Armour**', being submitted by Mr. Unsanhame Mawkhlieng to the Indian Institute of Technology Delhi, for the award of the degree of Doctor of Philosophy, is a record of bonafide research work carried out by him. He has worked under my guidance and supervision and fulfilled the requirements for submission of the thesis which has attained the standard required for a PhD degree of this Institute.

The results contained in this thesis have not been submitted, in part or in full, to any other university or institute for the award of any degree or diploma.

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ACKNOWLEDGEMENTS

On the very onset, I would like to thank God Almighty for bestowing upon me wisdom, strength, peace of mind, and good health which enabled me to finish this research work on time. I thank Him for all the wonderful people that He has brought into my life. The journey of my PhD would have not been easy if not for the altruistic support of my supervisor, professors, friends, and well-wishers. On this note, I express my sincerest admiration towards to my supervisor, Prof. Abhijit Majumdar for believing in me and for constantly supporting me through thick and thin throughout my PhD journey. I thank him for his immense patience, understanding and endless upliftment that have enabled me to complete this work with ease. He has shown me the qualities that a good academician ought to have. I am highly grateful to my SRC members, Prof. Alagirusamy, Prof. Rawal and Prof. Bhatnagar (Department of Mechanical Engineering) for their invaluable suggestions that have helped me improve the quality of my work. I also would like to extend my gratitude to Prof. Butola for his selfless guidance and inputs that have become an integral part of my work. It is also my desire to express my gratitude to the entire faculty of the Department of Textile and Fibre Engineering for its efforts in setting up various laboratories with state-of-the-art instruments that have helped me expedite my experiments. I would especially like to express my deepest gratitude to Dr. Sanskrita for her moral support and for being ever ready to impart technical assistance. Her contribution to the publication of my research articles is commendable. I thank Defence Research and Development Organisation (DRDO) for providing financial assistance for this research work. My gratitude also goes to the Ballistic Evaluation of Materials (BEM laboratory) at Terminal Ballistic Research Laboratory (TBRL) for rendering the testing facility

to conduct the ballistic experiments. The technical input and suggestions of the team have helped me in the analysis of the results.

I am grateful to the reviewers of my research and review articles for their treasured feedback and suggestions. Their inputs have helped improve the quality of my work and polished my research approach. Next, I would like to take this opportunity to thank all the laboratory technicians and other staff of our department for their kind help. Here, I express special appreciation to Mr. Kundu, Mr. Singh, Mr. Sharma, Mr. Biswal, Mr. Khatkar, and Dr. Khattar who often reached out to extend their services beyond the call of their duties. I would like to specifically affirm the contributions of Dr. Sanchi, Dr. Aranya, Mr. Prakash and Dr. Swati for their guidance and hands-on instructions of various instruments that have helped me complete this research on time. I highly appreciate the contributions of Dr. Shahid, Dr. Animesh, Dr. Anshu, Dr. Manjunath and Dr. Samsu and admire them for being ever ready to lend a helping hand whenever required.

Mr. Ganesh and Mr. Mukesh deserve special declaration for their selflessness, their constant encouragement and upliftment in good and bad times. No word can express my sincerest gratitude to the ministration of my supervisor Prof Majumdar, Prof. Butola, Dr. Sanskrita, Dr. Sanchi, Dr. Aranya, Dr. Ashish, Mr. Manoj, Dr. Swati, Dr. Sumit, Dr. Kameswara, Mr. Fai, Mr. Prateek, Mr. Thochi, Mr. Jijo and family, and Mr. Devaraj for standing by my side during the unfortunate times of my PhD journey. I found hope because of the love and care that was shown to me. I thank all my friends and colleagues with whom I have spent most of my free time and from whom I have learnt a lot, making life in the campus lively and cheerful. On this note, I wish to acknowledge Dr. Sumit, Dr. Rupayan, Mr. Prasun, Mr. Satya, Mr. Nagendra, Ms. Rupali, Ms. Priyal, Mr. Sockalingam, Ms. Priyanka, Mr. Rahul,

Mr. Sateesh, Mr. Sandeep, Ms. Mani, Mr. Sidhharth, Ms. Shashi, Mrs. Manisha, Mr. Danvendra, Mr. Kuldip, Mr. Gourav, Dr. Bhabatosh, Mr. Chetan, Mr. Kapil, Mr. Bharat, Mr. Satish, Mr. Jyotirmoy and Mr. Zimad. I also like to express my gratitude to all my friends in the hostel who have always been ready to help in times of need. My thankfulness goes out to all the past and present members of ProTech group for their direct and indirect contributions to the completion of my work. In addition, I express my sincerest gratitude to the teachers and mentors of my life who have shared their expertise and values at all stages of my life. Last, but not the least, I believe that my PhD journey has been blessed because of the love and sacrifice of my late mother, my father, my sisters, my brother, my sister-in-law, my nieces and all my loved ones and well-wishers. Their constant inspiration and motivation have given me a purpose to move ahead and far in life.

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ABSTRACT

Soft body armour has been used for many decades to ensure protection against low and medium threats. The increasing need for body armour due to uprising terror attacks, communal riots, and civil unrest has driven the authorities and research fraternity to venture for alternative approaches to either enhance the performance of existing armour or to reduce the armour weight while maintaining the required level of protection. Consequently, different forms of treatment and modification of present materials have birthed and proven to be beneficial for impact applications. The use of shear thickening fluid (STF) stands out to be one of the most effective methods to augment the impact resistance of high-performance fabrics used in soft body armour. STF treatment has been explored extensively in literature, and while the observation of enhanced performance of treated fabrics has been consistent, the role that STF plays, is however, debatable. While a group of researchers believes that the inherent shear thickening property of the fluid do contribute to the observed impact resistance improvement, others opine that the only part that STF plays is friction enhancement. Thus, in the first part of this research, an attempt was made to decipher the role of STF. An indirect approach of correlation among rheological behaviour of the STF, friction in the fabric, and fabric energy absorption during dynamic impact analysis was adopted. The difference in rheological behaviour of the fluid was obtained through polydispersity of silica nanoparticles used to make the STF. Thus, different STFs were prepared using mono- or bidispersed silica particles, and their rheological behaviour was studied on a rheometer. Two grades of commercially available *p*-aramid fabrics, Kevlar® 802F (low sett) and Kevlar® 363 (high sett) were treated with the different STFs. It was observed that the level of friction, estimated through yarn pull-out, in each fabric type was the same. However, the energy absorption of fabrics treated with those

different STFs showed a specific trend akin to that of the rheological behaviour of the STFs studied separately. The observation was more prominent in the case of Kevlar® 802F having lower sett. If friction was the only role of STF, the energy absorption should have been the same in all the fabrics treated differently. However, because the energy absorption was least in the fabrics treated with STFs with the least shear thickening intensity, it was concluded that STF plays dual roles.

In the second part of the research, an attempt was made to study the efficacy of STF against an impact velocity of $165 \text{ m}\cdot\text{s}^{-1}$. To achieve this, the concept of multiphase STF was adopted wherein graphene nanoplatelets were used to intensify the shear thickening. It was found that with increasing amount of graphene nanoplatelets, the shear thickening increased. The same two grades of Kevlar® fabrics explored in the first part of the research were used in this experiment as well. It was found that the performance of fabrics treated with the graphene reinforced STFs in terms of yarn pull-out force and energy absorption increased corresponding to the rheological response of the STF. Thereafter, three panels from each grade of Kevlar® fabrics were prepared- the first, untreated; the second, treated with regular STF (i.e., without graphene reinforcement) and the last, treated with multiphase STF. The panels were evaluated for their energy absorption (through residual velocity ballistic test) at $165 \text{ m}\cdot\text{s}^{-1}$. For Kevlar® 802F, the energy absorption increased gradually from neat to STF treated to multiphase STF treated panels. For Kevlar® 363, the number of bullets stopped increased progressively from 1 in neat panel, to 2 in STF treated panel, and finally to 3 in multiphase STF treated panel.

In the third part of the experiment, an attempt was made to study the design strategy of hybrid panels composing of STF treated fabrics. More specially, the study was conducted to understand the role of modulus, fabric structure, and the placement strategy in a hybrid panel

to obtain minimum back face signature (BFS) against an impact velocity of $430 \text{ m}\cdot\text{s}^{-1}$. Two yarns, very high modulus aromatic polymer (VHMAP or A) and ultra-high molecular weight polyethylene (UHMWPE or PE) with varying modulus were chosen from which two 2-dimensional (2D) fabrics were manufactured. The impact energy absorption of VHMAP fabrics was superior to that of UHMWPE fabrics. Ten panels having areal density of around $4.9 \text{ kg}\cdot\text{m}^{-2}$ were made using the said fabrics in neat and STF treated conditions in combination with commercially available Dyneema® SB51 UD sheets ($250 \text{ g}\cdot\text{m}^{-2}$). The panels were varied in the layering sequence of unidirectional (UD) laminates, woven neat and woven STF impregnated fabrics. Evaluated for ballistic performance in terms of BFS against $9 \times 19 \text{ mm}$ lead core bullet fired at $430 \text{ m}\cdot\text{s}^{-1}$ impact velocity, the panels showed better performance when UD fabrics were placed at the strike face and STF treated very high-modulus fabrics at the back face. Further, panels having STF treated fabrics showed lower BFS, particularly when placed at the rear. It was, thus, proposed that by placing a high stiffness fabric at the front as well as at the back, the BFS will be lessened due to extensive bullet expansion by the strike face and enhanced restraint from the backing layers.

Finally, in the last part of the experiment, the blunt trauma mitigation of different non-ballistic grade backing materials was explored, the performance of which was compared against that of the commercially available anti-trauma liner. Expanded polyethylene foam and polyester spacer fabric were explored in the experiment. Preliminary test was initially conducted to study the effect of number of foam layers as backing material against 16 layers of UD laminates. The results showed that with increasing number of foam layers, the BFS reduction was significantly high, whereas the weight addition was comparatively very low. Further, the panels were prepared under additional constraints to lower the panel areal density

to $3.4 \pm 0.3 \text{ kg} \cdot \text{m}^{-2}$ in accordance with IS 17051:2018. The results showed that the panels backed with foam gave much lower BFS as compared to those backed with spacer fabric or anti-trauma liner. Further, the design strategy proposed in the previous part of the experiment wherein placement of high stiffness fabrics both at the front and at the back could help reduce the BFS was validated. A certain panel having areal density of $3.42 \text{ kg} \cdot \text{m}^{-2}$, designed using 11 layers of UD laminate as the strike face, backed with nine layers of foam, and further restrained with two layers of stiff UD laminates at the rear provided a BFS of 16 mm.

सारांश

सामान्य खतरों के खिलाफ सुरक्षा सुनिश्चित करने के लिए कई दशकों से सॉफ्ट बॉडी आर्मर का इस्तेमाल किया जा रहा है। आतंकी हमलों, सांप्रदायिक दंगों और नागरिक अशांति के कारण शरीर के लिए सुरक्षा कवच की बढ़ती जरूरत ने अधिकारियों और अनुसंधान बिरादरी को मौजूदा कवच के प्रदर्शन को बढ़ाने या समान प्रदर्शन दक्षता बनाए रखते हुए कवच के वजन को कम करने के लिए वैकल्पिक दृष्टिकोणों के लिए प्रेरित किया है। नतीजन, उपचार के विभिन्न रूपों और वर्तमान सामग्रियों के संशोधन ने जन्म लिया है जो अनुप्रयोगों के लिए फायदेमंद साबित हुए हैं। शियर थिक्निंग फ्लूइड (एसटीएफ) का उपयोग सॉफ्ट बॉडी आर्मर में उच्च प्रदर्शन कपड़े के प्रदर्शन को बढ़ाने के लिए सबसे प्रभावी तरीकों में से एक है। एसटीएफ से उपचारित उच्च प्रदर्शन कपड़ों का साहित्य में बड़े पैमाने पर अध्ययन गया है, और जबकि अवलोकन है कि एसटीएफ उपचारित कपड़े के प्रदर्शन में लगातार सुधार हुआ है, हालांकि, यह एक बहस का मुद्दा है, जबकि शोधकर्ताओं के एक समूह का मानना है कि तरल पदार्थ की अंतर्निहित शियर थिक्निंग विशेषता प्रतिरोध में सुधार करने के लिए योगदान करता है, अन्य समूह का मानना है कि एसटीएफ केवल घर्षण वृद्धि करता है। इस तरह इस शोध के पहले भाग में एसटीएफ की भूमिका को समझने का प्रयास किया गया। एसटीएफ के रियोलॉजिकल व्यवहार, कपड़े में घर्षण और गतिशील प्रभाव के दौरान कपड़े में ऊर्जा अवशोषण के बीच सहसंबंध का एक अप्रत्यक्ष दृष्टिकोण अपनाया गया था। तरल पदार्थ के रियोलॉजिकल व्यवहार में अंतर एसटीएफ बनाने के लिए इस्तेमाल किए जाने वाले सिलिका कणों की पॉलीडिसपर्सिटी के माध्यम से प्राप्त किया गया था। इस प्रकार, मोनो या बाइडिसपर सिलिका कणों का उपयोग करके विभिन्न एसटीएफ तैयार किए गए थे, और उनके रियोलॉजिकल व्यवहार का अध्ययन रियोमीटर पर किया गया था। व्यावसायिक रूप से उपलब्ध केवलर® कपड़े, केवलर® ८०२ एफ (कम सेट) और केवलर® ३६३ (उच्च सेट) के दो ग्रेड अलग एसटीएफ के साथ उपचारित किये। यह देखा गया कि प्रत्येक कपड़े के प्रकार में यार्न पुल-आउट के माध्यम से अनुमानित घर्षण का स्तर समान था। हालांकि, विभिन्न एसटीएफ के साथ उपचारित किए गए कपड़ों के ऊर्जा अवशोषण ने अलग से अध्ययन किए गए एसटीएफ के रियोलॉजिकल व्यवहार के समान एक विशिष्ट प्रवृत्ति

दिखाई। अवलोकन में पाया कि केवलर® ८०२ एफ (कम सेट) वाले कपड़े में अधिक था। यदि घर्षण एसटीएफ की एकमात्र भूमिका थी, तो विभिन्न एसटीएफ के साथ उपचारित किए गए सभी कपड़ों में ऊर्जा अवशोषण समान होना चाहिए था। हालांकि, क्योंकि ऊर्जा अवशोषण कम शीयर थिक्निंग तीव्रता के साथ एसटीएफ के साथ उपचारित कपड़े में कम था, यह निष्कर्ष निकाला गया था कि एसटीएफ दोहरी भूमिका निभाता है।

शोध के दूसरे भाग में १६५ मीटर·सेकंड^१ के प्रभाव वेग के खिलाफ एसटीएफ की प्रभावकारिता का अध्ययन करने का प्रयास किया गया। इसे हासिल करने के लिए मल्टीफेज एसटीएफ की अवधारणा अपनाई गई जिसमें शीयर विस्कोसिटी को बढ़ाने के लिए ग्राफीन नैनोप्लेटेलेट्स का इस्तेमाल किया गया। यह पाया गया कि ग्राफीन नैनोप्लेटेलेट्स की बढ़ती मात्रा के साथ, शीयर विस्कोसिटी बढ़ गयी। शोध के पहले भाग में खोजे गए केवलर® कपड़ों के समान दो ग्रेड इस प्रयोग में भी उपयोग किए गए थे। यह पाया गया कि यार्न पुल-आउट बल और ऊर्जा अवशोषण के मामले में ग्राफीन के साथ उपचारित किए गए कपड़ों के प्रदर्शन में एसटीएफ की रियोलॉजिकल प्रतिक्रिया के अनुरूप वृद्धि हुई। इसके बाद, केवलर के प्रत्येक ग्रेड से तीन पैनल® कपड़े तैयार किए गए थे- पहला, अनुपचारित; दूसरा, नियमित एसटीएफ के साथ उपचारित (यानी, ग्राफीन सुदृढीकरण के बिना) और अंतिम, मल्टीफेज एसटीएफ के साथ उपचारित किया। पैनलों का मूल्यांकन उनके ऊर्जा अवशोषण (अवशिष्ट वेग बैलिस्टिक परीक्षण के माध्यम से) के लिए १६५ मीटर·सेकंड^१ पर किया गया था। केवलर® ८०२ एफ के लिए, ऊर्जा अवशोषण धीरे-धीरे अनुपचारित से एसटीएफ व मल्टीफेज एसटीएफ उपचारित पैनल में बढ़ गया। केवलर® ३६३ के लिए, रोकी गयी गोलियों की संख्या अनुपचारित पैनल में १, एसटीएफ ट्रीटेड पैनल में २ और अंत में मल्टीफेज एसटीएफ ट्रीटेड पैनल में ३ हो गई।

थीसिस के तीसरे भाग में एसटीएफ उपचारित कपड़े फैब्रिक कंपोजिंग हाइब्रिड पैनल्स की डिजाइन स्ट्रेटेजी का अध्ययन करने का प्रयास किया गया। विशेष रूप से, यह अध्ययन ४३० मीटर·सेकंड^१ वेग के प्रभाव खिलाफ न्यूनतम बैक फेस सिग्नेचर (बीएफएस) प्राप्त करने के लिए हाइब्रिड पैनल में मॉड्यूलस, कपड़े संरचना और प्लेसमेंट रणनीति की भूमिका को समझने के

लिए किया गया था। अलग-अलग मॉड्यूलस के साथ दो धागे, बहुत उच्च मॉड्यूलस अरोमेटिक बहुलक (वीएचएमएपी या ए) और उच्च आणविक वजन पॉलीथीन (यूएचएमडब्ल्यूपीई या पीई) चुने गए थे, जिनमें से चार कपड़े (दो दिविमीय और दो त्रिविमीय कपड़े) का निर्माण किया गया था। वीएचएमएपी कपड़ों का प्रभाव ऊर्जा अवशोषण यूएचएमडब्ल्यूपीई कपड़ों से बेहतर था। व्यावसायिक रूप से उपलब्ध डायनीमा® एसबी५१ यूडी शीट (२५० ग्राम·मी^{-२}) के संयोजन में अनुपचारित और एसटीएफ उपचारित उक्त कपड़ों का उपयोग करके लगभग ४.९ किग्रा·मी^{-२} के क्षेत्रीय घनत्व वाले १२ पैनल बनाए गए थे। सभी पैनल यूडी व बुने गए अनुपचारित और बुने हुए एसटीएफ उपचारित कपड़े के लेयरिंग अनुक्रम में भिन्न थे। ४३० मी·सेकंड^{-१} प्रभाव वेग पर १९ मिमी लीड कोर बुलेट के खिलाफ बैक फेस सिग्नेचर के संदर्भ में बैलिस्टिक प्रदर्शन का मूल्यांकन किया गया, पैनलों बेहतर प्रदर्शन दिखाया जब यूडी कपड़े सबसे आगे और एसटीएफ उपचारित उच्च मॉड्यूलस कपड़े पीछे रखे गये थे। इसके अलावा, एसटीएफ उपचारित कपड़े वाले पैनल कम बीएफएस दिखाते हैं, खासकर जब पीछे की तरफ रखा जाता है। इस प्रकार, यह प्रस्तावित किया गया था कि सामने और साथ ही पीछे एक उच्च कठोरता वाले कपड़े रखकर, स्ट्राइक फेस द्वारा व्यापक बुलेट विस्तार और बैकिंग परतों से बेहतर संयम के कारण बीएफएस को कम किया।

अंत में, प्रयोग के अंतिम भाग में, विभिन्न गैर-बैलिस्टिक ग्रेड बैकिंग सामग्री के कुंद आघात शमन का पता लगाया गया था, जिसके प्रदर्शन की तुलना व्यावसायिक रूप से उपलब्ध एंटी-ट्रॉमा लाइनर से की गई थी। प्रयोग में विस्तारित पॉलीथीन फोम और पॉलिएस्टर स्पेसर फैब्रिक का पता लगाया गया। यूडी लेमिनेट की १६ परतों के खिलाफ समर्थन परतों के रूप में फोम परतों की संख्या के प्रभाव का अध्ययन करने के लिए किए गए प्रारंभिक परीक्षण से पता चला है कि फोम परतों की बढ़ती संख्या के साथ, बीएफएस में कमी काफी अधिक थी, जबकि वजन इसके अलावा तुलनात्मक रूप से बहुत कम था। इसके अलावा, पैनलों को आईएस १७०५१:२०१८ के अनुसार पैनल क्षेत्रीय घनत्व को ३.४ ± ०.३ किलोग्राम·मी^{-२} तक कम करने के लिए अतिरिक्त बाधाओं के तहत तैयार किया गया था। परिणामों से पता चला है कि फोम के साथ समर्थित पैनलों ने स्पेसर फैब्रिक या एंटी-ट्रॉमा लाइनर के साथ समर्थित लोगों की तुलना में बहुत कम बीएफएस दिया। इसके अलावा, प्रयोग के पिछले

भाग में प्रस्तावित डिजाइन रणनीति जिसमें सामने और पीछे दोनों में उच्च कठोरता कपड़े की नियुक्ति बीएफएस को कम करने में मदद कर सकती थी। एक निश्चित पैनेल जिसमें क्षेत्रीय घनत्व 3.82 किलोग्राम·मी⁻² है, जो स्ट्राइक फेस के रूप में यूडी की ११ परतों का उपयोग, फोम की नौ परतों और पीछे की तरफ कड़े यूडी लैमिनेट्स की दो परतों के साथ डिजाइन किया गया है, जिससे १६ मिमी का बीएफएस पाया गया है।

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