

**DEVELOPMENT AND IMPACT PERFORMANCE
ANALYSIS OF SHEAR THICKENING FLUID
TREATED 2D AND 3D FABRIC STRUCTURES**

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ANALYSIS OF SHEAR THICKENING FLUID
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by

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Department of Textile Technology

Submitted

in fulfilment of the requirements of the degree of

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to the



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Dedicated to my family

CERTIFICATE

This is to certify that the thesis titled '**Development and Impact Performance Analysis of Shear Thickening Fluid Treated 2D and 3D Fabric Structures**', being submitted by **Mr. Animesh Laha** 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 Ph.D. 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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Animesh Laha

ABSTRACT

Soft body armours are generally made of fabrics woven from high performance yarns. Impact resistance of woven fabrics mostly depends on fiber type, weave and thread density. Of late, woven fabrics made from high performance yarns are being impregnated with shear thickening fluids (STF) to enhance their impact resistance. Yarn pull-out, yarn extension and yarn rupture are found to be the three major modes of energy absorption during an event of impact.

In first part of this research, effects of weave and fabric thread density on yarn pull-out force was studied. Fabrics having five different weaves (plain, 2/2 twill, 3/1 twill, 2/2 matt and 5 end satin) and three levels of thread density (25×25 , 30×30 and 35×35 inch⁻¹) were woven using *p*-aramid Technora yarns (720 denier). The highest yarn pull-out force was obtained in case of plain weave and the lowest in case of satin weave. Yarn pull out force increased concomitantly with the increase in thread density. After the STF treatment, yarn pull-out force increased significantly for all the fabrics. A very good correlation was found between yarn pull-out force and energy absorption (J) during low velocity (6 m s^{-1}) impact test. Yarn pull-out force increased after STF and silica-water treatments whereas it reduced after water and poly-ethylene glycol (PEG) treatments. Yarn pull-out force was always higher for two consecutive yarns as compared to that for two yarns with single yarn gap.

All fifteen woven fabrics having five different weaves and three levels of thread density prepared for the first part of this research, were also used in the second part of research. Impact resistance of all the fabrics were evaluated before and after the STF (60% w/w) treatment following ASTM D3763. In untreated condition, for all levels fabric thread density, plain woven fabrics was the best, whereas 2/2 matt woven fabrics was the worst in terms of impact energy absorption. Impact resistance showed concomitant increase with the

increase in thread density. A strong association was found between the impact energy absorption and the number of yarn interlacement points in a given area of fabric. However, if the fabric thread density was low ($25 \times 25 \text{ inch}^{-1}$), then effect of weave on impact energy absorption was negligible. The effect of weave, indicated by the number of interlacement points, on impact energy absorption became dominant with the increase in thread density. After STF treatment, impact energy absorption increased for all the fabrics except for plain woven fabric with thread density of $35 \times 35 \text{ inch}^{-1}$. Highest impact resistance was obtained in case of STF treated plain woven fabric having thread density of $30 \times 30 \text{ inch}^{-1}$. Analysis of jammed fabric structure with lenticular yarn cross-section revealed that the fabric got jammed when the thread density was around $32 \times 32 \text{ inch}^{-1}$. Therefore, fabric having thread density of $35 \times 35 \text{ inch}^{-1}$ did not show any increase in impact energy absorption after STF treatment. It was also found that percentage increase in impact energy absorption after STF treatment was more for infirm fabrics i.e. fabrics having lower values of thread density and lower number of interlacement points (2/2 matt and satin). Multilayer plain woven fabrics were also evaluated with low velocity bullets ($165 \pm 15 \text{ m s}^{-1}$). Untreated panels having four layers of fabrics were not able to stop the bullets irrespective of thread density. However, all the STF treated fabric panels were able to stop the low velocity bullets (five out of five).

In the third part of research, an attempt was made to enhance the effectiveness of STF by adding nano fillers. Halloysite nanotubes (Hal nanotubes) was chosen due to its easy availability and low cost. Kevlar fabrics (802F and 363) were treated with virgin STF with 60% and 65% (w/w) silica content and compounded STF with 0.05, 0.1, 0.2, and 0.5% Hal nanotube content. Addition of Hal nanotubes with the STF facilitated the shear thickening as the critical shear rate reduced and peak viscosity increased with the increase in content of Hal nanotubes. The optimum content of Hal nanotubes in STF, for maximizing the impact resistance, was found to be dependent on the type of fabric and silica content in STF. For

Kevlar 802F fabric, which is having water repellent finish, 0.5% Hal nanotubes in STF (60% or 65% w/w) was found to maximize the impact resistance of treated fabrics. On the other hand, for Kevlar 363 which is scoured fabric, 0.2% and 0.05% Hal nanotubes in 60% and 65% STF, respectively, was found to maximize the impact resistance of treated fabrics.

In the last part of research, five different 3D orthogonal fabrics were woven by changing the ratio of stuffer to binder yarns at three levels (3:2, 3:1 and 4:1) and also by changing the relative positions of binder yarns. All the fabrics were treated with STF having 65% (w/w) silica content. The ballistic evaluation was carried out at low velocity ($165 \pm 15 \text{ m s}^{-1}$) as well as at high velocity ($430 \pm 15 \text{ m s}^{-1}$). During low velocity ballistic evaluation of single layer 3D fabrics, it was found that higher ratio of stuffer to binder (4:1) is beneficial for improving the impact energy absorption. STF treatment improved the impact energy absorption capacity of 3D woven fabrics consistently. When double layer 3D fabrics were evaluated, all the bullets (four out of four) were stopped in case of STF treated 3D woven fabrics having 4:1 stuffer to binder ratio. The synergistic effect of 3D fabric structure and STF reinforcement ensured the best performance in ballistic test. During back face signature measurement (bullet velocity of $430 \pm 15 \text{ m s}^{-1}$), 3D woven fabric panels (eight layers of Kevlar XPS and one layer of 3D fabric) with stuffer to binder ratio of 3:1 and 4:1 were able to stop all the bullets and the BFS value was less than 39 mm which is well below the NIJ standard of 44 mm.

सार

आमतौर पर नरम रक्षा कवच उत्त्व प्रदर्शन धागों से बुने कपड़े से बनाए जाते हैं। कवच की संघात प्रतिरोधक क्षमता फाइबर, कपड़े की संरचना और धागों के घनत्व पर निर्भर करती है। हाल ही में उत्त्व प्रदर्शन धागों से बुने हुए कपड़ों की संघात प्रतिरोधक क्षमता बढ़ाने के लिए इन्हें शियर थिकेनिंग फ्लूईड (एस. टी. एफ.) से परिपूर्ण किया जा रहा है। धागों का कपड़े से बाहर आना, उनका खिंचना एवम् आखिरकार टूट जाना, संघात के समय पर उर्जा अवशोषण क्षमता के तीन मुख्य तंत्र माने गये हैं।

इस शोध के पहले भाग में कपड़े की संरचना एवम् कपड़े में धागों के घनत्व का कपड़े से धागा खिंचे जाने पर पड़ने प्रभाव का अध्ययन किया गया। ७२० डेनियर के पेरा-अरामिड टेकनोरा धागे का इस्तेमाल करके पाँच अलग तरह की बुनाई (प्लेन, २/२ ट्विल, ३/१ ट्विल, २/२ मैट, और ५-एंड सैटिन) एवम् धागों के घनत्व के तीन अलग स्तर (२५×२५, ३०×३०, ३५×३५) वाले कपड़े बुने गये। इस अध्ययन में यह पाया गया कि धागे खींचने के लिए प्लेन कपड़े में उच्चतम बल एवम् सैटिन कपड़े में न्यूनतम बल की आवश्यकता होती है। धागों के घनत्व के बढ़ने पर कपड़े से धागा खींचने के लिए ज़्यादा बल की आवश्यकता होती है। कपड़े को एस. टी. एफ. से परिपूरित करने के उपरांत उन में से धागा खींचने में लगने वाले बल में पर्याप्त वृद्धि हुई। कम वेग वाले संघात परीक्षण (६ मीटर प्रति सेकेंड) में धागा खींचने के बल में एवम् उर्जा अवशोषण में अच्छा सह-संबंध पाया गया। एस. टी. एफ. एवम् सिलिका-जेल से परिपूरित कपड़े में धागा खींचने में लगने वाले बल में वृद्धि हुई, जबकि जल-पॉलयेथिलेन से परिपूरित कपड़े में धागा खींचने में लगने वाला बल कम हो गया।

शोध के प्रथम भाग के लिए पाँच विभिन्न प्रकार कि बुनाई और तीन स्तर के धागे घनत्व से पंद्रह बुने हुए कपड़े बनाए गए और इसका उपयोग शोध के दूसरे भाग में भी किया गया है। स.टी.फ(६०% .) परिपूर्णता के पूर्व एवम् पश्चात सभी कपड़ों का ऐ.स.टी.एम डी३७६३ के अनुसार संघात प्रतिरोधक क्षमता का परीक्षण किया गया। अनुपचारित अवस्था में सभी विभिन्न धागे घनत्व वाले कपड़ों में सादा बुना हुआ कपड़ा सबसे अच्छा पाया गया जहाँ २/२। बुनाई वाले कपड़े की संघात उर्जा अवशोषण सबसे निम्नतम था। बढ़ते हुए धागे घनत्व के साथ संघात प्रतिरोधकता भी बढ़ती हुई पाई गई। कपड़े के एक दिए हुए क्षेत्र में संघात उर्जा अवशोषण क्षमता और धागा बुनाई के मध्य मजबूत संबंध मिला। जब धागा घनत्व बहुत कम था (२५/२५ इंच-१) तब संघात उर्जा अवशोषण क्षमता पर बुनाई का प्रभाव नगण्य पाया गया। धागा घनत्व बढ़ने के साथ साथ बुनाई का प्रभाव जो गुथाइ बिंदु से प्रदर्शित है, बढ़ता गया। स.टी.फ परिपूर्णता के पश्चात संघात उर्जा अवशोषण क्षमता सिर्फ सादा बुनाई (३५×३५ इंच-१) कपड़े को छोड़कर अन्य सभी कपड़ों की बढ़ गई। स.टी.फ परिपूर्ण सादा बुनाई कपड़े की संघात उर्जा प्रतिरोधक क्षमता सबसे अधिक पाई गई जिसका धागा घनत्व (३०×३० इंच-१) था। कसे हुए कपड़े का विश्लेषण करने पर जिसके

धाने का अनुप्रस्थ काट मँसुराकार था, यह पाया गया कि कपड़े के पूर्णतः कसे जाने की परिस्थिति में धागा घनत्व (३२×३२ इंच-१) था। अर्थात्, ३५×३५ धागा घनत्व वाले कपड़े की संघात उर्जा अवशोषण क्षमता में एस. टी. एफ. परिपूर्णता के बाद कोई वृद्धि नहीं पायी गयी। यह भी पाया गया कि कमज़ोर कपड़े, जिनके धागा घनत्व एवम् गुथायीबिंदु कम हो (२/२ मीट और ५-एंड सैटिन), उनमें एस. टी. एफ. परिपूर्णता के बाद संघात उर्जा प्रतिरोधकता में ज़्यादा वृद्धि होती है। बहुपरतों वाला प्लेन बुनाई वाले कपड़े का मूल्यांकन कम वेग वाली गोलियों (१६५ मीटर प्रति सेकेंड) के साथ भी किया गया। कपड़ों की चार परतों से बने अनुपाचारित पेनल गोलियों को नहीं रोक पाये, चाहे वह किसी भी धागे घनत्व के हो, जबकि एस. टी. एफ. परिपूर्ण कपड़ों से बने पेनल कम वेग वाली गोलियों को रोकने में कामयाब रही।

शोध के तीसरे भाग में, एस. टी. एफ. के प्रभाव को बढ़ाने के लिए अति-सूक्ष्म भराब कणों का प्रयोग किया गया। हलोसिएट नैनो-ट्यूब का वजन उनकी सरल उपलब्धता एवम् कम मूल्य के कारण किया गया। केवलर से बुने (८०२ एफ और ३६३) कपड़ों को ६०% और ६५% सिलिका मात्रा वाले एस. टी. एफ. एवम् हलोसिएट नैनो-ट्यूब मिश्रित (०.०५, ०.१, ०.२ और ०.५%) एस. टी. एफ. से परिपूरित किया गया। हलोसिएट नैनो-ट्यूब मिश्रित एस. टी. एफ. ने शियर थिकेनिंग में मदद की जिससे क्रिटिकल शियर रेट कम हुआ और उच्चतम गढ़ापन, हलोसिएट नैनो-ट्यूब की मात्रा के साथ बढ़ा। इष्टतम मात्रा की हलोसिएट नैनो-ट्यूब को एस. टी. एफ. में डालने से जिसका उपयोग अधिकतम संघात प्रतिरोधक क्षमता प्राप्त करने के लिए किया गया वो कपड़े के प्रकार एवम् एस. टी. एफ. में सिलिका की मात्रा पर निर्भर करता है। केवलर के ८०२एफ कपड़े में जिस में जल प्रतिकर्षी लेप लगा हुआ है उसको ०.५% हलोसिएट नैनो-ट्यूब वाले एस. टी. एफ. (६०% एवं ६५% भार/ भार) से परिपूरित किया गया और ये पाया गया कि उसमें अधिकतम संघात प्रतिरोधक क्षमता होती है। दूसरी ओर स्कवर्ड केवलर ३६३ कपड़े को ०.२% और ०.०५% हलोसिएट नैनो-ट्यूब को ६०% और ६५% एस. टी. एफ. क्रमशः में अधिकतम संघात प्रतिरोधक क्षमता पाई गयी।

शोध के अंतिम हिस्से में पाँच अलग अलग तरह के तीन आयाम वाले ओर्थोगोनल कपड़े बनाये गये जिसमें स्ट्रफर व बाइंडर धागों को तीन अनुपातों (३:२, ३:१ और ४:१) में लिया गया। इसके साथ साथ कपड़े में इन धागों के सापेक्ष स्थान को भी बदला गया। तत्पश्चात्, सभी कपड़ों को ६५% सिलिका की मात्रा वाले एस. टी. एफ. से परिपूर्ण किया गया और इन पर कम वेग (१६५ मीटर प्रति सेकेंड) और उच्च वेग (४३० मीटर प्रति सेकेंड) से गोलियाँ चला कर इनके बेलिस्टिक प्रदर्शन का परीक्षण किया गया। तीन आयाम वाले कपड़ों की एक परत पर कम वेग पर किए गये बेलिस्टिक परीक्षण में यह पाया गया कि स्ट्रफर व बाइंडर धागों का उच्च अनुपात गोली के संघात पर उत्पन्न हुई उर्जा को ज़्यादा मात्रा में अवशोषित करता है। शोध में यह पाया गया कि एस. टी. एफ. के उपयोग से कपड़ों की संघात-उर्जा अवशोषण क्षमता में लगातार सुधार हुआ। जब एस. टी. एफ. परिपूर्ण, ४:१ स्ट्रफर व बाइंडर धागों से बने तीन आयाम वाले कपड़ों की दो परतों का बेलिस्टिक निरीक्षण किया गया, तब सभी गोलीयों (चार की चार) पार नहीं

हुई। इन नतीजों से यह निष्कर्ष निकाला जा सकता है कि कपड़े की तीन आयाम संरचना एवम् एस. टी. एफ. सुदृढ़ीकरण के योजक प्रभाव से सबसे अच्छा प्रदर्शन सुनिश्चित किया जा सकता है। ३:१ और ४:१ स्टर व बाइंडर धागों वाले एस. टी. एफ. परिपूर्ण कपड़े की एक परत के साथ केवलार एक्स.पी.एस की आठ परतें जोड़ कर पेनल तैयार किए गये और उनका बैक फेस सिग्नेचर मापा गया। इन दोनों पेनल में ३९ मिलीमीटर से कम पाया गया जो कि एन. आई. जे. मानक (४४ मिलीमीटर) से भी कम था।

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