STAB RESISTANCE BEHAVIOUR OF HIGH-PERFORMANCE TEXTILE MATERIALS AND STRUCTURES

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Dedicated to my mother

CERTIFICATE

This is to certify that the thesis titled **"Stab Resistance Behaviour of High-Performance Textile Materials and Structures"** being submitted by Mr. Jyotirmoy Das 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 our 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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Abstract

In recent years, stab protection is getting increasing attention from the researchers and practitioners. However, unlike ballistic protection, the roles of materials, structures, and test parameters on the stab resistance are still not well-understood. This study systematically examines the effects of fibre type, weave and stabbing direction on the quasistatic and dynamic stab resistance of woven fabrics followed by augmenting the stab resistance performance utilising ceramic coating and shear thickening fluid (STF). For quasistatic stab test, *P*-aramid (Kevlar®), aromatic polyester (Vectran®), and ultra-high molecular weight polyethylene (Spectra®) fibres were used to weave plain, 3/1 twill and 2/2 twill fabrics of same areal density. All the fabrics were tested using a P1 knife (NIJ 0115.00 standard). Among the fibres, Spectra® demonstrated the highest stab resistance followed by Vectran®. Plain woven fabric showed higher stab resistance than the other two weaves in bias direction. For all weaves, stab resistance was also found to be higher in bias direction followed by weft and warp. In dynamic stab testing of multilayer fabric panels, fibre type, fabric sett, denier per filament (DPF) and yarn linear density, significantly influenced dynamic stab resistance performance. Coarser yarns and higher fabric sett facilitated stab resistance. Besides, the direction of stabbing altered the dynamic stab resistance performance of these panels, with bias direction showing superior performance followed by warp and weft directional stabbing. Angular stacking of fabric layers in multi-layered panels further increased the rigidity of the panel and was found detrimental for stab resistance applications. In an attempt to develop stab-resistant armours for different impact energy levels, multi-layer neat and STF treated Kevlar® fabrics were used. The panel containing 16 layers of STF-treated Kevlar® fabric met the requirements at normal and over-test conditions showing penetration depth lower than 7 mm and 20 mm, respectively. For stabbing at high energy level (≥ 24 J), the effect of number of Kevlar® fabric layers was found to be highly beneficial in case of STF-treated condition and not so for the neat ones. STF treatment reduced the stab penetration depth by 40-68 % at 24-36 J energy level without any increase in effective weight of the panel. Using a novel sharpness tester and optical microscopy, it was found that the tip of knife is deformed, and sharpness declines at a faster rate in case of STF-treated fabric. A combined effect of hard boron carbide (B_4C) ceramic particles and STF on stab resistance of p-aramid fabric showed interesting outcomes. Acrylic co-polymer-based thickeners were found to be unsuitable for stab resistance applications due to the stiffness and rigidity they impart to the fabric which deteriorate the performance. In contrast, an oil-water emulsion-based thickener maintained flexibility of the fabric coated with ceramic particles. While increased ceramic particle content enhanced stab resistance, poor adhesion to the fabric created a practical challenge. A comprehensive solution was developed, by combining ceramic particles coated and STF impregnated p-aramid fabrics, which utilised the synergistic benefit of both approaches. When ceramic coated and STF impregnated fabric layers were placed at the strike face and rear side respectively, the fabric panel significantly outperformed its counterparts with individual treatments.

सारांश

हाल के वर्षों में, शोधकर्ताओं और व्यवसायियों द्वारा छुरा-रोधी सुरक्षा पर तेजी से ध्यान दिया जा रहा है। हालाँकि, बैलिस्टिक सुरक्षा के विपरीत, छुरा प्रतिरोध पर सामग्री, संरचनाओं और परीक्षण मापदंडों की भूमिका अभी भी पूरी तरह से समझी नहीं गई है। यह अध्ययन व्यवस्थित रूप से बुने हुए कपड़ों के अर्ध-स्थैतिक (क्वासिस्टैटिक) और गतिक (डायनामिक) छुरा प्रतिरोध पर फाइबर के प्रकार, बुनाई और छुरा घोंपने की दिशा के प्रभावों की जांच करता है। इसके बाद, सिरेमिक कोटिंग और शियर थिकनिंग फ्लूइड (एस.टी.एफ.) का उपयोग करके छुरा प्रतिरोध प्रदर्शन को बढ़ाने का प्रयास किया गया है। अर्ध-स्थैतिक छुरा परीक्षण के लिए, समान क्षेत्रीय घनत्व वाले प्लेन, ३/१ ट्विल और २/२ ट्विल कपड़ों को बुनने के लिए पी-एरामिड (केवलर), एरोमैटिक पॉलिएस्टर (वेक्ट्रान) और अल्ट्रा-हाई मॉलिक्यूलर वेट पॉलीइथाइलीन (स्पेक्ट्रा) फाइबर का उपयोग किया गया। सभी कपड़ों का परीक्षण पी-१ चाकू (एन.आई.जे. ०११५ .०० मानक) का उपयोग करके किया गया। फाइबरों में, स्पेक्ट्रा ने सबसे अधिक छुरा प्रतिरोध प्रदर्शित किया, जिसके बाद वेक्ट्रान का स्थान रहा। तिर्यक (बायस) दिशा में प्लेन बुने हुए कपड़े ने अन्य दो बुनाई की तुलना में उच्च छुरा प्रतिरोध दिखाया। सभी बुनाई के लिए, छुरा प्रतिरोध तिर्यक दिशा में सबसे अधिक पाया गया, जिसके बाद बाने और ताने दिशा का स्थान रहा। बहु-परतीय (मल्टीलेयर) फैब्रिक पैनलों के गतिक छुरा परीक्षण में, फाइबर के प्रकार, फैब्रिक सेट, डेनियर प्रति फिलामेंट (डी.पी.एफ.) और धागे के रैखिक घनत्व ने गतिक छुरा प्रतिरोध प्रदर्शन को काफी प्रभावित किया। मोटे धागे और उच्च फैब्रिक सेट ने छुरा प्रतिरोध को सुगम बनाया। इसके अलावा, छुरा घोंपने की दिशा ने इन पैनलों के गतिक छुरा प्रतिरोध प्रदर्शन को बदल दिया, जिसमें तिर्यक दिशा ने बेहतर प्रदर्शन दिखाया, और उसके बाद ताने और बाने दिशा में छुरा घोंपने का स्थान रहा। बहु-परतीय पैनलों में कपड़े की परतों की कोणीय स्टैकिंग ने पैनल की कठोरता को और बढ़ा दिया, जो छुरा प्रतिरोध अनुप्रयोगों के लिए हानिकारक पाया गया। विभिन्न प्रभाव ऊर्जा स्तरों के लिए छुरा-रोधी कवच विकसित करने के प्रयास में, बहु-परतीय नीट और एस.टी.एफ. उपचारित केवलर कपड़ों का उपयोग किया गया। १६ परतों वाले एस.टी.एफ.-उपचारित केवलर कपड़े वाले पैनल ने सामान्य और ओवर-टेस्ट स्थितियों में आवश्यकताओं को पूरा किया, जिसमें भेदन गहराई क्रमशः ७ मिमी और २० मिमी से कम दिखाई दी। उच्च ऊर्जा स्तर ($\geq$ २४ जूल) पर छुरा घोंपने के लिए, केवलर कपड़े की परतों की संख्या का प्रभाव एस.टी.एफ.-उपचारित स्थिति में अत्यधिक लाभकारी पाया गया, जबकि नीट कपड़ों के लिए ऐसा नहीं था। एस.टी.एफ. उपचार ने पैनल के प्रभावी वजन में किसी

भी वृद्धि के बिना २४ – ३६ जूल ऊर्जा स्तर पर छुरा भेदन गहराई को ४० – ६८ % तक कम कर दिया। एक नए तीक्ष्णता परीक्षक (शार्पनेस टेस्टर) और प्रकाशीय सूक्ष्मदर्शी का उपयोग करते हुए, यह पाया गया कि एस.टी.एफ.-उपचारित कपड़े के मामले में चाकू की नोक विकृत हो जाती है और उसकी धार तेजी से कम हो जाती है। पी-एरामिड कपड़े के छुरा प्रतिरोध पर कठोर बोरॉन कार्बाइड (बी-४-सी) सिरेमिक कणों और एस.टी.एफ. के संयुक्त प्रभाव ने दिलचस्प परिणाम दिखाए। एक्रिलिक को-पॉलीमर-आधारित थिकनर छुरा प्रतिरोध अनुप्रयोगों के लिए अनुपयुक्त पाए गए क्योंकि वे कपड़े को कड़ा और कठोर बना देते हैं, जिससे प्रदर्शन खराब हो जाता है। इसके विपरीत, एक तेल-पानी इमल्शन-आधारित थिकनर ने सिरेमिक कणों के साथ लेपित कपड़े के लचीलेपन को बनाए रखा। जबकि सिरेमिक कणों की बढ़ी हुई मात्रा ने छुरा प्रतिरोध को बढ़ाया, लेकिन कपड़े के साथ उनके खराब आसंजन ने एक व्यावहारिक चुनौती पैदा की। इस समस्या का एक व्यापक समाधान सिरेमिक कणों से लेपित और एस.टी.एफ. से संसेचित पी-एरामिड कपड़ों को मिलाकर विकसित किया गया, जिसने दोनों दृष्टिकोणों के सहक्रियात्मक लाभ का उपयोग किया। जब सिरेमिक लेपित और एस.टी.एफ. संसेचित कपड़े की परतों को क्रमशः प्रहार सतह और पीछे की तरफ रखा गया, तो फैब्रिक पैनल ने व्यक्तिगत उपचार वाले अपने समकक्षों की तुलना में काफी बेहतर प्रदर्शन किया।

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