MECHANICAL ANALYSIS OF WEAVING PROCESS TOWARDS SIZE-FREE WEAVING
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Abstract
To achieve efficient weaving of cotton warp yarns with reduced or no size, exploratory efforts towards comprehensive mechanical analyses of various loom components and mechanisms are presented. Theoretical and experimental studies are suggested which involve: 1) modification of loom components made of composite materials in order to withstand desired dynamic stresses due to fatigue, vibration, and impact; 2) relating the effect of specially coated loom components (mainly the reed) and stress variations on a size-less yarn during high speed weaving-like process; and 3) estimation of abrasion rate of such a yarn subjected to a high speed (weaving-like) travel and attrition through loom components made of modified materials, profiles, and/or coatings. The presented conceptual studies when conducted efficiently and successfully should help in the fundamental understanding of the size-less weaving process and, consequently, in developing improved yarn structures, weaving settings, conditions and design of critical loom components for minimizing warp yarn stresses, abrasion and damage during weaving. Any new knowledge gained would be useful for accomplishing efficient weaving with “reduced warp sizing,” “no warp sizing,” and even “traditional warp sizing.”

Introduction
More than 50% of all textiles produced globally are woven fabrics and approximately 80% of cotton produced worldwide goes into woven fabrics. Hence, the weaving industry is by far the largest market for cotton. The central aim of textile industry is to produce quality and cost-effective fabrics efficiently. The major components affecting performance of the weaving process are: the type of fabric; the quality, abrasion resistance, and hairiness of yarn; the yarn preparation involving winding, warping, and tensioning; the warp sizing formulation and the slashing machine parameters; and the weaving machine parameters, e.g. loom type, speed, settings, and mechanisms. The fundamental analyses of these components mainly involve textile manufacturing technology, textile engineering, chemical engineering, and mechanical engineering analysis and design.

In the existing art of manufacturing woven fabrics, the vital processes are warp sizing for efficient weaving and fabric de-sizing for desired finishing of the woven fabric. The warp sizing is the process of applying a protective coating to the yarn to enable it to withstand the complex stresses during the harsh mechanical actions of the weaving process, meanwhile maintaining or even enhancing the tensile strength of the yarn. The warp sizing involves materials such as, starch, polyvinyl alcohol, carboxymethyl cellulose, acrylic, and various other polymers. In the textile finishing of a woven fabric, the process of fabric desizing is essential to remove sizing chemicals that were applied to warp yarns prior to weaving and to achieve adequate finishing of fabric such as bleaching, dyeing, and/or any special finishing (flame retardancy, Durable Press, etc.). Removal of the size from fabric mainly involves enzymes, excessive hot water, detergent, soda and alkali.

The sizing of warp yarn and desizing of fabric woven with sized warp yarn are costly, complex and environmentally-sensitive, as they involve expensive chemicals, significant amount of energy for heating and recycling water and sizable cost for waste water treatment. The U.S. Environmental Protection Agency (EPA) have reported that the process of desizing is considered one of the textile industry’s largest sources of wastewater pollutants and often contributes up to 50 percent of the BOD load in wastewater from wet processing. In order to make the next generation textile industries cost effective and profitable, the United States Department of Agriculture (USDA) and
the National Cotton Council of America (NCC) have redirected research at SRRC to study the feasibility of reduced-size or size-free weaving on modern high-speed weaving machines.

To realize the goal of size-free weaving on modern high-speed weaving machines, several research approaches have been suggested and they are: (a) Improvement of yarn quality and structure, (b) Modification of conventional size preparation to significantly reduce size-add-on without affecting weaving performance, (c) Improving warp yarn preparation, and (d) Modification of profiles and/or surface characteristics of critical loom components. To demonstrate some of these concepts, about 50 meters of a light-construction fabric were recently woven, using a specially prepared size-free warp of good quality cotton yarn on a fly-shuttle loom operating under mill-like conditions, with no warp yarn failure/loom stoppage. The success of this weaving trial led to a more aggressive research on size-free weaving, using a modern high-speed weaving machine. It is a great pleasure to report here that we now have successfully woven, without warp sizing, a light-construction 100% cotton fabric on a modern Sultex flexible-rapier weaving machine operating under mill-like conditions and speed. Using a specially prepared size-free cotton warp, about 60 yards of fabric were woven (on October 27-29, 2004) without a single yarn failure or loom stoppage.

However, it may be noted that when the weaving speed was raised to the machine maximum (550 rpm) and the fabric construction was made close to the maximum cover factor feasible (i.e., the pick density was increased to 56 ppi), numerous nep-like, or minor-slub-like balls were formed causing some objectionable and even unacceptable defects in the fabric, although still no yarn-failure or machine-stoppage occurred. Although the research for the first time has shown that size-free weaving of 100% cotton yarns on a modern high-speed weaving machine is at least “mechanically feasible” for certain types of yarns, fabrics, and applications, the fundamental studies on the mechanical analyses of the weaving process are needed to fully understand the phenomenon of yarn abrasion for size-free weaving, in order to minimize the stated fabric defects and establish a technology that can be successfully implemented in textile industry.

In the last four decades numerous studies have been conducted towards the mechanical analysis of weaving process that mainly included the performance of yarn behavior, analysis of fatigue behavior, abrasion resistance, design and optimization of the weaving components, and modification of weaving mechanisms towards the successful weaving of conventionally sized yarns on high-speed weaving machines. Traditionally, the performance of warp yarn was evaluated based upon its tensile and breaking strength characteristics. However, during the weaving process the warp yarn breakage may occur even if and when the yarn tension is far below its breaking strength. Therefore, it is believed and confirmed through previous studies that such breakage is not only dependent on the tensile strength but also attributed to the repeated/cyclic stresses and strains, friction with metal components by coming into contact with the back-rest roller, drop wires, harness and reed, and even to the “inter-yarn” friction. Yarn failure may occur at the yarn regions of lower-than-average twist (thick places in the yarn), whereas the thin places in yarn due to high twist may have high abrasion resistance. Warp stress in a weaving cycle varies and reaches the state of highest stress when shed is fully open and at the moment of the reed beat-up. In the past several studies were carried out relating such breakage to fatigue phenomenon. The cumulative damage of the yarn is also argued due to repeated imposition of relatively low tensile load and abrasion. The breakage rate also depends on other factors such as weave, warp quality, loom speed, shed geometry, working conditions, etc. However, most of the existing studies are limited in evaluating and improving the performance of the sized warp yarn. Our aim here is to achieve comprehensive mechanical analysis in assessing and enhancing the weaving process and performance of the size-free or reduced-sized warp yarn.

**Mechanical Analysis of Loom Components and Mechanisms**

The loom components, such as the reed and heddles/frames, experience extreme inertial stress and vibrations due to current high weaving speeds on modern looms. These components are usually made of high carbon steel or aluminum and they generally have inferior fatigue flexural strength and bending stiffness compared to carbon-fiber-epoxy composite materials and polymers. Recently, it has been shown that natural frequencies of heddle frames made of composite materials were improved by 27%-43% compared to existing aluminum frames and maximum stresses were only 66% of aluminum frame at loom speed of 550 rpm. Their performance during high-speed operation is superior compared to steel and aluminum because they can have high specific modulus, high specific strength, and fatigue...
endurance. Also, because of their high damping capacity, the composite materials can be used in reducing large noise and vibration of structures, which eliminates the peak dynamic stresses in the loom components.

Figure 1: A schematic of weaving mechanisms showing representative dynamic measurement points.

This can be determined and verified by putting tri-axial accelerometers on the loom components and measuring dynamic tension variations of the yarn. A schematic of the main mechanisms of a weaving machine and some representative measurement sites are shown in Figure 1. Primary mechanical analysis deals with accumulating the dynamic behavior of the loom components during the weaving process. The tension variations in the (unsized) yarn and the dynamic characteristics of the loom component can be correlated to establishing the dynamic stress distribution on the yarn as well as the loom components. This, in turn, can be the basis for any design modification of the component(s). Simultaneously, analytical static and dynamic analyses of the loom components can be conducted by using standard finite element software. The fatigue behavior, stress analysis and vibration characteristics can be simulated for different material properties, geometry, and loading conditions. This type of analysis can be useful in determining the suitable composite material and the design parameters for the various loom components.

The main idea behind a comprehensive mechanical analysis of loom components and mechanisms is to analyze the interaction of size-less warp yarn and metallic and non-metallic (composite material) surfaces. Some representative analytical investigation schemes are given here. For example, the variation of tension force in the yarn due to the oscillation of heddles and reed is governed by the following differential equation,

$$\frac{\partial^2 u}{\partial t^2} = c^2 \frac{\partial^2 u}{\partial x^2},$$

(1) where, $c = \sqrt{F/\rho}$ is the wave propagation speed of disturbance in the stress along the yarn, $F$ is the yarn tensioning force and $\rho$ is the mass per unit of the yarn. By using separation of variables and converting the governing equation into an eigenvalue problem, the relationship between the frequency of oscillation and the tensioning force can be obtained. By using finite element simulations, the stress contours corresponding to different accelerations can even determine the fatigue life of the loom component. The key issue really is that of finding or approximating the abrasion rate of unsized yarn due to the contact against the loom components made of different materials. By using the fracture analysis, the surface flaw sizes on a loom component can be estimated. For example, the Griffith failure criteria can be used for brittle composite Glass fiber materials as,
\[ d = \frac{EG}{\pi^2S^2}, \]

(2) where, \( d \) is the surface flaw size on loom components and \( E \) is the modulus of elasticity, \( G \) is the fracture toughness and \( S \) is the strength of the unsized yarn. In general the mechanical analysis will include the following: (a) studies on abrasion resistance of unsized yarn subjected to non-metallic surfaces, (b) dynamic stress distribution in unsized yarn and composite loom components during weaving process, (c) static, dynamic, fatigue and impact behavior of loom components made of composite materials and (d) relationship between the high frequencies of weaving operation and the instability of stresses (sudden peak stresses).

**Lab-scale experimentation**

Figure 2: Schematic of a lab-scale yarn endurance tester to assess weavability of a size-less, reduced-size, or even a conventionally sized yarn.

In order to achieve successful weaving of a size-free yarn, a fundamental study of the yarn abrasion/damage on a lab scale instrument (simulating weaving-like conditions) will be useful. A schematic of a prototype version of such an instrument was proposed and shown in the Beltwide Conferences last year. The proposed experimentation on a slightly modified version of the instrument, Figure 2, targets accumulation of data in real time environment, such as speed of yarn, yarn friction, tension in yarn, and abrasion rate of the yarn when passing through drop wires, heddles and reed made of different geometry or profile and different metallic and non-metallic materials. The data can be obtained by integrating different sensors with the LABVIEW software that will enable us to program different modules of the weaving process and acquire the data simultaneously. The whole process can be monitored through the...
programmed code using a specifically designed control panel. The required data-acquisition card, accelerometers and LABVIEW software can be acquired through Louisiana State University (LSU), Baton Rouge, the Mechanical Engineering faculty of which has gladly agreed to cooperate with USDA-ARS-SRRC in this priority research on size-free weaving. Other required instruments such as friction tester, dynamic tension measuring digital meters, hairiness measurement sensors, etc., are available in SRRC. Thus, by manufacturing the heddles and reed wires made of modified materials, geometries, and/or finishes, several parametric studies for the analysis of abrasion behavior of unsized yarn can be successfully conducted.

These studies may eventually establish: (a) the effect of loom components, tension of the yarn, and speed of weaving on the abrasion rate of size-less yarn, (b) optimum fabric construction that can be efficiently woven without traditional warp sizing at the weaving machine’s normal running speed and (c) the maximum weaving speed at which a commercially acceptable standard fabric construction can be efficiently woven without traditional sizing.

**Conclusions**

To achieve efficient weaving with warp yarns of reduced or no size, exploratory efforts towards comprehensive mechanical analysis of various loom components and mechanisms are presented. Theoretical and experimental studies are suggested which involve: 1) modification of loom components made of composite materials in order to withstand desired dynamic stresses due to fatigue, vibration and impact; 2) relating the effect of newly developed loom components and stress variations on a size-less yarn during high speed weaving-like process; and 3) estimation of abrasion rate of such a yarn subjected to a high speed (weaving-like) travel and attrition through loom components made of modified materials, profiles, and/or coatings. The presented conceptual studies when conducted efficiently and successfully should help in developing improved yarn structures, weaving settings, conditions and design of critical loom components for minimizing warp yarn stresses, abrasion and damage during weaving and contribute to the new knowledge that would be useful for accomplishing both the “reduced-size” and “no-size” weaving of fabrics and for improving even the traditional weaving with conventionally sized yarns.

**References**


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