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Failure Mechanism of Staple Yarns: A Critical Review

B. R. Das[*], S. M. Ishtiaque and R. S. Rengasamy
Department of Textile Technology, Indian Institute of Technology, New Delhi-110016, India

ABSTRACT

The breaking strength of spun yarn is accepted as one of the most important parameters for assessment of yarn quality and one basic way to increase profit and quality in textile process is to hold yarn breakage to a minimum level. The mechanism of yarn failure under tensile loading decides the strength of staple yarns. This article presents the critical review of various theoretical and experimental works pursued on static and dynamic failure mechanism of ring, rotor, air-jet and friction spun staple yarns. The reported failure mechanism of yarns in woven fabrics is also summarized. The various material, spinning and testing parameters influencing the static and dynamic failure mechanism are discussed.

Keywords: Dynamic failure, Fiber break, Fiber slip, Static failure, Yarn strength

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1. Introduction

The staple yarn is a twisted fibrous structure and twists in the staple fiber yarns have the primary function of binding the fibers together by friction to form a strong yarn. The coherence built up in the yarn is because of the frictional forces brought into play by the lateral pressure arising from the application of tensile stress along the yarn axis. The magnitude of the coherence is built up from zero at fiber ends and reaches a maximum at the middle of the fiber length, as theoretically proven by Pan [1]. Because of gradual building up of the cohesion force in a staple fiber yarn during yarn extension, slippage occurs between the fibers at fiber ends, where the coherence is not great enough to grip the fiber tips. All the fibers in a staple yarn will partially slip at their ends and will be tightly gripped at a central region, depending on fiber properties, fiber orientation in the yarn and most importantly, the twist level of the yarn. Turner [2] and Navkal et al [3] pointed out that the proportions of fibers slip or break during yarn failure are dependent on the degree of twist in the yarn. Clegg [4] explained that in ordinary yarns, breakage of a higher percentage of constituent fibers is invariably associated with the yarn breakage; though the results do not show the degree of twist at which the fiber breakage begins to predominate over the fiber slippage. The actual failure behavior of staple yarn can be explained by slippage, breakage and both slippage & breakage of fibers during tensile loading.

An important aspect of the dynamic tensile testing of the yarns is the possibility of predicting the performance of yarn in subsequent process. The single thread tensile test method gives the value of tensile strength, which is sometimes referred to as static yarn strength and the mechanism leading to such yarn failure is treated as static yarn failure mechanism. The static yarn strength cannot accurately predict the running behavior of yarn on subsequent machines. Continuous tensile testing of yarn involves transporting the yarn under constant tension at constant output speed. Thus, in continuous tensile testing every inch or millimeter of yarn is tested to generate true elongation of yarn at specific dynamic tension & speed condition and tensile characteristics are continuously assessed. Lawson Hemphill Constant Tension Transport (CTT) instrument is used to measure the dynamic strength (g) and dynamic extension (%) of staple yarns. Dynamic yarn strength is the maximum tension level under which the yarn is transported without any break for a length of 200 m at a speed of 40 m/min. The measured extension at this maximum tension level is considered as the dynamic extension (%) and the mechanism causing the yarn failure with little increase in yarn tension above the dynamic yarn strength is considered as the dynamic yarn failure mechanism. The continuous testing simulates actual manufacturing conditions more closely than static tensile testing [5-8]. Hence, the failure mechanism of staple yarn under dynamic conditions has more resemblance with yarn failure in post spinning operations than failure under static condition.

2. Static Failure Mechanism

The mechanism of yarn failure is usually explained on the basis of stress-strain characteristics of yarns. The staple yarn may fail either because of fiber slippage (e.g. in low twist ring, rotor and air-jet yarns) or slippage and/or breakage in medium and highly twisted yarns. The nature of breakages in different regions is explained in Figure 1. The Figure 1 reveals that the nonlinear mechanical behavior of a yarn with linearity restricted for very small stress only (region I), where slippage is prevented by friction. In region II, fibers start to slip and for higher stress (region III), both slippage and breakage of fibers occur until yarn breakage can be observed [9].

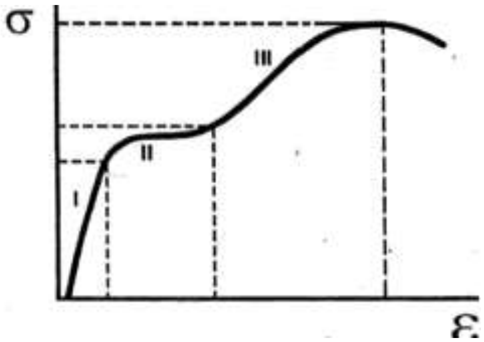


Figure 1. Stress-strain curve for a staple yarn [9]

The percentage of broken and slipped fibers as well as the structure at the region of yarn failure reflects some interesting information from which an insight into the mechanism of spun yarn failure is obtained. In addition, these provide more direct evidence of the failure characteristics of spun yarns. Gulati et al [10] found a close relationship between percent fiber rupture and yarn strength. According to their study, the correlation coefficient between the percent fiber rupture and yarn strength were 0.94, 0.97, and 0.99 for 20^s, 30^s and 40^s count ring yarns. Tallant et al [11] found that if a fiber has to rupture during tensile failure of a yarn, it should have a certain minimum length. Further, such a length at each end of a fiber is unavailable for rupture and therefore incapable of contributing appreciably to yarn tenacity. To find this minimum fiber length, he proposed a mathematical model for translation of fiber bundle strength to yarn tenacity, as expressed below (Equation 1):

$$Y = a \times f(l, x) \times S + b \qquad (1)$$

Where, Y is the single yarn tenacity; S, the fiber bundle strength; l is the length distribution of cotton; x, the critical or the minimum length of fiber; $f(l, x)$, the effective weight, and a & b, the constants. It was found that fibers shorter than about 3/8 inch do not contribute to yarn tenacity and a 3/8 inch portion of each longer fiber is ineffective. It is implied that on an average, the 3/16 inch tip at each end of each fiber doesn't contribute to the yarn tenacity. Their investigation gave interesting findings that the "zero" gauge fiber bundle test is superior to the 1/8 inch gauge length test as a criterion for relating bundle to yarn tenacity, if the gauge length value is modified by the effective weight. Gulati et al [10] observed that fibers below 0.5 inch length don't contribute to yarn strength. Balasubramanian et al [12] reported that the minimum fiber length requirement for rotor yarn is higher than that for ring yarn. This phenomenon was explained briefly on the basis of the structural differences between ring and rotor yarns. The work reported by Hearle et al [13] on the tensile behavior of staple yarns mainly concerns ring spun yarns and based on ideal helical geometry. They explained the tensile properties of a staple yarn in terms of the combined effects of obliquity and fiber slippage, which cause yarn strength losses.

2.1 Static Failure Mechanism of Single Component Staple Yarns

According to Ghosh et al [14], the phenomenon of spun yarn failure is strongly dependent on the yarn structure namely, the configuration, alignment and packing of the constituent fibers in the yarn cross-section. They have studied the tensile failure mechanism of ring , rotor, air-jet and friction spun yarns at wide range of varying strain rates (from 5 mm/min to 400 m/min) and gauge length (from 0 mm to 500 mm). They found that the failure zone length of ring spun yarn is smallest compared to other yarns at higher gauge length because of better migration of fibers in comparison to other spun yarns, but air-jet spun yarn displays the shortest failure zone length at lower gauge length (less than fiber staple length) and highest strength, which can be attributed to the fact that it comprises around 80% of core fibers in the cross-section and at lower gauge length, the both the ends of the fibers are gripped by the jaws. The failure mechanism is dominated by slippage mechanism at low strain rate, as more time is available for a fiber to change its position and in the process relieve its tension, whereas at higher rate of loading, impact loading at high strain rate is responsible for more fiber breakage. Singh et al [15] used the optical isolation of tracer fiber technique for assessment of fibers breaking or slipping during failure of a cotton ring spun yarn under tensile loading. They reported an increase in yarn strength with an increase in extension rate for the range 0.1 cm/min to 100 cm/min. When tested at different strain rates, it was observed that, except for very low strain rates, increase in tensile strength with strain rate is a direct contribution of increased strength contribution due to fiber rupture and that frictional contribution remains essentially constant except very low strain rate of 0.1 cm/min.

Nanjundayya [16] did some work on strength of cotton ring yarn with special reference to the structure at the region of break. He concluded that the yarn generally breaks at thinnest place during strength testing. The length of slippage decreases with increase in yarn twist. The strength of a cotton yarn has been examined critically with reference to the twist, diameter and number of fibers at the place of break. Two cotton yarns showed that a majority of specimens broke at a place where the diameter was minimum and the twist maximum. The results were also used to examine the relationship between the diameter, turns per inch and twist angle. Counts of the number of fibers at various points in the broken specimen under the microscope made possible an estimation of the number of broken fibers and the percentage of fiber strength used in yarn rupture and these were compared with the theoretical predictions made from Kohler's formula. The percentage of fibers broken and the percentage of fiber strength utilized in yarn strength were much higher than those recorded by previous workers, the reason for this being that the present values were based on the actual number of fibers present in the cross section at the place of break. In addition, some data on the length of slippage, apparent density and their relationships were given. Köhler [17] derived a relationship between the fiber length and the number of broken fibers at the yarn breakage zone. He assumed a cotton yarn having n fibers of length l mm in each yarn cross-section, x mm as the length of fiber that slips during the yarn failure, that is, if a fiber has to break during the yarn failure, it has to reach more than $x/2$ mm beyond either side of the place of break and this length is referred to as the 'length of slippage'. If the fibers are evenly distributed along the yarn, there will be within a length of x mm, nx/l fibers slipping apart. However, yarns are not spun from fibers of only one length, but the above-mentioned value of nx/l applies even when the average length of fibers is equal to l mm and all fibers are of length greater than the length of slippage. Hence, the percentage of fibers in the yarn cross-section that slip apart is equal to $100x/l$ and the percentage of fibers that break, z is given by (Equation 2):

$$z = 100(1 - \frac{x}{l}) \tag{2}$$

Realff et al [18] studied the mechanism of yarn failure for cotton and polyester ring, rotor and air-jet spun yarns at different gauge lengths. They proposed that at longer gauge lengths, yarn failure was found to be the result of combined slippage and breakage of fibers. At shorter gauge length, yarn failure was shown to result from a greater extent of fiber breakage and less slippage. The balance between fiber slippage and breakage was shown to vary with the yarn structure. According to their observation the length of the failure zone was found to vary with the spinning technologies and gauge lengths. Broughton et al [19] studied the failure mechanism of ring spun polyester yarn for analyzing an industrial problem involving inter-fiber friction. The defective yarn strength was approximately 10% of the normal yarn strength. The major difference they noted that the fibers in the normal yarn exhibit a 59% greater inter-fiber frictional force than those from the defective yarn. The normal yarn was strong and exhibited a "pop" when broken, but the defective yarn was weak and just slipped apart as it failed. This slippage was readily visible when yarn was observed under the microscope during breaking. Observation of the broken ends revealed a rather abrupt break in the normal yarn, covering a distance of perhaps 0.25 inch. The defective yarn break extended for over 1 inch and involved a gradual reduction in the number of fibers. The normal yarn obviously had a large number of broken fibers, whereas the defective yarn had very few.

Ishtiaque et al [20] studied the static failure mechanism of carded and combed cotton yarns of various counts (16^s, 20^s, 24^s, 30^s and 40^s) with three levels of twist multiplier (3.7, 4.0 and 4.3) made from 80 % J-34 cotton and 20% Sankar-4 cotton. They classified the broken ends into three groups, namely sharp, taper and slipped ends, based on their captured breaking zone images, as shown in Figure 2 (a, b & c). The percentage of sharp broken ends is more in combed yarn than in carded yarn and the percentage of tapered and slipped ends is less in the combed yarn than in the carded yarns. This is because of the higher packing coefficient of combed yarn due to higher proportion of long fibers. Carded yarn has higher percentage of short fibers. Short fibers are susceptible to slippage because of lower contact area with neighboring fibers, which results in poor fiber-fiber cohesion in the yarns. The percentage of sharp broken ends increases with the increase in yarn twist multiplier and yarn count. The increase in percentage of sharp broken ends with increase in yarn twist multiplier is because of the increase in yarn compactness, leading to higher crossing points between the fibers, fiber-fiber cohesion. This synergetic effect of fiber cohesion and increased compactness offer higher resistance to fiber slippage during the yarn rupture. As the same twist multiplier level was applied for three counts of the yarn, the packing coefficient of yarn increases with the increase in yarn fineness is due to increase in twist/inch value. As the yarns are made out of the same fiber mix the higher number of fibers in the coarser yarn leads to higher fiber slippage. They observed that the yarn count is dominating the yarn twist multiplier in deciding the percentage of sharp broken ends.

(a) (b) (c)

Figure 2. Classification of broken end structures: (a) sharp broken end, (b) tapered broken end (c) slipped broken end [20]

Rengasamy et al [21] studied the failure mechanism of ring, rotor, air-jet spun 20^s Ne viscose staple yarns and broken ends collected from fabric tensile testing. Fabrics were produced with ring/ring, rotor/rotor and air-jet/air-jet warp & weft combinations. They observed that the mechanism of yarn failure inside the fabric is different that of single yarn and the former exhibits more fiber rupture, which is due to the interactive binding effect between warp and weft yarns inside the fabric under the application of load.

2.2 Static Failure Mechanism of Blended Staple Yarns

The first theoretical work published concerning the mechanics of blended yarn was by Hamburger [22]. He was concerned with the fact that the blended yarns have breaking strengths lower than those expected from the summation of the proportioned constituent fiber component strengths. Considering the two components *A* and *B* (with *A* representing viscose and *B* representing polyester), to have independent load elongation curves and to be under tension in parallel, he predicted the behavior of the blended yarn from the tensile behavior of its components. The tensile behavior of the viscose and polyester fiber used in his research is shown in Figure 3. For a blended yarn, the tensile resistance will correspond to the blend-proportion weighed average of the tensile resistance of the two components up to the limit of strain, at which the less extensible component *A* failed. At strains beyond this point, yarn resistance is fully corresponds to the resistance of the unbroken component. Thus a blended yarn was expected to have two breaking points- one for its less extensible component and the other for its more extensible one. The breaking strength of the blend was reported as the higher of these two values. The first rupture level would be maximum for a yarn made of 100 % of fiber *A*, and its minimum would occur in a yarn containing no portion of fiber *A*. The first rupture point would never fall to zero in the absence of component *A*. Similarly, the second rupture level will be maximum for a yarn containing 100% of fiber *B* and would be minimum for yarns containing less or no portion of fiber *B*. The solid lines of Figure 4 reflect the generally reported variations of breaking strength with blend levels. In general the first and second ruptures are as given below (Equation 3 and 4):

$$P_1 = \frac{bD}{100}(aS_A + bS_B) \tag{3}$$

$$P_2 = \frac{bD}{100} S_B \tag{4}$$

Where, P_1 = first rupture, P_2 = second rupture, D = total yarn denier, S_A= breaking tenacity of fiber A, S_B = breaking tenacity of fiber B, and a & b are weighted ratios of fiber A and B in the yarn.

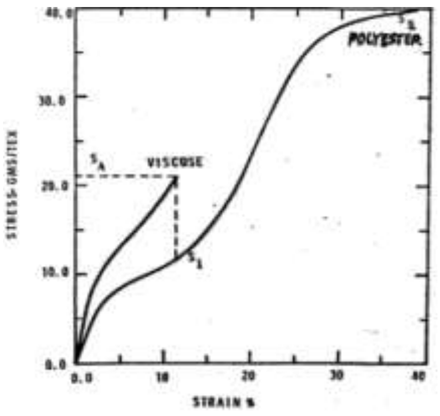


Figure 3. Stress-strain curves of viscose and polyester fibers [22]

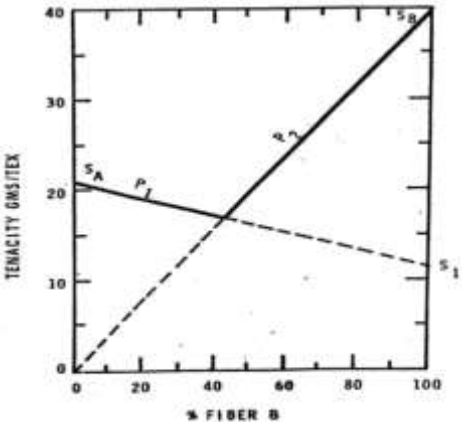


Figure 4. Theoretical effect of blend proportion on yarn strength [22]

Cybulska [9] investigated the failure mechanism of 29 Tex, 30 Tex and 24 Tex 50/50 cotton/polyester blended ring, rotor and air-jet spun yarns respectively and 22 Tex cotton vertex yarn. He investigated the failure mechanism of the above yarns based on the image analysis process. The yarns were subjected to uniaxial loading on a tensile tester and images of the yarn before and after breaking are recorded. For ring spun yarns the failure occurred in the region of minimum yarn diameter and maximum Δd (difference in yarn diameter before and during breaking) values for the ring spun yarn. The failure was a mixed mode of fiber slippage and breakage. The twist angle in the failure region in most of the cases has relatively low or minimum values. The wrapper fibers in vortex yarn in the failure region were loose and folded in the form of loops, so they could not prevent the core fibers from slipping. The failure in case of open end and air-jet yarns occurred due to fiber slippage. He explained that the yarns (ring, rotor, air-jet & vortex) with higher diameter and more uniform diameters can be characterized by higher breaking load, elongation at break and energy to break, despite yarn technology resulting in different migration and relative disposition of fibers. The parameter Δd gives more useful information for predicting the tensile behavior of yarns than the co-efficient of variation of yarn diameter, because this parameter can reflect the way fiber ends are distributed along the yarn axis better than the CV% of diameter. Yarn regions with relatively higher Δd values can be characterized by higher than average numbers of fiber ends, which can result in lower frictional resistance and easier fiber slippage in those regions. The parameter d and Δd explains the failure behavior of all types of yarn, but these values cannot appropriately explain the failure behavior of air-jet spun yarns. The failure region in air-jet spun yarn can be characterized by the low number of wrapper fibers and high distance between wrapper fibers. The expression of Δd is as follows (Equation 5):

$$\Delta d = \left| d_i - d_{i-1} \right| \tag{5}$$

Kemp et al [23] investigated the stress-strain characteristics of a series of nylon/cotton blended and cotton staple yarns. The cotton fibers in the blended yarns sustain a high stress at strains above which all cotton yarns break. This stress, in fact, rises considerably above the breaking stress of all-cotton yarns. They have found that at high strains the cotton fibers often broke more than once and the ultimate strength of blended yarns are lower due to the different breaking strains of the components.

The failure mechanism in blended yarns is completely different than the pure staple yarns. Pan [24] explained that there are several aspects that make blended structures much more difficult to analyze. There is difference in their contributions towards the overall behavior of the structure, due to the diverse mechanical properties of the constituent fibers. The interaction between the two constituents alters the nature of yarn behavior, especially during fracture. The yarn strength become higher, lower or remain constant when the amount of reinforcing fiber increases, depends on the difference between the fiber-breaking strains of the two fiber types. The interaction between two fiber types leading to "hybrid effect" complicates the failure analysis. Harlow [25] defined "hybrid effect" as positive or negative deviation of a certain mechanical property from the rule of mixtures behavior. Pan [26] theoretically demonstrated that, the effect of the fiber slippage at fiber ends in staple fiber yarns during yarn extensions becomes negligible when the yarn twist level is reasonably high. Pan et al [27] studied the interaction between the fibers, the local stress redistribution due to fiber breakage, hybrid effects in blended yarns. They determined the minimum and critical blend ratios of the reinforcing fibers and the effect of fiber breaking strains on hybrid effect.

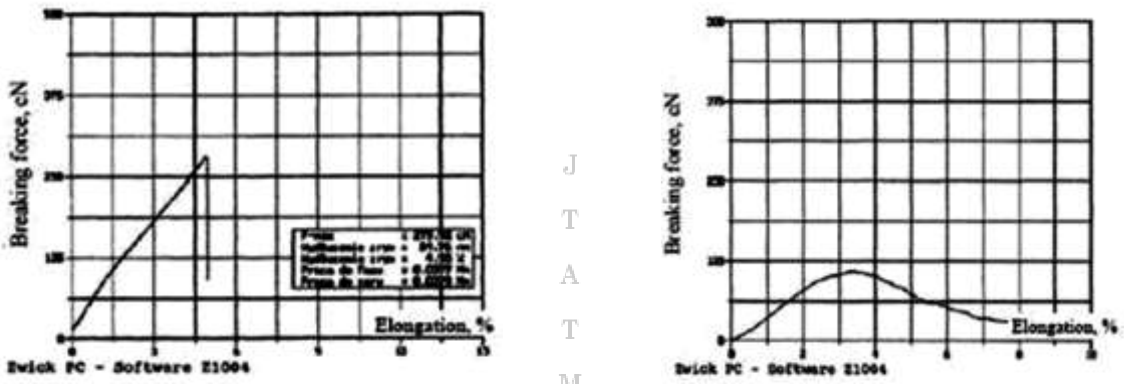
Cheng et al [28] studied the breakage mechanism of polyester/cotton blend yarns using scanning electron microscope. The low tensile strength of blended yarn may be related to the low friction coefficient between cotton and polyester fibers. They explained that the cotton fibers fail first because of its low strain to break. The studies on blended twisted yarn by Machida [29], Monego et al [30] and staple yarns at small extensions by Carnaby et al [31] and Narota et al [32] explained that the stress-strain curves of ring spun yarns can be divided in to at least three regimes: an initial non linear regime, and a secondary linear regime and a third low average tangential modulus regime with load undulation. The initial two zones reflect the cooperative contribution of the cotton and polyester fiber stress-strain behavior; the third regime reflects the stress- strain behavior of the polyester fiber accompanied by multiple breakages of cotton fibers. Therefore, the boundary between the second and third regimes should be yarn strain, which can initiate cotton fiber breakage in a blended yarn. Brody [33] carried out breakage analysis studies on polyester and polyester/cotton blend spun yarns. He postulated that the yarn breakage takes place in two stages: an initial yarn rupture, followed by breakage of polyester fibers spanning the gap. Initial rupture is probably caused when a critical fraction of broken fibers is exceeded. The breakage of 100% polyester yarns seems to be initiated by the breakage of the small but significant fraction of fibers, breakage continues catastrophically. He claimed that mill breaks occur by fiber slippage before the yarn was fully developed, probably at the drafting stage. Önder et al [34] were studied the stresses breakage analysis in worsted yarns. They explained that the fiber slippage and breakage do not happen together during breakage of ideal yarns. Their results support that the fiber slippage can be a more effective factor in the failure mechanism of worsted yarns.

Rossettos et al [35] have used a micromechanical model to study the hybrid effects of blended yarns at the breaks. They developed the model consisting of an equal number of low elongation (LE) and high elongation (HE) fibers undergoing axial extension. They indicated how the slip region of a broken fiber and an associated friction play a role in this effect. The stresses concentration close to the fiber break depends on the whether the broken fiber is an LE or an HE fiber. The hybrid effect intensifies, if the principal fibers are LE fibers. Rossettos et al [36] studied the effect of frictional shear forces along slipping fibers near a fiber break for blended yarns consisting of an equal number of low elongations (LE) and high elongation (HE) fibers undergoing axial extension, which also supported the hybrid effect as explained earlier.

The failure behavior of yarn in real application (fabric form) is equally important like the post spinning performance of yarn. Seo et al [37] studied the failure behavior of yarn in woven fabric form and compared with free-state yarn failure. The zero gauge length test of free-state yarns, is similar to the tensioned yarns became jammed between cross yarns before straightening in woven fabric. However, when fabric structure was such that tensioned yarns could straighten without cross yarn jamming, the resulting failure zones were considerably longer, with a mixture of fiber fracture and slippage similar to that observed in long gauge length tests of free-state yarns.

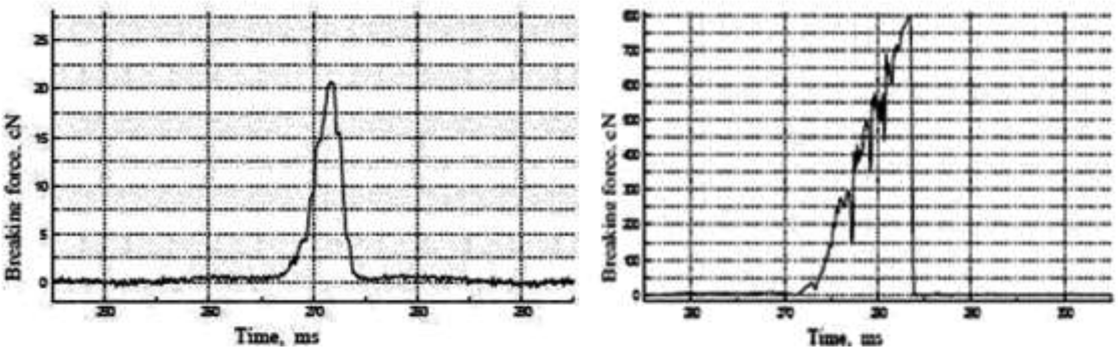
3. Dynamic Failure Mechanism of Staple Yarns

The dynamic failure of different textile structures are least concerned in research work. Slodowy et al [38] described that continuity loss of yarn during various processes is due to fiber slippage or yarn breakage. Failure situations under static condition have been explained based on stretching diagrams, as shown in Figure 5 (a & b). They developed the method to differentiate the mechanism of continuity loss under dynamic conditions of the longitudinal loading of a loose linear fiber product which occurs by means of fiber breakage and fiber slippage, as shown in Figure 6 (a & b). They claimed that the twist of the product has an essential influence on the products strength under dynamic loading.



(a) (b)

Figure 5. Continuity loss of staple yarns: (a) breakage of fibers (b) slippage of fibers [38]



(a) (b)

Figure 6. Yarn breakage diagrams in dynamic conditions: (a) breakage of fibers, (b) slippage of fibers [38]

Ishtiaque et al [19] studied the dynamic failure mechanism of carded and combed cotton yarns of various counts (16^s, 20^s, 24^s, 30^s and 40^s) with three levels of twist multiplier (3.7, 4.0 and 4.3) made from 80 % J-34 cotton and 20% Sankar-4 cotton. The trend of effect of yarn count and twist multiplier on dynamic failure mechanism is similar to static failure mechanism; however the rate of increase is quite low in dynamic testing. They characterized the interactive effect of yarn TM, yarn count and dynamic testing speed along with their individual influence on the dynamic failure mechanism. It was observed that the effect of yarn twist multiplier is dominating the yarn failure mechanism than other influencing factors.

4. Conclusions

The foregoing discussion gives an overview of the various theoretical and experimental aspects of the static and dynamic failure mechanism of staple yarns. The yarns representing different spinning technologies are concerned. The failure mechanism of free state staple yarn and the same yarn in woven fabric is compared. Finally, an inference may be drawn that the discussions made in this article is useful for the textile researchers as a tool for further research in the area of failure mechanism of staple yarns. The next generation research on failure mechanism of staple yarns in warping and weaving process using sophisticated image analysis tool could boost up the production efficiency providing complete hold over controlling the frequency of end breakages.

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