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Static Failure Mechanism of Staple Yarns: A Critical Review

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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 study presents the critical review of various theoretical and experimental works pursued on static failure mechanism of ring, rotor, air-jet and friction spun staple yarns. The reported failure mechanisms of slivers androvings and yarns in woven fabrics are also summarized. The aterial, spinning and testing parameters influencing the static failure mechanisvarious mm are discussed.

Key words: Fibre break, fibre slip, staple yarn, static failure, yarn strength

INTRODUCTION

The staple yarn is a twisted fibrous structure and twists in the staple fibre yarns have the primary function of binding the fibres together by friction to form a strong yarn. The coherence built up in the yarn is because of the twist, which depends on the frictional forces brought in to play by the lateral pressures between fibres arising from the application of tensile stress along the yarn axis. The magnitude of the coherence is built up from zero at fibre ends and reaches a maximum at the middle of the fibre length (Pan, 1992). Because of gradual building up of the cohesion force in a staple fibre yarn during yarn extension, slippage occurs between the fibres at fibre ends, where the coherence is not great enough to grip the fibre tips. All the fibres in a staple yarn will partially slip at their ends and will be tightly gripped at a central region, depending on fibre properties, fibre orientation in the yarn and most importantly, the twist level of the yarn. Navkal and Turner (1930) pointed out that the proportions of fibres slip or break during yarn failure are dependent on the degree of twist in the yarn (Turner, 1928; Navkal and Turner, 1930). Clegg (1940) explained that in ordinary yarns, breakage of a higher percentage of constituent fibres is invariably associated with the yarn breakage; though the results do not show the degree of twist at which the fibre breakage begins to predominate over the fibre slippage. The actual failure behaviour of staple yarn can be explained by slippage, breakage and both slippage and breakage of fibres during tensile loading. 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.

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 fibre slippage (e.g., in low twist ring, rotor and

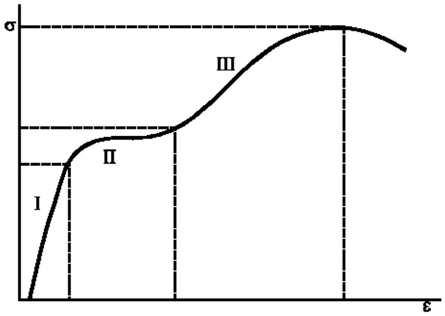

Fig. 1: Stress-strain curve for a staple yarn

air-jet yarns) or slippage and/or breakage in medium and highly twisted yarns. The nature of breakages in different regions is explained in Fig. 1. It is revealed from the figure that the nonlinear mechanical behaviour of a yarn with linearity restricted for very small stress only (region I), where slippage is prevented by friction. In region II, fibres start to slip and for higher stress (region III), both slippage and breakage of fibres occur until yarn breakage can be observed (Cybulska *et al.*, 2001).

The percentage of broken and slipped fibres 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 and Turner (1930) found a close relationship between percent fibre rupture and yarn strength. According to their study, the correlation coefficient between the percent fibre 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.* (1963) found that if a fibre 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 fibre is unavailable for rupture and therefore incapable of contributing appreciably to yarn tenacity. To find this minimum fibre length, he proposed a mathematical model for translation of fibre bundle strength to yarn tenacity, as expressed below (Eq. 1):

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

where, Y is the single-yarn tenacity; S is the fibre bundle strength; l is the length distribution of cotton; x is the critical or the minimum length of fibre; f (l, x) is the effective weight and a and b, the constants.

It was found that fibres shorter than about 3/8 inch do not contribute to yarn tenacity and a 3/8 inch portion of each longer fibre is ineffective. It is implied that on an average, the 3/16 inch tip at each end of each fibre doesn't contribute to the yarn tenacity. Their investigation gave interesting findings that the zero gauge fibre 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 (Tallant *et al.*, 1963). Gulati and Turner (1930) observed that fibres below 0.5 inch length don't contribute to yarn strength. Salhotra and Balasubramanian (1986) reported that the minimum fibre 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 and Wong (1977) on the tensile behaviour 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 fibre slippage, which cause yarn strength losses.

Static failure mechanism of single component staple yarns: According to Ghosh *et al.* (2005) the phenomenon of spun yarn failure is strongly dependent on the yarn structure namely, the configuration, alignment and packing of the constituent fibres 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 to 400 m min^{-1}) and gauge length (from 0 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 fibres in comparison to other spun yarns, but air-jet spun yarn displays the shortest failure zone length at lower gauge length (less than fibre staple length) and highest strength, which can be attributed to the fact that it comprises around 80% of core fibres in the cross-section and at lower gauge length, the both the ends of the fibres are gripped by the jaws. The failure mechanism is dominated by slippage mechanism at low strain rate, as more time is available for a fibre to change its position and in the process relieve its tension, where as at higher rate of loading, impact loading at high strain rate is responsible for more fibre breakage (Ghosh *et al.*, 2005). Singh and Sengupta (1977) used the optical isolation of tracer fibre technique for assessment of fibres 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 to 100 cm min^{-1}. 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 fibre rupture and that frictional contribution remains essentially constant except very low strain rate of 0.1 cm min^{-1} (Singh and Sengupta, 1977). Nanjundayya 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 fibres 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 fibres at various points in the broken specimen under the microscope made possible an estimation of the number of broken fibres and the percentage of fibre strength used in yarn rapture and these were compared with the theoretical predictions made from Kohler's formula. The percentage of fibres broken and the percentage of fibre 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 fibres present in the cross section at the place of break. In addition, some datas on the length of slippage, apparent density and their relationships were given (Nanjundayya, 1966). Realff *et al.* (1991) 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 fibres. At shorter gauge length, yarn failure was shown to result from a greater extent of fibre breakage and less slippage. The balance between fibre 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.

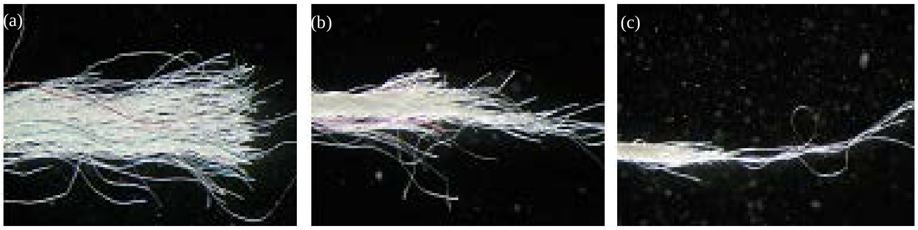

Fig. 2: Classification of broken ends structure: (a) sharp broken end (b) tapered broken end and (c) slipped broken end

Broughton *et al.* (1992) studied the failure mechanism of ring spun polyester yarn for analysing an industrial problem involving inter-fibre friction. The defective yarn strength was approximately 10% of the normal yarn strength. The major difference they noted that the fibres in the normal yarn exhibit a 59% greater inter-fibre 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 fibres. The normal yarn obviously had a large number of broken fibres, whereas the defective yarn had very few (Broughton *et al.*, 1992). Ishtiaque *et al.* (2008) 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 Fig. 2a-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 fibres. Carded yarn has higher percentage of short fibres. Short fibres are susceptible to slippage because of lower contact area with neighboring fibres, which results in poor fibre-fibre 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 fibres, fibre-fibre cohesion. This synergetic effect of fibre cohesion and increased compactness offer higher resistance to fibre 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 fibre mix, the higher number of fibres in the coarser yarn leads to higher fibre slippage. They observed that the yarn count is dominating the yarn twist multiplier in deciding the percentage of sharp broken ends (Ishtiaque *et al.*, 2008). Rengasamy *et al.* (2008) studied the failure mechanism of ring, rotor, air-jet spun 20^sNe 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 and weft combinations. They observed that the mechanism of yarn failure inside the fabric is different that of single yarn and the former exhibits more fibre rupture, which is due to the interactive binding effect between warp and weft yarns inside the fabric under the application of load (Rengasamy *et al.*, 2008).

Static failure mechanism of blended staple yarns: Cybulska 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 Äd (difference in yarn diameter before and during breaking) values for the ring spun yarn. The failure was a mixed mode of fibre slippage and breakage. The twist angle in the failure region in most of the cases has relatively low or minimum values. The wrapper fibres in vortex yarn in the failure region were loose and folded in the form of loops, so they could not prevent the core fibres from slipping. The failure in case of open end and air-jet yarns occurred due to fibre slippage. He explained that the yarns (ring, rotor, air-jet and 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 fibres. The parameter Δd gives more useful information for predicting the tensile behaviour of yarns than the co-efficient of variation of yarn diameter, because this parameter can reflect the way fibre 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 fibre ends, which can result in lower frictional resistance and easier fibre slippage in those regions. The parameter d and Δd explains the failure behaviour of all types of yarn, but these values can not appropriately explain the failure behaviour of air-jet spun yarns. The failure region in air-jet spun yarn can be characterized by the low number of wrapper fibres and high distance between wrapper fibres (Cybulska *et al*, 2001). The expression of Δd is as follows (Eq. 2):

$$\Delta d = \left| d_i - d_{i-1} \right| \tag{2}$$

Kemp and Owen (1955) investigated the stress-strain characteristics of a series of nylon/cotton blended and cotton staple yarns. The cotton fibres 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 fibres often broke more than once and the ultimate strength of blended yarns are lower due to the different breaking strains of the components (Kemp and Owen, 1955).The failure mechanism in blended yarns is completely different than the pure staple yarns. Pan explained that there are several aspects that make blended structures much more difficult to analyze. There is difference in their contributions towards the overall behaviour of the structure, due to the diverse mechanical properties of the constituent fibres. The interaction between the two constituents alters the nature of yarn behaviour, especially during fracture. The yarn strength become higher, lower or remain constant when the amount of reinforcing fibre increases, depends on the difference between the fibre-breaking strains of the two fibre types. The interaction between two fibre types leading to hybrid effect complicates the failure analysis (Pan, 1996).

Harlow defined hybrid effect as positive or negative deviation of a certain mechanical property from the rule of mixtures behaviour (Harlow, 1983). Pan (1993) theoretically demonstrated that, the effect of the fibre slippage at fibre ends in staple fibre yarns during yarn extensions becomes negligible when the yarn twist level is reasonably high. Pan and Postle (1995) studied the interaction between the fibres, the local stress redistribution due to fibre breakage, hybrid effects in blended yarns. They determined the minimum and critical blend ratios of the reinforcing fibres and the effect of fibre breaking strains on hybrid effect (Pan and Postle, 1995). Cheng *et al.* (1975) 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 fibres. They explained that the cotton fibres fail first because of its low strain to break (Cheng *et al.*, 1975). The studies on blended twisted yarn by Machida, Monego and Backer (1968) and staple yarns at small extensions by Carnaby and Grosberg (1976) and Narota *et al.* (1970) 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 fibre stress-strain behaviour; the third regime reflects the stress- strain behaviour of the polyester fibre accompanied by multiple breakages of cotton fibres. Therefore, the boundary between the second and third regimes should be yarn strain, which can initiate cotton fibre breakage in a blended yarn (Machida, 1963; Monego and Backer, 1968; Carnaby and Grosberg, 1976; Narota *et al.*, 1970). Brody 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 fibres spanning the gap. Initial rupture is probably caused when a critical fraction of broken fibres is exceeded. The breakage of 100% polyester yarns seems to be initiated by the breakage of the small but significant fraction of fibres, breakage continues catastrophically. He claimed that mill breaks occur by fibre slippage before the yarn was fully developed, probably at the drafting stage (Brody, 1979). Onder and Baser (1996) were studied the stresses breakage analysis in worsted yarns. They explained that the fibre slippage and breakage do not happen together during breakage of ideal yarns. Their results support that the fibre slippage can be a more effective factor in the failure mechanism of worsted yarns (Onder and Baser, 1996). Rossettos and Godfrey (2002) 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) fibres undergoing axial extension. They indicated how the slip region of a broken fibre and an associated friction play a role in this effect. The stresses concentration close to the fibre break depends on the whether the broken fibre is an LE or an HE fibre. The hybrid effect intensifies, if the principal fibres are LE fibres (Rossettos and Godfrey, 2002). Rossettos and Godfrey (2002) studied the effect of frictional shear forces along slipping fibres near a fibre break for blended yarns consisting of an equal number of Low Elongations (LE) and High Elongation (HE) fibres undergoing axial extension, which also supported the hybrid effect as explained earlier (Rossettos and Godfrey, 2005).

The failure behaviour of yarn in real application (fabric form) is equally important like the post spinning performance of yarn. Seo *et al.* (1993) studied the failure behaviour 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 fibre fracture and slippage similar to that observed in long gauge length tests of free-state yarns (Seo *et al.*, 1993). Slodowy and Rutkowska (2004) described that continuity loss of yarn during various processes is due to fibre slippage or yarn breakage. Failure situations under static condition was explained based on the stretching diagrams (Slodowy and Rutkowska, 2004), as shown in

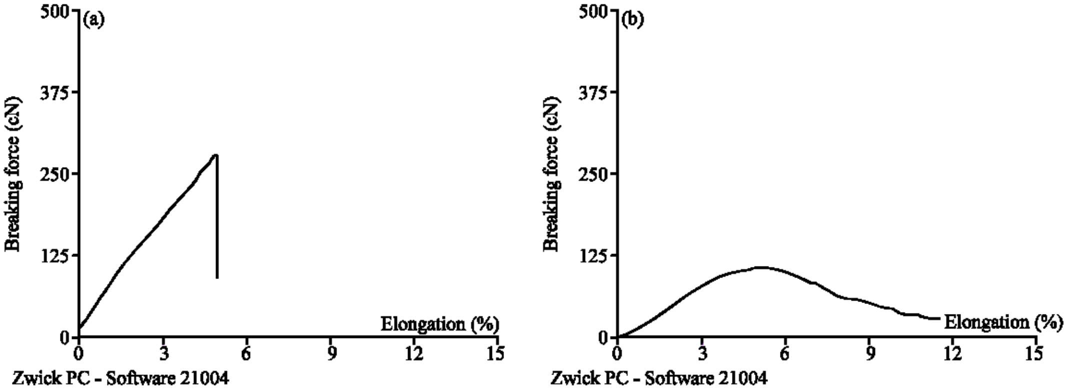

Fig. 3: Continuity loss of staple yarns: (a) breakage of fibres and (b) slippage of fibres

Fig. 3a and b. The sharp increase in the breaking force with increase in the elongation% is higher in Fig. 3a than Fig. 3b, which could be ascribed to increase in the proportion of fibre breakages.

CONCLUSIONS

The foregoing discussion gives an overview of the various theoretical and experimental aspects of the static failure mechanism of staple yarns that have been reported so far in the literature since the interest of the topic made a beginning. The yarn representing different spinning technologies and their intermediate semi-finished products has also been concerned in this study. 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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