©2021 International Transaction Journal of Engineering, Management, & Applied Sciences & Technologies

ISSN 2228-9860 eISSN 1906-9642 CODEN: ITJEA8

International Transaction Journal of Engineering, Management, & Applied Sciences & Technologies

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Multiple Yarn Pull-out Response on E-Glass Twill 4/1 Woven Fabric

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Paper ID: 12A9E

Volume 12 Issue 9

Received 29 July 2021
Received in revised form 14 October 2021
Accepted 22 October 2020
Available online 26 October 2021

Keywords:
Yarn pull-out test; Fabric direction; Fabric elongation performance; Woven fabric direction; Yarn linear density; Fabric weft direction; Fabric density; Yarn crimp factors; E-glass twill friction force; Twill 3D model; Warp direction;.

Abstract

Yarn pull-out is an evaluation to determine the friction force behavior of yarn within woven fabric during a pull-out action. It is imperative to investigate the yarn pull-out performance as it can predetermine the mechanical tensile strength and impact resistance performance of the woven fabric. To understand the friction force response of E-glass twill 4/1 woven fabric sample, multiple yarn pull-outs are conducted using different numbers of yarn; 10, 20, and 30 yarns. Multiple yarn pull-out behaviour represents the most realistic frictional mechanism of yarn being pulled out from woven fabric due to impact penetration and tensile elongation conditions. This paper intends to discuss the influence of multiple yarn pull-out performance according to woven fabric direction, fabric density, yarn linear density, and yarn crimp factors. It was found that an increased number of yarns significantly improve the friction force, in which the 30 yarn recorded the highest value of 21.38 N at the weft direction while the 10 yarn recorded the lowest friction value of 4.02N at warp direction. Meanwhile, weft direction with the least fabric density and yarn crimp of 29 yarn.cm^{-1} and 3.33%, respectively, produced an excellent force-elongation performance than warp direction. In-depth determination on the average force and yarn tenacity of individual yarn indicates that fabric direction plays a major influence. Fabric weft direction generated the highest average force and yarn tenacity for individual yarn with 0.7 N and 2.1 cN. Tex compared with warp direction.

Disciplinary: Textile Technology, Materials Science

Cite This Article:

Zulkifli, N. F., Yahya, F., Ahmad, R., and Ghani, S. A. (2021). Multiple Yarn Pull-out Response on E-Glass Twill 4/1 Woven Fabric. *International Transaction Journal of Engineering, Management, & Applied Sciences & Technologies, 12*(9), 12A9E, 1-11. http://TUENGR.COM/V12/12A9E.pdf DOI: 10.14456/ITJEMAST.2021.173

1 Introduction

Recently, textile woven fabric preforms have been aggressively adopted in various technical fields due to the strength-to-weight ratio factor (Nasrun *et al.*, 2018). This factor allows the textile woven fabric to substitute steel and aluminum materials for certain body parts in automotive, aerospace, and body armor applications. Woven fabric is formed based on the yarn interlacement within the weave structure by holding the structural integrity. Woven fabric is constructed base on a yarn interlacing sequence between two sets of yarn, warp and weft directions.

Apart from forming the weave structure, yarn interlacement between warp and weft directions also plays a major role in the inter-yarn friction behavior during yarn pull-out from woven fabric. Multiple studies agree that understanding yarn pull-out behavior is necessary to improve the mechanical performance of woven fabric particularly in impact resistance (Das *et al.*, 2015; Feng *et al.*, 2018; Nilakantan & Nutt, 2018). Researchers suggest that a yarn pull-out situation can be defined as yarn being pulled out by a certain amount of force from woven fabric (Bilisik, 2017). Several extensive studies on yarn pull-out proposed that it is commonly affected by physical characteristics such as type of fibre, yarn linear density, fabric density, yarn crimp, and weave structure (Bai *et al*., 2018; Majumdar & Laha, 2016).

2 Literature Review

It has been widely accepted that the type of high-performance fibre plays a crucial influence on its mechanical tensile and impact resistance properties. In the past, Bilisik & Korkmaz (2011), and Bilisik & Yolacan (2011) conducted investigations on the yarn pull-out behavior based on different types of high-performance fibre, E-glass, and Aramid. Comparative evaluation between both types of fibres indicates that aramid fibre possesses a 15 N friction force which outperformed e-glass with 0.8 N. The result shows that aramid fibre bundle within a single yarn is capable of attaining a greater stretch force during being pulled out from the woven fabric. The high friction force of individual yarn definitely will help to contribute better impact resistance and tensile elongation buffering as more yarns will being pulled out simultaneously.

Many extensive research works have been explored by researchers into various strategies to manipulate yarn pull-out performance. Remarkably, the modification of physical characteristics of yarn is able to improve friction force. Hwang *et al.* (2015) attempted to develop hybrid yarn physical properties by plying aramid yarn with nanowire to increase the inter-yarn friction. Surprisingly, it was observed that aramid-nanowire is able to enhance energy dissipation 23 times higher than common woven fabric. Meanwhile, only a few investigations involve on the effect of yarn linear density towards inter-yarn friction were documented. Cornelissen *et al* (2013) worked on the PAN-carbon fibre woven fabric with linear density at 198 and 800 Tex respectively. Arora *et al.* (2019) studied UHMWPE fibre woven fabric with yarn linear density at 400 and 1350 deniers respectively. Both studies reported that the increment number of yarn linear density positively increases the inter-yarn friction force. Modification of physical yarn structure through the plying approach with metal wire gave more twist or spiral characteristics on the yarn surface and increase yarn stiffness. Furthermore, increment yarn friction force due to a high amount of yarn linear density suggested that the number of filaments within individual yarn were increased and thus, enhances the yarn breaking force resistance and inter-yarn friction performance.

Aside from yarn properties, studies on the alteration of woven fabric physical property also promoted a fascinating outcome. A scientific study (El-Messiry & El-Tarfawy, 2014) was conducted to investigate the inter-yarn friction between the type of weave structure and fabric weave density. Study on the weave structure with Twill 8/12, 6/14, Weft rib 2x2 and 4x4 indicated that weave structure with shorter yarn float exhibits high friction force than longer float. Triki & Dolez (2019) performed a scientific investigation to find out the relationship between weave structure and inter-yarn friction. Researchers found out that plain weave structure results in higher friction force than twill weave. Arora *et al.* (2019) investigated the influence of different fabric weave densities at 22.5, 25, and 27.5 square inches. The results indicate that higher fabric weave density was able to produce excellent friction force at 89.9 N than the other counterparts. The distinct type of 2D weave structure indicates that yarn float length plays an important role in the improvement of yarn friction force performance. As the float length becomes shorter, there will be more yarn interlacement point and yarn crimps percentage within the weave structure and thus, the friction force will be elevated. Meanwhile, the increment number of the fabric weave density parameter demonstrated the compactness of yarn present within warp and weft directions inside the woven fabric. Subsequently, a high amount of fabric weave density also resulted in the enhancement of yarn crimp percentage.

Recently, chemical surface modification on woven fabric has been studied by many researchers. Surface modification by using shear thickening fluid (STF) shows prominent improvement in inter-yarn friction performance. Khodadadi *et al.* (2019), Xu *et al.* (2017), and Bai *et al.* (2019) are some of the researchers that have worked on STF strategies to improve yarn pull-out performance. Research observation indicates that the impregnation of STF on the woven fabric surface greatly helps the inter-yarn friction mechanism. Impact energy absorption performance can achieve up to 40% improvement compared with untreated woven fabric samples. This increment of performance of inter-yarn friction is because of the high volume of silica particles incorporated which leads to fabric stiffness. STF impregnation allows the woven fabric to maintain its structural integrity longer than common woven fabric when subjected to braking force.

With the advance of computational analysis capability, yarn pull-out performance is further carried out by using modeling and simulation methods. This approach allows the researcher to investigate the finite element simulation of yarn pull-out performance. In the past, Duan *et al.* (2005, 2006) developed a yarn length scale finite element model by using the solid element to investigate the effect of projectile shape and friction between yarn during impact. The inter-yarn friction simulation studies reported that manipulation of energy absorption can be achieved through the increment of impact load. However, it is also noted by researchers that this modeling approach is computationally high in time and processing consumption. Meanwhile, Yahya *et al.*

(2014) employed different friction coefficients on finite element 2D plain weave models between 0.5, 0.7, and 0.9 settings. The simulation outcome promoted that high friction coefficient can significantly improve the puncture impact resistance. Besides, researchers correlated high friction with high stress-strain performance, thus leading to the enhancement of inter-yarn friction. Since most literature only focuses on single-ply fabric, Nilakantan & Nutt (2018) developed a finite element model to evaluate the yarn pull-out mechanism on multiply orientation woven fabric. Researchers agreed that tailoring yarn linear density plays a great factor in energy dissipation during impact penetration events. Some of these validated finite element simulation works offer an important predictive capability and insight in understanding the inter-yarn friction mechanism at a multi-scale level. In-depth information on the yarn-yarn interaction is able to help researchers to develop and improve the mechanical tensile and impact resistance performance with less time and money consumption.

In this research work, twill 4/1 woven fabric is chosen as the main material for the investigation. Multiple yarn pull-out tests were conducted to analyze the friction force response based on fabric direction, fabric density, and yarn crimp properties.

3 Method

3.1 Material Preparation

E-glass 2D woven fabric twill 4/1 sample was used in this study. The weave structure drafting plan is displayed in Figure 1. The woven fabric sample was acquired from Textile Weaving Workshop at the Faculty of Applied Science, Universiti Teknologi MARA (UiTM) Shah Alam. The woven fabric physical properties are listed in Table 1.

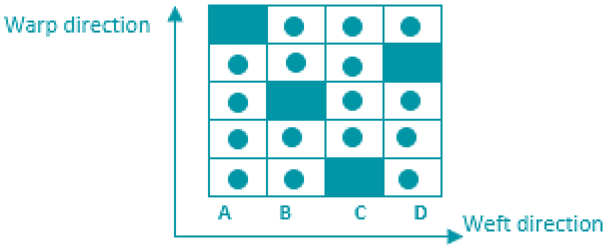

Figure 1: Drafting plan of 2D twill 4/1 woven fabric

In Figure 1, a schematic diagram of twill 4/1 woven fabric drafting plan shows that there are black dot and black box which represents warp and weft yarns respectively. On line A, it can be seen that there are four continuous black dots followed by one black box sequence. It shows that the warp yarn is floating upward on four individual weft yarns. Later, the warp yarn is interlaced under a single weft yarn. This yarn interlacement sequence is repetitive for the next lines B, C, and D. For a better understanding, a 3D model of twill 4/1 is generated to show the cross-sectional view in Figure 2. To further analyze the twill 4/1 woven fabric physical characteristic at the micro-level, micro image analysis was conducted by using a portable Proscope HR to measure the yarn interlacement measurement.

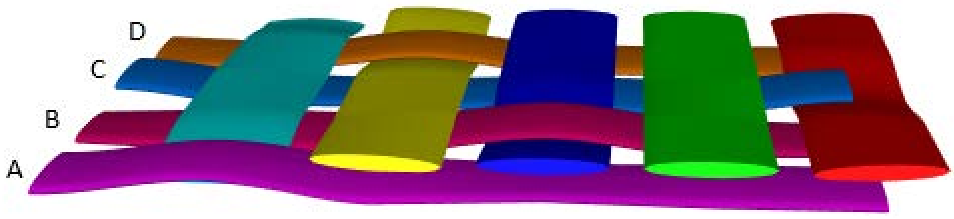

Figure 2: Cross-sectional view of Twill 4/1 weave structure by using TexGen software

Figure 3 displays the measurement of yarn interlacement between warp and weft yarns within twill 4/1 weave structure. It can be seen that indicators A and B represent the warp yarn measurement on float length and width. Meanwhile, C and D indicate the weft yarn measurement on float length and width. The summary of yarn interlacement measurement is listed in Table 2.

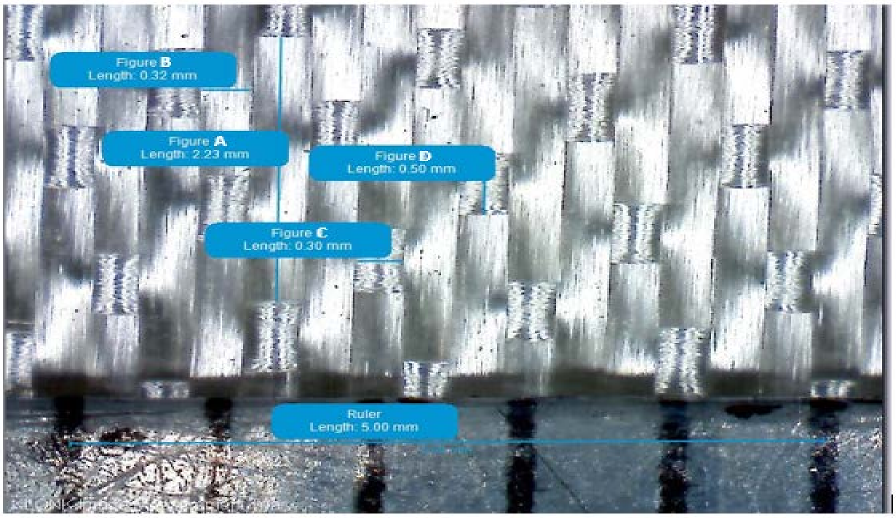

Figure 3: Top view micro image on actual Twill 4/1 woven fabric sample

Table 1: Twill 4/1 physical characteristics

Fabric Direction	Yarn Linear Density (Tex)	Fabric Density (yarn per cm)	Yarn Crimp (%)
Warp	32. 6	30	6.25
Weft		29	3.33

Table 1 shows the woven fabric physical characteristic parameter based on the yarn linear density, fabric weave density, and yarn crimp percentage. Both E-glass warp and weft yarns have an identical yarn linear density at 32.6 Tex. Measurement of fabric weave density represents the compactness of yarn within the woven fabric. It demonstrates that the warp direction has a higher fabric weave density at 30 yarns per centimeter than the weft direction with 29 yarns per centimeter. As the amount of fabric weave density increases, the yarn crimp percentage will also be significantly influenced. Yarn crimp percentage suggested the length of undulated yarn being interlaced within the weave structure. The result promoted that warp direction displays higher yarn crimp with 6.25 % than weft with 3.33 %.

Table 2: Yarn interlacement measurement on Twill 4/1

Fabric Direction	Float length (mm)	Width length (mm)
Warp	2.23	0.32
Weft	0.30	0.50

Table 2 depicts the yarn interlacement measurement during micro image analysis (refer to Figure 3). The yarn float measurement between warp and weft direction has shown that warp direction produced greater float length than the counterpart, weft direction at 2.23 and 0.30 mm respectively. It is consistent with the theoretical drafting plan that was introduced early in Figure 1. Meanwhile, the yarn width length indicates that the weft yarn produces results with a wider measurement than the counterpart, warp yarn at 0.50 and 0.32 mm respectively. The inconsistent width outcome suggests that warp yarn is being compressed on the weave interlacement structure.

3.2 Yarn Pull-out Analysis

The basic set-up of the yarn pull-out test on the woven fabric sample in this research work is shown in Figures 4a and 4b. The yarn pull-out sample test template was prepared accordingly to Figure 4a. The whole width and length for the sample are 90 and 115 mm respectively. The sample template area is divided into three sections. Section A indicates the area where only vertical or straight multiple individual yarns are left for pulling action from the woven fabric, the length of yarn is 35 mm. Section B designates the body area of the woven fabric section, the length of the body is 40 mm. Meanwhile, section C labels the foot area for clamping purposes, the length of the foot is 40 mm. It can be noticed that there is a gap area between both foot parts. It is purposely cut out to ensure that the multiple individual yarns in section A were not being clamped during pull-out action.

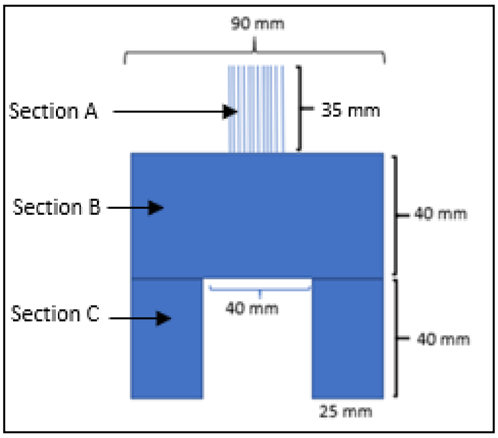

Figure 4a: Yarn pull-out sample template

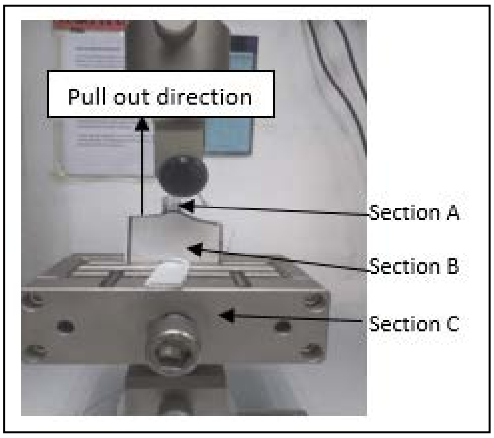

Figure 4b: Yarn pull-out test set-up

Further set-up position for the yarn pull-out test on the Tensolab testing machine is shown in Figure 4b. Multiple individual yarns in section A are tied on the clamper wheel and clamped together. Meanwhile, both feet were tightly clamped with a clamp bar to ensure the woven fabric sample did not lose during the yarn pulling action. Later, the sample was slightly stretched with a pretension of 0.18N to give some stiffness to the sample. Then, the individual yarns were pulled out simultaneously from the woven fabric with constant clamp speed at 100 mm/min with a 5 kN load cell to record the friction force response on e-glass twill 4/1 woven fabric. The yarn pull-out test is repeated 5 times to obtain consistent and average results.

4 Result and Discussion

Figures 5 and 6 below presents multiple yarn pull-out responses at warp and weft directions. The force-elongation curve trend is separated into two phases. In phase 1, the yarn decrimping region where it shows the force-elongation behavior when the yarn being straightened from the yarn interlacement sequence. Meanwhile for phase 2, the yarn pulling region where it demonstrates the force elongation behavior when the yarn being pulled out from the weave structure.

The multiple yarn pull-out force-elongations response between 10, 20, and 30 yarns at warp direction are illustrated in Figure 5. In phase 1, 30 yarns are shown to have the highest friction force needed at 12.45 N to straighten the yarn followed by 20 and 10 yarns at 8.14 and 4.02 N respectively. Meanwhile, the yarn elongation response recorded an identical elongation at peak for the 10 and 30 yarns at 12 mm while 20 yarns display slightly higher elongation at 14.2 mm. In phase 2, all numbers of yarn show an oscillation curve trend on force-elongation from 15 to 85 mm elongation. Later, all force-elongation curves show a similar flat line trend from 85 to 100 mm elongation.

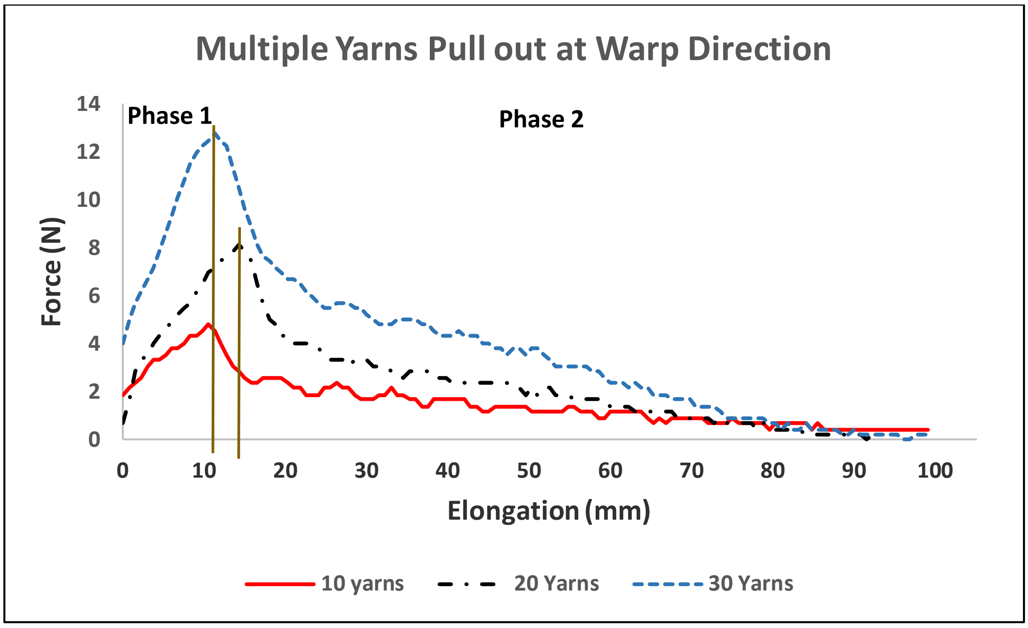

Figure 5: Multiple yarn pull-out force-elongation response at warp direction

On the other hand, Figure 6 depicts multiple yarns pull-out force-elongation responses between 10, 20, and 30 yarns at the weft direction. In phase 1, 10 yarns produced the lowest friction force needed to decrimp the yarn at 6.96 N followed by 20 and 30 yarns at 13.63 and 21.38 N respectively. The elongation at the peak curve line on all yarns indicated an increment trend as the number of yarns elevated. 10 yarns generated the minimum elongation at peak with 13.5 mm followed by 30 and 20 yarns at 16.5 and 18.8 mm. In phase 2, only 10 and 20 yarns display a significant oscillation on the force-elongation curve line from 15 to 85 mm elongation while 30 yarns generated slight oscillation on the curve line from 20 to 85 mm elongation.

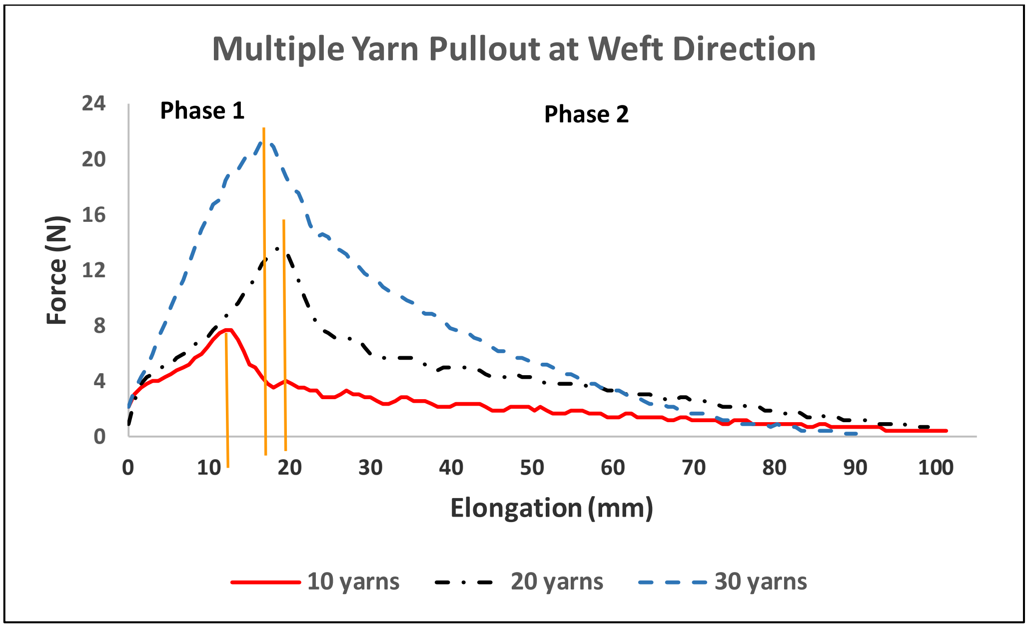

Figure 6: Multiple yarn pull-out force-elongation response at weft direction

In general, multiple interesting yarn pull-out responses can be seen in both Figures 5 and 6. The increased amount of friction force needed to decrimp the yarn due to the increment number of yarn involves during pull-out action is because of the increasing amount of inter-yarn friction generated by multiple yarns simultaneously. Meanwhile, the comparative measurement between warp and weft shows that weft yarn required higher friction force needed to straighten the yarn compared to warp yarn. This situation mainly happens because the amount of weft yarn crimp percentage is lower than the warp yarn. Less amount of yarn crimp tends to generate higher friction force due to less yarn undulation movement within the weave structure. Consequently, it is also able to minimize damage on the fibre-fibre build-up stretch resistance within the individual yarn. Besides that, the yarn elongation response between warp and weft direction shows that weft yarn produced significant changes in yarn elongation as the number of yarn pull-out was increased. The yarn elongation changes occurred because of the different amounts of fabric density present. Higher fabric density on warp direction than weft caused additional yarn interlacing point for weft yarn. Similar findings on multiple yarn pull-out were published by Bilisik & Korkmaz (2011, 2011) where researchers have determined that the force-elongation behavior of single and multiple yarn pull-out is significantly influenced by the yarn crimp, yarn linear density, and fabric density.

Table 3 Summary of Yarn Pull-out Response on E-Glass Twill 4/1 woven fabric

Fabric Direction	No of Yarn	Multiple Yarn Friction Force at Peak (N)	Individual Yarn Friction Force at Peak (N)	Individual Yarn Tenacity (cN/Tex)	Multiple Yarn Elongation at Peak (mm)	Individual Yarn Elongation at Peak (mm)	Strain
Warp	10	4.02	0.402	1.23	12	1.2	1.03
	20	8.14	0.407	1.25	14.2	0.71	1.02
	30	12.45	0.415	1.27	12	0.4	1.01
Weft	10	6.96	0.696	2.13	13.5	1.35	1.03
	20	13.63	0.682	2.09	18.8	0.94	1.02
	30	21.38	0.713	2.19	16.5	0.55	1.01

A summary of the multiple yarn pull-out response on the E-glass twill 4/1 woven fabric sample is shown in Table 3. In general, the highest multiple yarn pull-out force-elongation response is at 30 weft yarns with 21.38 N and 16.5 mm respectively. Meanwhile, the lowest force-elongation performance is at 10 warp yarns with 4.02 N and 12 mm respectively. In order to determine the average force-elongation behavior of an individual yarn, Equation (1) is used where X represents the value of multiple yarns either for force or elongation, and n indicates the number of yarns involved.

$$\frac{X}{n} \qquad (1).$$

An interesting outcome on the average force-elongation shows that yarn direction plays a significant influence on the average friction force of individual yarn. Weft direction is able to produce a higher friction force with an average of 0.7 N per individual yarn compared with warp direction with an average of 0.4 N per individual yarn. This situation happens because the weft yarn direction recorded the least crimp percentage than warp. Less amount of yarn crimp measurement is able to minimize the damage on fibre-fibre build-up stretch force resistance during yarn straightening. Surprisingly, the average elongation performance of individual yarn indicates a reduction trend as the number of yarns increases.

5 Conclusion

Multiple yarn pull-out test on E-glass twill 4/1 woven fabric was conducted to evaluate the yarn friction force response during pull-out action. The research outcome portrayed that a larger amount of multiple yarns involves during pull action will significantly improve the friction force resistance needed where 30 yarns produced the highest amount of force at both warp and weft directions at 12.45 and 21.38 N respectively. A remarkable note can be made that the yarn tenacity outcome depicts elevation performance as the number of yarn involves increased. Further evaluation could be done to compare yarn pull-out performance according to a different amount of yarn linear density and yarn construction.

6 Availability of Data And Material

Data can be made available by contacting the corresponding authors.

7 Acknowledgement

The authors would like to thank the Faculty of Applied Science for providing facilities and Universiti Teknologi MARA particularly for providing REI 5/3 (018/2018) grant scheme to support this research work.

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