Engineering the geometry of novel yarns for flexible, hybrid composites Part II:
Maximising the tensile properties

Malek Alshukur¹,² ⓒ and George Stylios¹

Abstract
Part I of this study established the concept and built the theoretical basis for a novel composite yarn. Part II deals with practical aspects of producing the yarn structural parameters necessary for flexible textile composite uses. This study investigates how to maximise the number of breaks of the core or foundation component of the yarn by using the design of experiment method. The results have shown that the number of these breaks vary between 1.4 and 6 times in comparison with only one break that would result from a typical conventional ply yarn. The analysis of the results indicates that a low overfeed ratio of 121% of the undulating component can lead to ∼4.7 breaks of the foundation component in comparison with only ∼2.6 breaks that would result using an overfeed ratio of 158%. To increase the number of breaks of the foundation component, it is necessary to use a high number of wraps, a low overfeed ratio, more than one input yarn for the foundation component and an undulating component of high tensile strength, which enhances its synergy with the foundation component by self-locking during breaking. Increasing the number of breaks of the yarn enhances the performance and safety of flexible composites.

Keywords
Novel yarn, design of experiment, flexible composites, hybrid composites, textile composites

Introduction
The yarn structure proposed as a novel reinforcement for making flexible FRPM composites is made of several components. These components are yarns of their own right, as shown in Part I of this study. Several researchers tried to understand the behaviour of this yarn by studying its yarn structure for decorative purposes. A few of other studies were carried out to understand the effect of false twist on the yarn structure and its tensile properties,¹ the effect of tension on the core or foundation component on the final structure² and the effect of the bending stiffness of the undulating or effect component.³ The use of low tension on the foundation component may result in good quality bouclé undulations, which are being used in the traditional industry, whilst a low bending stiffness undulating component yarn helps to create a high number of regular small undulations while a high bending stiffness leads to a low number of irregular and larger undulations, producing undesirable appearance. It was also found that false twist should always be used to regulate the formation, appearance and number of undulations of the final structure.

A few other studies were concerned with the effect of the component yarns’ interactions on the whole structure. A study conducted to understand the interaction of bending stiffness of both the foundation and undulating components on the final yarn structure⁴ confirmed the results of the previous study⁵ and showed that a stiffer foundation component can produce larger undulations. In another study that tried to map the interaction of the overfeed ratio and the number of wraps,⁶ it was shown that the ratio between the number of wraps and the overfeed ratio should be set to a specific value in order to control the formation of the resultant undulations. The value should be between 1.9 and 2.5 wpm to make gimp yarns and between 0.88 and 1.2 wpm to make bouclé yarns, and it was called ‘Structural Ratio of

¹Research Institute for Flexible Materials, School of Textiles and Design, Scottish Borders Campus, Heriot-Watt University, Galashiels, UK
²Faculty of Mechanical and Electrical Engineering, Department of Mechanical Engineering of Textiles Industries and their Technologies, Damascus University, Damascus, Syria

Corresponding author:
Malek Alshukur, Research Institute for Flexible Materials, School of Textiles and Design, Heriot-Watt University, Scottish Borders Campus, Netherdale Road, Galashiels TD1 3HF, UK.
Email: malekshukur@yahoo.com
Multi-thread Fancy Yarn'. The manufacturing process and its interaction with yarn parameters was investigated in a few studies. They considered the three parameters of the hollow-spindle system: the supply speed of the undulating, the rotational speed of the hollow-spindle and the delivery speed of the final yarns, and by using response surface methodology experimental designs, they devised regression models that can predict the specifications of the undulations such as the number, height or width of these undulating profiles. The predicted undulations were not always regular or uniform and were limited to one particular type.

Another two studies showed that changing the overfeed ratio, the hollow-spindle rotational speed, the tex and bending stiffness of the undulating component can lead to changes to the intermediate product within the spinning zone. In particular, the higher the overfeed ratio, the wider the diameter of the undulating component helices, while the higher the speed of the hollow spindle, the higher the number of the undulating-thread helices, but with a reduction in their diameter. These changes affected the appearance of fancy yarns; in that, the high number of helices resulted in more undulations, while wider helices resulted in bulkier undulations. It has been considered that an undulating yarn with high stiffness may be needed to make the yarn structure more uniform. However, at a low number of wraps of the wrapping component, the thickness of the undulating yarn may be more important than its stiffness. It should also be pointed out that if the thickness and stiffness of the undulating yarn and the rotational speed of the machine were all controlled properly, it is possible to change the resultant undulations to produce bouclé profiles, gimp profiles, wavy profiles or loop profiles even when using the same number of wraps and overfeed ratio.

A different approach was adopted in two other similar studies on the structure of a yarn that was made by combining a hollow-spindle and a ring-spindle system in one operation. It was found that the overfeed ratio of the undulating component and the number and direction of wraps of the wrapping component affect the height and number of the undulating bouclé profiles. The tensile properties of a bouclé yarn, a wrap yarn and a spiral yarn made on the ring spinning system, using three-component and two-component yarns were the subject of another study. It was shown that there were two breaks for the three-component wrap yarn and bouclé yarn, and only one break for the three-component spiral yarn. All yarns made with only two-components had only one break. It is inferred from these results that although limited to only two breaks, the use of three input components is essential for obtaining more than one break and for increasing the performance of the final yarn.

Studies involving seven factors were also conducted to understand this novel yarn structure. The linear density of the final yarn, its aesthetics and structural properties, its tensile strength and elongation at the first break and the maximum tensile strength that it can endure after several breaks have been studied in relation to spinning conditions. The seven factors studied were the delivery speed, the supply speed, the rotational speed, the false twist, the material type and form of the foundation, and the undulating and the wrapping components. The overfeed ratio and the number of wraps, resulting from the interactions of the three speeds of the hollow-spindle machine, were also studied. The outcomes using design of experiment of these studies have established the significant factors and interactions that affected the properties of the yarn, and regression models that can predict these properties.

Regardless of the type of input materials and method of manufacture, several studies were conducted to establish rules for the assessment of the uniqueness of the yarn structure and how to classify and model the yarn structure mathematically. Mathematical models of the geometry of similar composite yarns made for decorative applications were also devised for modelling the tensile strength of the yarn. In one particular study, to describe the structures of eight yarn variants, a mathematical model was introduced by considering the lengths of the undulating and foundation components and taking into account that the undulation component has both sinusoidal (wavy) segments and sigmoidal segments (or helical segments). These yarn variants were simple wavy yarn, gimp yarn, gimp yarn derivatives, spiral yarn, overfed fancy yarn, bouclé yarn and semi-bouclé (or bouclé-like) yarn. Other geometrical models focused on the length of the wrapping component, and its effect on yarn appearance.

All those studies in the literature have been conducted for understanding the aesthetic appearance and properties of traditional yarns called fancy or bouclé yarns, which can have three-component yarns, using the same spinning system, and have not considered the construction, characteristics, production and performance of these yarns for industrial end uses such as in flexible composites. In Part I, we have explored the concept and provided the theoretical background for the use of these yarns in flexible composites, and in this Part II, we try to show how the tensile performance of this yarn can be maximised by increasing the number of yarn breaks prior to total failure. Hence, a flexible polymeric composite reinforced by these novel yarns may sustain high strains without a complete failure by engineering successive breakages of the foundation component yarn which is sustained by its self-locking when subjected to tensile loading. This will be shown in the following sections.

**Methodology**

The manufacturing route used in this study was based on the hollow-spindle spinning system, type Gemmill and Dunsmore MK3. The details of this system are beyond the

scope of this study, and the reader is referred to a previous study for further information. The factors affecting multiple yarn breaks are related to the input of the yarn components, the technical parameters of the machine used and the structural parameters of the yarn assembly. Since the reinforcement yarn is suitable for making flexible FRPM composites rather than stiff FRPM composites, the use of expensive high-performance fibres is not required, and any fibre combinations may suffice to show the performance of this yarn. On that basis, relatively inexpensive input materials, shown in Table 1, were used in this investigation. The total number of factors used was \( k = 7 \). These were assigned to standard symbols used in DOE as shown in Table 1. Factor A denotes the material type and form of foundation or core component of the reinforcing yarn. Factor B represents the material type and form of the wrapping component of the reinforcing yarn. Factor C is the material type and form of the undulating component of the reinforcing yarn. Factor D is the supply speed of the undulating component in m/min. Factor E represents the rotational speed of the hollow-spindle machine in r/min. Factor F is the delivery speed of the reinforcing yarn in m/min, and factor G stands for the false-twist hook that is attached to the bottom outlet of the hollow spindle, which can be on or off.

The input yarns were first conditioned in accordance with BS EN ISO 139:2005 and their linear density was measured according to BS EN ISO 2060:1995. The tensile properties were measured using the Instron universal testing machine according to BS ISO 2062:2009. During these experiments, the number of specimens was 20 for each input yarn and the specimen length 250 mm at 250 mm/min rate of extension, as stipulated in the standard. The properties of the input materials are given in Table 2. The input yarns have typical yarn structures such as in Figure 1.1 and 1.2.32

Due to the high number of factors involved, the design of experiment (DoE) method was used to establish important interactions. Two levels (\( n = 2 \)) were chosen for each factor, and since there are combinations of discrete factors (e.g. factor G) and continuous factors (e.g. factors D, E, F), a factorial design was chosen for these experiments. For the continuous factors, two physical values are selected in such a way that takes into account the manufacturing process, the maximum production speed, the productivity of the machine and the overfeed ratio achievable for each type of yarn structure. Further details on the selection of the factor levels can be found in a previous study.17 Since a full factorial design would require a high number of trials, that is, \( n^k = 2^7 = 128 \) trials, a fractional factorial design was used to reduce to 8 the number of trials; \( k + 1 = 7 + 1 = 8 \) trials. The format of this fractional factorial design is shown in Table 3.

This experimental design was an orthogonal array33 of an ‘alias structure’ producing confounding effects. The general alias structure for the main effects and two-level interactions are defined33 as follows

\[
\begin{align*}
A &= BD = CE = FG \\
B &= AD = CF = EG \\
C &= AE = BF = DG \\
D &= AB = EF = CG \\
E &= AC = BG = DF \\
F &= AG = BC = DE \\
G &= AF = BE = CD
\end{align*}
\]

The eight trials of the experiment were conducted in a random manner, as shown in Table 3, to minimize relation bias. The experiment itself with its eight trials was repeated.
five times in the same random order used for the first replicate. For each experimental trial, a hybrid complex-structure reinforcing yarn was obtained; thus, eight different reinforcing yarns were obtained for each replicate. Each yarn was wound on a package, so the total number of packages for the five replicates was 8 (yarn trials) × 5 (packages) = 40 packages. The five yarn packages made for each trial represent one yarn structure. Similar to the input yarns, the resultant novel yarns were tested to measure their tensile properties as shown above. For each of the eight novel yarn structures, the total number of specimens was 20, where 4 specimens were taken from each of the 5 relevant yarn packages (4 × 5 = 20). The specimens were randomly selected before being tested. The mean and standard deviation values were then calculated.

**Results and discussion**

**Initial results**

Images of the yarns made using the experimental design are shown in Figure 1 while examples of the load-elongation charts of the yarns are given in Figure 2. This figure shows

| Material type and form | Usage | Factor (and its level) | Number of yarn per level | Maximum load (cN) | Elongation at maximum load (mm) |
|------------------------|-------|------------------------|--------------------------|-------------------|---------------------------------|
| An open-end rotor-spun cotton yarn; Ne=20s | Core component | A (−1) | 2 | 327.74 | 19.23 |
| A two-ply combed ring-spun cotton yarn; Ne=30s/2 | Wrapping component | A (+1) | 1 | 540.91 | 23.91 |
| A textured multifilament polyester yarn, 34 filament; 16.7 tex/34 | Wrapping component | B (−1) | 1 | 609.04 | 103.32 |
| A multifilament nylon yarn, 77 filaments; 14.5 tex/77 | Undulating component | B (+1) | 1 | 418.36 | 86.77 |
| A three-ply ring-spun yarn made of chemically spun bamboo fibres; Ne=24s/3 | Undulating component | C (−1) | 1 | 980.6 | 44.847 |
| A three-ply carded ring-spun cotton yarn; Ne=30s/3 | C (+1) | 1 | 942.3 | 24.6 |
the breaking patterns of four representative specimens sampled from one of the five packages of each of the eight yarns. It is shown that the yarn components have broken more than once. For instance, using the concept of complete breaks as defined in Part I of this study, eight complete breaks of the foundation component have resulted in the case of Trial 1. This is seen by the red and green tensile load-elongation plots in the figure. All plots of Figure 2 show that the number of breaks of the foundation component are different in each trial. These breaks are important and have practical influence on a FRPM composite performance, as already discussed in Part I, so the results of the five replicates are given in Table 4.

### Table 3. Fractional factorial experimental design of this study.

| Randomised order of trials | Standard order of trials | Factors of the experiment |
|---------------------------|--------------------------|----------------------------|
|                           | A | B | C | D | E | F | G |
| 5                         | 1 | - | - | - | + | + | - |
| 2                         | 2 | - | - | + | + | - | - |
| 4                         | 3 | - | + | - | - | + | - |
| 1                         | 4 | - | + | + | - | - | - |
| 6                         | 5 | + | - | - | - | + | + |
| 7                         | 6 | + | - | + | - | + | - |
| 3                         | 7 | + | + | - | + | - | - |
| 8                         | 8 | + | + | + | + | + | + |

**Figure 2.** Load-elongation charts for the composite yarns made as shown by the experimental design. All these yarns are made using different materials, technological parameters of the machine, number of wraps or overfeed ratio.
Analysis and discussion of the initial results

The initial results given in Table 4 were analysed using Minitab 14 to determine the effects of each factor as shown in Table 5. The Pareto chart of the number of breaks of the foundation component is shown in Figure 3. This figure indicates that the foundation component (i.e. factor A) was a highly important factor. It is also shown in Table 5 that using two parallel yarns for the foundation component (level \( +1 \)) instead of only one two-ply yarn (level \( -1 \)) increased the number of the foundation breaks by almost two-fold, that is, from 2.7 reaching 4.7 peaks. Figure 3 indicates that the undulating component (i.e. factor C) was also an important factor because it acts as a locking mechanism, so that every time the foundation yarn breaks the wrapping and undulating components lock, it is such that the structure does not fail but continues to carry the load over a number of successive breaks of the foundation yarn. These component yarns act in synergy with each other and this can be engineered to tailor the load-carrying capacity of the whole yarn.

It is also shown that even though the Ne = 24s/3 three-ply bamboo yarn (used in Level \(-1\)) and the Ne = 30s/3 three-ply cotton yarn (used in Level \(+1\)) were approximately similar in tensile strength, see Table 3, the Ne = 24s/3 bamboo yarn allowed for a higher number of breaks for the foundation component. This is because the Ne = 24s/3...
bamboo yarn was approximately two times more extensible at break than the Ne = 30s/3 cotton ply yarn (Table 3). Therefore, the higher extensibility allowed this component to get entangled with both the wrapping and foundation components producing higher successive number of breaks of the foundation component yarn than in the case of the less extensible Ne = 30s/3 cotton yarn. So the broken yarn segment of the foundation component is re-entangled and re-locked into the structure and hence carrying the tensile load again until the next break over several times in succession depending on the individual properties of the component yarns and the spinning process parameters. The more extensible the undulating component, the higher the number of the foundation component breaks.

Figure 2 indicates that the wrapping component (i.e. factor B) is also an important factor, and that the use of two different types of yarn leads to different results. The nylon non-textured multifilament wrapping component was weaker and less extensible than the textured polyester multifilament, shown in Table 3. The less extensible nylon multifilament can force the undulating component to become entangled with the broken foundation components more quickly. Therefore, it has the ability of locking the broken foundation component segments, which is reflected in obtaining the several peaks seen in the tensile load-elongation charts, as confirmed in Table 5 which shows that the first and second levels of the wrapping component – the polyester and nylon multifilament – were responsible for obtaining 3 and 4 breaks for the foundation component, respectively. At the same time as the three components become entangled, they all can take part in carrying the load. This explains the increase of the tensile load that is recorded after the first break of the foundation component. The frictional force of the wrapping component with the foundation and the undulating components may also influence the locking mechanism of the broken segments of the foundation component. Since the nylon component is not textured, a high number of its filaments have contact with the other two components, while only a few filaments of the textured polyester component contact the same surfaces of the component yarns. So greater friction of the wrapping component assists synergistically the breaking mechanism of the foundation component.

Figure 3 also indicate that the weakest factor was factor E which is the rotational speed of the hollow-spindle, with only 8.19% influence, and the second weakest factor was factor G (false twist) which had only a small contribution; so both of these factors can be ignored. With regard to false twist (Factor G), a previous investigation of the hollow-spindle system indicated that using the false-twist hook that is attached to the output hole of the hollow-spindle is useful in producing a highly wavy-shaped-structure yarns, such as gimp and semi-boucle yarns, made by the wrapping process.1 Such a highly wavy-shaped yarn structure can promote the role of the undulating component in helping the wrapping component to lock the broken segments of the foundation component. A 0.5 increase of the number of foundation component breaks can be seen in Table 5.

The supply speed (or factor D) does not have a direct influence on the foundation component. This is because, by design, the supply rollers do not control the foundation component, and they do not push it forward in any hollow-spindle spinning or wrapping system. Instead the foundation component is pulled forward by the delivery rollers that control the final yarn structure.

Regarding the effect of confounded interactions AB, EF, and CG on the number of the foundation component breaks, and considering the nature of the manufacturing process, the interaction CG between the undulating component and false twist has no practical meaning, and can be ignored from the analysis. The interaction EF represents the number of wraps of the wrapping component because the number of wraps is calculated by dividing the rotational speed by the delivery speed. The relationship between the number of wraps and the number of the foundation component breaks is given in Table 6. This table indicates that there was no direct relationship between the number of the foundation component breaks and the number of wraps. Therefore, the interaction AB between the foundation and the wrapping component would claim the effect on the number of wraps. This relationship is evident from the analysis above to be responsible for the self-locking mechanism and the synergy between these two components, as already discussed. The importance of this interaction is shown in Figure 4 which indicates that a strong interaction has resulted using two single yarns for the foundation component (Level –1) and a multifilament nylon yarn for the wrapping component (Level +1).

With regard to the delivery speed (factor F), it was inferred from Table 6 that raising the delivery speed from 60 to 70 m/min increased the number of the foundation component breaks from about 3 to 4. Therefore, potentially, the delivery speed could be another important factor to be considered. This is because the higher the delivery speed, the higher the foundation yarn tension, so the higher the entanglement of the yarns between each other. This also promotes greater frictional forces between the components.

Table 6. Effect of number of wraps on number of breaks of the core component.

| Rotation speed (rpm) | Delivery speed (m/min) | The number of wraps (wpm) | Number of rupture of the core component |
|----------------------|------------------------|---------------------------|----------------------------------------|
| 16,000               | 60                     | 266.7                     | 3.1                                    |
| 21,000               | 60                     | 350                       | 3.2                                    |
| 16,000               | 70                     | 228.5                     | 4.1                                    |
| 21,000               | 70                     | 300                       | 4.3                                    |
With regard to the rotational speed (factor E), this factor is confounded with the interaction DF that represents the overfeed ratio of the undulating component. The overfeed ratio is calculated by dividing the supply speed by the delivery speed, as shown in Table 7. This table also provides the corresponding number of breaks of the foundation component for each value of the overfeed ratio, and it shows that when the overfeed ratio decreased from 158% to 121%, the number of the foundation component breaks increased from 2.63 up to 4.49 peaks. Based on that, the interaction DF representing the overfeed ratio is the one that can claim the effect on this property, and its value should be as small as possible to maximise the number of breaks of the foundation component. Consequently, this analysis has revealed that the main factors are the material type and form of the foundation component A, the wrapping component B, and the undulating component C; and the delivery speed of the reinforcing yarn F, while the main interactions being the interaction between the foundation and the wrapping component which claims the effect on the number of wraps, being responsible for the self-locking mechanism and the synergy between these two components AB, and the overfeed ratio of the undulating component DF, which should be as small as possible to maximise the number of breaks of the foundation component.

Statistical analysis for the number of breaks of the core component

Minitab 15 was used to obtain a regression model to measure the number of practical breaks of the foundation component based on all factors established in the above investigation. Accordingly, the regression model of equation (1) was obtained. The p-values of the terms of this model were found to be all significant at a significance level α = 0.05, except for factor D which had a p-value = 0.095; thus, it was significant only at α = 0.10. Based on our analysis given in the section Analysis and Discussion of the Initial Results, it is inferred that factor D is not the important factor, instead the effect is claimed by the interaction AB. Therefore, by replacing factor D in equation (1) by the interaction AB, the regression model took its final form in equation (2). A method of calculating an interaction of factors is given elsewhere. Therefore, equation (2) should be used to estimate the number of complete breaks of the novel structure

\[
\text{The number of complete breaks of the core component} = 3.661 - 1.006 A + 0.5337 B - 0.7687 C - 0.9988 D + 0.1487 E + 1.059 F \ldots \tag{1}
\]

\[
\text{The number of complete breaks of the core component} = 3.661 - 1.006 A + 0.5337 B - 0.7687 C - 0.9988 AB + 0.1487 DF + 1.059 F \ldots \tag{2}
\]

where A, B, and C are the english counts based on the Cotton System for the foundation, the wrapping, and the undulating components, respectively; (h/lb), and D and F are supply and delivery speeds, respectively, in m/min.

Variation in the number of breaks of the core component

The results from the analysis using Minitab 15 indicate that the constant of the experimental design for the number of the foundation yarn breaks was 3.7 as shown in Table 5. The value of standard deviation (SD) of the number of breaks of the foundation component for each yarn, are shown in Table 8. This table also indicates that the constant of the experimental design, or the process, was SD = 0.6 breaks. Consequently, the CV value was \((0.6/3.7) \times 100 \approx 16\%\). Although this value is relatively high, it is not expected to be translated in the final flexible FRPM composite because it is related to the experimental design rather than of the individual reinforcing yarns. In all cases, the sources of variability were identified and presented in Table 8, and they

![Interaction Plot for the Number of Breaks of the Foundation Component](image)
were mainly the rotational speed, the core component, and the undulating component; the remaining factors were weak and therefore ignored. Table 8 shows that high rotational speeds (equalling 21,000 m/min) caused the greatest variability.

**Conclusions**

Part II of this study was conducted to investigate the materials-process-structure relationships and to show how they affect the number of breaks of the foundation component. The study continued with how to maximise the number of breaks of the foundation component of the novel reinforcing yarn structure, as introduced in Part I. The results from the factorial design indicated that the number of the foundation component breaks is related to the material type and form of the foundation, wrapping and undulating components, the delivery speed, the use of false twist, the interaction between the foundation component and the wrapping component, and the overfeed ratio. Specifically, it was found that a higher number of the foundation component breaks resulted when using:

- a relatively low overfeed ratio of the undulating component, that is, 120%–130% instead of more than 150%;
- a high value of the delivery speed, that is, 70 m/min;
- two single yarns for the foundation component, even if they were weaker and less extensible than one stronger ply yarn;
- an undulating yarn with high extensibility;
- using a non-textured nylon multifilament wrapping component, even if it is weaker and less extensible than for instance a textured polyester multifilament; and
- by maximising the interaction between the foundation component and the wrapping component due to friction using two single yarns for the core component and non-textured nylon multifilament for the wrapping component.

This study is presenting a novel flexible high-performance composite yarn assembly which is comprised of a minimum of three yarns. The configuration of this yarn is interesting because as it is shown, it can provide a locking mechanism to a foundation yarn by wrapping it and, hence, allows the structure to carry a load by successive structural breaking and locking. This mechanism is explored in this study for the first time for the purpose of high performance because all other studies focused primarily on the aesthetic appearance of fancy yarns that are made by the same process and fancy garments made of them. This investigation has shown how the geometry of this yarn and its process interaction can produce high-performance load-bearing yarns desirable for flexible FRPM and other industrial end uses.

**Declaration of conflicting interests**

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

**Funding**

The author(s) received no financial support for the research, authorship, and/or publication of this article.

**ORCID iD**

Malek Alshukur ☐ http://orcid.org/0000-0002-4042-7311

**References**

1. Alshukur M and Fotheringham A. Role of false twist in the manufacturing process of multi-thread fancy yarn on hollow spindle spinning machines. *J Text Inst* 2014; 105: 42–51. DOI: 10.1080/00405000.2013.810367.

2. Alshukur M and Sun D. Effect of core thread tension on structure and quality of multi-thread boucle yarn. *Indian J Fibre Text Res* 2016; 41: 367–372.

3. Alshukur M, Fotheringham A and Gong H. The influence of component stiffness on the structure of multi-thread fancy boucle yarn. *J Ind Text* 2020; 49: 889–905. DOI: 10.1177/1528083718801365.

4. Alshukur M, Fotheringham A and Gong H. Relationship between the interaction of bending stiffness of component yarns and the structure of fancy boucle and semi-boucle yarns. *Fibers Polym* 2020; 21: 437–446. DOI: 10.1007/s12221-020-8156-0.

5. Alshukur M and Fotheringham A. Structural ratio of multi-thread fancy yarn: interaction effect of both the number of wraps and the overfeed ratio on fancy boucle yarn structure. *J Nat Fibers* 2019. accepted and in-press.

6. Petruyte S and Petrulis D. Influence of twisting on linen fancy yarn structure. *J Nat Fibers* 2014; 11: 74–86. DOI: 10.1080/15440478.2013.842512.

---

**Table 8. Estimated standard deviation (SD) of number of core component breaks at factor’s levels.**

| Term                          | SD at the first level (break) | SD at the second level (break) | Estimated variability of the factors (break) |
|------------------------------|-------------------------------|-------------------------------|---------------------------------------------|
| Constant of the design or process |                               |                               | 0.6                                         |
| A: core component           | 1                             | 0.2                           | −0.8                                        |
| B: wrapping component       | 0.6                           | 0.7                           | 0.1                                         |
| C: undulating component     | 1                             | 0.3                           | −0.7                                        |
| D: supply speed             | 0.6                           | 0.6                           | 0.0                                         |
| E: rotation speed           | 0.2                           | 1.1                           | 0.9                                         |
| F: delivery speed           | 0.5                           | 0.7                           | 0.2                                         |
| G: false twist              | 0.7                           | 0.6                           | −0.1                                        |
7. Ragaisiene A. Interrelation between the geometrical and structural indices of fancy yarns and their overfeed and twist. *Fibres Text East Eur* 2009; 17: 26–30.
8. Ragaisiene A. Influence of overfeed and twist on fancy yarns structure. *Mater Sci* 2009; 15: 178–182.
9. Petruyte S. Influence of technological parameters on the periodical effects of fancy yarns. *Fibres Text East Eur* 2008; 16: 25–29.
10. Petruyte S. Analysis of structural effects formation in fancy yarn. *Indian J Fibre Text Res* 2007; 32: 21–26.
11. Ragaisiene A and Petrulyte S. Design of fancy yarns with worsted and elastomeric covered components. *Mater Sci* 2003; 9: 414–418.
12. Alshukur M and Yurchenko D. Experimental study on the spinning geometry of multi-thread fancy yarn on hollow-spindle spinning machines: Part I. *Int J Clothing Sci Technol* 2018; 30: 496–506. DOI: 10.1108/IJCST-05-2017-0064.
13. Alshukur M and Yurchenko D. Experimental study on the spinning geometry of multi-thread fancy yarn on hollow-spindle spinning machines: Part II. *Int J Clothing Sci Technol* 2019; 31: 454–461. DOI: 10.1108/IJCST-05-2017-0065.
14. Nergis BU and Candan C. Performance of Bouclé Yarns in various knitted fabric structures. *Text Res J* 2006; 76: 49–56.
15. Nergis BU and Candan C. Performance of rib structures from boucle yarns. *Fibres Text East Eur* 2007; 15: 36–40.
16. Grabowska KE. Comparative analysis of fancy yarns produced on a ring twisting system. *Fibres Text East Eur* 2010; 18: 36–40.
17. Alshukur M and Fotheringham A. Studying the linear density of multi-thread fancy yarn made from natural fibers using the design of experiments. *J Nat Fibers* 2018; 15: 658–667. DOI: 10.1080/15440478.2017.1354741.
18. Alshukur M and Fotheringham A. Quality and structural properties of gimp fancy yarns using the design of experiments. *J Textile Instr* 2015; 106: 490–502. DOI: 10.1080/00405000.2014.927126.
19. Alshukur M and Fotheringham A. Studying the tensile properties at the first break of multi-thread fancy gimp yarns using the design of experiments. *J Nat Fibers* 2020; 17: 716–725. DOI: 10.1080/15440478.2018.1527741.
20. Alshukur M and Fotheringham A. Study of maximum tensile strength of fancy yarns using the design of experiments. *Mech Industry* 2019; 20: 403–413. DOI: 10.1051/meca/2019003.
21. Alshukur M. The quality of fancy yarn: Part I: methods and concepts. *Int J Text Fashion Technol* 2013; 3: 11–24.
22. Malek Alshukur MA. The quality of fancy yarn: Part II: practical experiments and application. *Int J Text Fashion Technol* 2013; 3: 25–38.
23. Grabowska KE, Ciesielska IL and Vasile S. Fancy yarns – an appraisal. *Autex Res J* 2009; 9: 74–81.
24. Grabowska KE. Mathematical basis for classification of twisted multiple fancy yarns. *Text Res J* 2010; 80: 1768–1776.
25. Grabowska KE. Mathematical modeling of tensile properties of fancy loop yarns. Theoretical: Part I. *Text Res J* 2010; 80: 1905–1916.
26. Alshukur M, Gong H and Styllos G. Structural modelling of multi-thread fancy yarn. *Int J Clothing Sci Technol* 2018; 30: 268–283. DOI: 10.1108/IJCST-05-2017-0063.
27. Grabowska KE. A Mathematical model of fancy yarns’ strength. The first model developed in the world. *Fibres Text East Eur* 2008; 16: 9–14.
28. Kuo C-M, Takahashi K and Chou T-W. Effect of fiber waviness on the nonlinear elastic behavior of flexible composites. *J Compos Mater* 1988; 22: 1004–1025. DOI: 10.1177/002199838802201101.
29. Grabowska KE. Experimental analysis of the tensile properties of fancy loop yarns. Part II. *Text Res J* 2010; 80: 1917–1929.
30. Petruyte S. Complex structure fancy yarns: theoretical and experimental analysis. *Mater Sci* 2003; 9: 120–123.
31. Petrusis D and Petruyte S. Predicting of coil length of component spirally arranged in complex structure yarn. *Mater Sci* 2003; 9: 224–227.
32. Goswami BC, Martindale JG and Scardino FL. *Textile Yarn: Technology, Structure, and Applications*. New York: John Wiley & Sons, 1977.
33. Lochner RH and Matar JE. *Designing for Quality: An Introduction to the Best of Taguchi and Western Methods of Statistical Experimental Design*. London: Chapman and Hall, 1990.