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Development of prediction model through linear multiple regression for the prediction of longitudinal stiffness of embroidered fabric

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Abstract

Embroidery through computer aided semi-automatic machines is one of the most widely used option for the surface ornamentation of apparel fabrics at present. Since the embroidery process includes addition of certain amount of embroidery-threads depending upon the design motif, it is quite obvious that basic physical and functional properties of fabric are subject to change. It is therefore important to develop an algorithm or empirical equation for proper prediction of the properties of the embroidered fabric, relevant to its required end-use in apparel industry. In this context, an effort has been made to determine a prediction equation through linear multiple regressions for the prediction of longitudinal stiffness of embroidered fabric in terms of flexural rigidity in warp direction of the base fabric, considering the input parameters as warp-way flexural rigidity of the base fabric, breaking load and linear density of the embroidery thread, stitch density, average stitch length and average stitch angle of the embroidery design. The final Prediction model is statistically verified taking new embroidery samples of different varieties. It is found that the model can predict with a very satisfactory level of accuracy. Also, the influences of the embroidery parameters in this context have been analyzed through the corresponding regression coefficients and the three dimensional (3D) surface curves. Stitch density has been emerged as the most influential parameter, followed by the stitch length and the stitch angle.

Keywords: Prediction of Stiffness of embroidered fabric, Computerized embroidery machine, Linear multiple regression, Apparel fabric, Flexural rigidity

Introduction

In the present days, embroidery on apparel fabrics is done mostly using the computer controlled embroidery machines (Campbell 2014; Henry 2006; Oladipto 2011; Suggett 2013). The machine has a multi-needle fixed 'embroidery head' and the pantograph or frame holder that moves according to the electronic instructions received from the computer aided design (CAD) file. The framed fabric in computerized embroidery machines moves in either of the two directions i.e. horizontal (X) direction and vertical (Y) direction so that the embroidery design can be sewn (Suggett 2013). Most of the available research works are in the domain of sewing and the effect of seam on fabric properties (Hui and Ng 2009; Hui et al. 2007; Nachiappan et al. 2009). A number of researches have been made on the effect of Seam and sewing on the drapeability, bending behaviour and stiffness of apparel fabrics (Gurarda 2015, Yucel 2012). Hu and Chung (1998), Sanad and Cassidy (2012) have also made extensive research on effect of various types of seam on the drape behavior of fabric and garment as well. But in the domain of machine embroidery, very few research works are reported in literatures, so far as the properties of embroidery fabrics are concerned. Radaviciene and Juciene (2012) had investigated the influence of embroidery threads on the accuracy of embroidery pattern dimensions. As an extension of the above work, Radavičienė et al. (2014) conducted a study of the nonconformity between the digital image and its corresponding actual image of embroidery element. It has been reported by the researchers that the samples embroidered with filling type FS exhibits the most significant mismatch in the shape and dimensions. The greatest nonconformities have been found by the researchers in the stitch direction of the embroidered element ranging from 0.7 to 4.6%. Radaviciene et al. (2012) and also, Radaviciene and Juciene (2013) studied the influence of embroidery threads on buckling of fabric inside of the embroidered element. Most of the few research works in the domain of the properties of embroidered fabric had reported that the addition of embroidery stitches increases the weight per unit area, the thickness, the bending stiffness and the tenacity of the textile fabrics. According to the research conducted by Pant and Rao (2015), the tearing strength of fabric was found to increase significantly due to the embroidery process. Maximum tearing strength was found in case of chain stitch. Whereas, the herringbone stitch was reported to exhibit the minimum tearing strength. Manal et al. (2012) reported another study in this domain. Three types of embroidery stitches i.e. satin, couching and crossed back were used. Embroidery were done by two methods i.e. hand embroidery and machine embroidery. Properties of embroidered fabrics, like, weight per unit area, thickness, bending stiffness, tensile strength and elongation were studied. The experimented results revealed that, in general, the addition of embroidery stitches increases the bending stiffness of the fabric, which increases with the increase in stitch density.

Furthermore, Daukantiene and Mikelionytė (2019) reported the study on the influence of the thread type on the amount of shape distortion of the actual embroidery motif compared to its corresponding digitized image. A couple of more researches are available in this domain of shape conformity of embroidery design (Juchnevičienė et al. 2017, 2019) with respect to its' corresponding digital image. Also, Juchneviciene et al. (2018) reported another very remarkable research on the evaluation of the uncertainty of the measurement techniques of the geometrical parameters of embroidered samples.

Dutta and Chatterjee (2019a) made a detailed study of the influence of basic embroidery parameters on the stiffness of fabrics. Significances of the input parameters were analysed through (Analysis of Variance) ANOVA technique, and the sample plan was based upon the Taguchi experiment design. This paper exclusively reported that the stitch density and the direction or the angle of embroidery stitches has a prominent effect on the stiffness of embroidered fabric. Moreover, Dutta and Chatterjee (2019a, b) developed a prediction model based upon fuzzy-logic algorithm for the prediction of subjective evaluation of the stiffness of embroidered fabric.

It is evident that no algorithm or empirical relationship is presently available for the prediction or pre-estimation of objective stiffness of the embroidered fabrics. In the present work an attempt has been made to develop a prediction model, based on linear multiple regression for prediction of longitudinal stiffness of embroidered fabrics. The prime philosophy of this work is to generate a user-friendly application module for pre-assessment of the longitudinal stiffness of embroidered apparel fabrics.

The use of linear multiple regression as a tool for predicting the material property is found in a number of research papers. Sanad and Cassidy (2012) developed prediction equations for the drape behavior of garments based on the principles of multiple regression. On the other hand, Hui and Ng (2009) used both multiple logarithm regression and artificial neural networks for the prediction of seam performance of commercial woven fabrics. In another example in this context, Ali and Nassif (2013) adopted the regression analysis in the study on the influence of sewing machine parameters on seam performance and quality of cotton woven fabrics. Also, Chen and Cheng (2019) and Khaled et al. (2018) reported the application of regression analysis for the study of the influence of sewing parameters on the seam performance. Multiple regression was also found to be used in case of a number of researches for the development of prediction models for the sewing thread consumptions (Abeysooriya and Wickramasinghe 2014; Dogan and Pamuk 2014; Jaouachi and Khedher 2013, 2015; Malek et al. 2019; Mariem et al. 2019; Midha et al. 2016; Sharma et al. 2017). Furthermore, Dutta and Chatterjee (2020) developed a prediction models using the principles of linear multiple regression for the prediction of gram per square meter (GSM) of the embroidered fabric.

Hence it is prominently evident that the multiple regression is a valid and scientific tool commonly adopted for development of empirical prediction models in the domain of properties and performances of textile and apparel materials. Linear multiple regression is suitably selected in this present research to develop simple and effective prediction model for prediction of the longitudinal stiffness of embroidered fabric.

Methods

Plan of material

Fabric

Plain woven P/C blended shirting fabrics of three different levels of stiffness are collected from regular fabric markets, and selected for embroidery work. The observed values of longitudinal i.e. warp-way stiffness in terms of warp-way flexural rigidity in dyne.cm are given in the Table 3.

Embroidery thread

A total nine varieties of 100% PET filament, 2 Ply, Z-twisted embroidery thread representing different values of linear densities (in terms of denier) and tensile behavior (in terms of gram-force) are selected from regular market, and used for preparation of embroidered samples. The relevant technical details i.e. denier and tensile strength of the embroidery threads procured are given in the Table 3.

Embroidery design details

Three embroidery designs are selected in such a way so that three different levels of stitch density are well represented. Designs are made in the embroidery CAD software 'Wilcom Embroidery Studio 4′. The embroidery is done on 21-head computerized embroidery machine with the specification as 21 head × 9 needle × 300 mm head interval × 1000 max RPM. The design details are represented by the Table 1.

Specifications of the embroidery needles

DB x 1(#55) needle has been used for all the embroidery samples.

Specification for the thread tension

The tension of the embroidery thread is adjusted at 125 CN (127.5 g-force approximately) and the bobbin thread tension has been adjusted at 144 CN (147 g-force approximately) for all the embroidery samples.

Design of experiment

With the objective of producing a number of embroidered fabrics by different combinations of all the input parameters, all the three varieties of base fabrics are used in random interactions with other process elements i.e. embroidery thread and embroidery designs. A total forty embroidery samples have been prepared. In addition to that, nine more samples are prepared according to Taguchi L9 orthogonal array experiment design taking three levels of each of the three parameters i.e. longitudinal stiffness of the base fabric, denier of the embroidery thread and stitch density of the

Table 1 Embroidery design details

Design Number	Repeat Area (X x Y) in mm	Total number of stitch per repeat	Stitch Density in no of Stitches/sq cm	Image of one full repeat of the design
ED1	300 × 410	7340	5.97	
ED2	300 × 320	24,209	25.22	
ED3	300 × 407	41,103	33.67	

Table 2 Directional anisotropy in terms of flexural rigidity of embroidered fabric with respect to average stitch angles (Dutta and Chatterjee 2019a)

Average stitch angle w.r.t warp direction (θwp)	Average warp way flexural rigidity of embroidered fabric in dyne.cm	Average weft way flexural rigidity of embroidered fabric in dyne.cm	Average difference between warp way and weft way flexural rigidities in dyne.cm
0.24	107.70	88.36	19.35
47.86	122.04	120.39	13.81
84.70	93.32	413.81	320.49

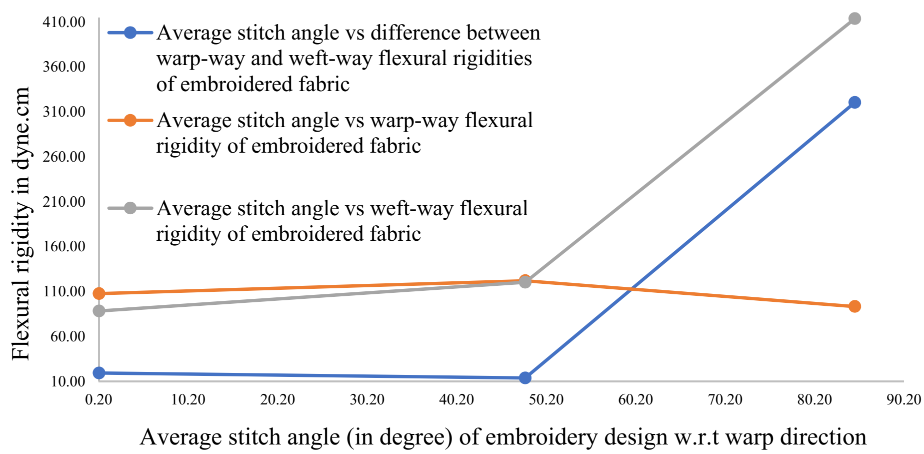

Fig. 1 Average stitch angle vs warp-way, weft-way flexural rigidities and difference between warp and weft way flexural rigidities of embroidered fabrics (Dutta and Chatterjee 2019a)

embroidery design, representing all the three elements i.e. fabric, thread and design respectively. Hence total 49 embroidery samples have been prepared considering the six input parameters as (i) longitudinal stiffness of the base fabric (ii) breaking load of the embroidery thread, (iii) denier of the embroidery thread (iv) stitch density of the embroidery design (v) average stitch length and (vi) average stitch angle (w.r.t the warp direction) of the embroidery design. Details of all the values of input parameters for all of the forty-nine embroidery samples are represented in the Table 3.

The inclusion of stitch angle as an input parameter is exclusively based upon the findings of Dutta and Chatterjee (2019a), where it has been reported that stiffness varies widely between that in warp-direction and weft-direction. Also, it is evident that such anisotropy is significantly influenced by the average stitch angle. This finding is further substantiated by the Table 2 and Fig. 1 (Dutta and Chatterjee 2019a).

The Table 2 and Fig. 1 clearly convey the philosophy that the difference between warp-way and weft-way flexural rigidities of embroidery fabric remains at lower level as long as the stitch angle w.r.t. warp direction remains below or around 45 degree. The difference increases rapidly as the stitch angle increases from 45 degree region towards 90 degree. It is also represented by the Fig. 1 that the warp-way flexural rigidity decreases as the stitch angle increases from the 45 degree region towards 90 degree. It can be explained by the fact that as the stitch angle w.r.t warp direction i.e.

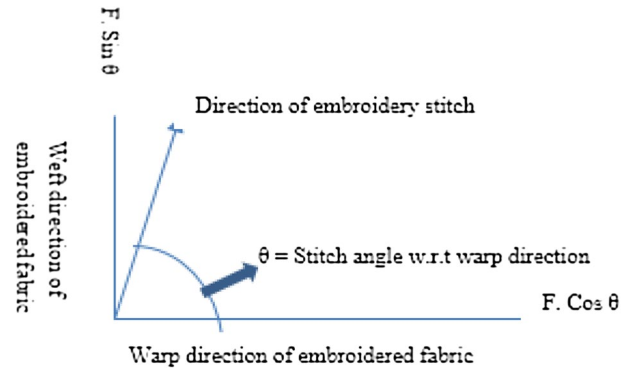

Fig. 2 Distribution of stitch angle between warp and weft directions of embroidery fabric (Dutta and Chatterjee 2019a)

θ in the Fig. 2 increases, more and more stitches start aligning more or less parallel to the weft direction. The component of binding force imparted by the embroidery threads along the weft direction, i.e. sin component of the binding force increases as the value of θ increases from around 45 degree towards 90 degree. Similarly, the force component decreases along warp direction as the cos θ value decreases at the higher values of θ. This ultimately causes the increase and decrease in flexural rigidities in weft and warp directions respectively. Also this sufficiently explains the importance of the stitch angle as a control parameter for the longitudinal stiffness of embroidered fabric.

The response or the output parameter

Longitudinal stiffness i.e. warp-way stiffness of the embroidered fabric in terms of flexural rigidity in dyne.cm is used as the response or the output parameter. All the relevant results of longitudinal stiffness of embroidered samples for all the forty-nine embroidered samples are shown in the Table 3.

Testing procedures

Testing of GSM of base fabric

Total ten readings have been taken for each of the fabrics, using a template size of 10 X 10 cm in each of the cases for testing the Gram Per Square Meter (GSM) of the base fabric. Testing is done according to ASTM D3776 standards of measurement of fabric areal density.

Testing of bending length and flexural rigidity of base fabric

Testing of both warp way and bending length is done on Shirley stiffness tester based on cantilever principle as per ASTM-D1388 standard. The Flexural Rigidity is calculated according to the following formula. Flexural rigidity in dyne.cm = $0.098 * w * l^3$, where w = GSM of the tested fabric, l = the bending length in cm.

Table 3 Experimented results of input and output parameters of embroidered fabric samples

Sl no	Warp way Flexural Rigidity (dyne.cm) of the base fabric	Embroidery thread breaking load (gf)	Embroidery Thread Denier	Stitch Density in no. of stitches per sq cm	Average Stitch Length in mm	Average angle between embroidery stitch and the warp direction of the base fabric	Longitudinal Flexural rigidity of embroidered fabric in dyne.cm
1	22.87	999.18	295	25.22	2.65	47.86	92.35
2	22.87	582.21	285	25.22	2.65	47.86	84.68
3	22.87	582.21	285	25.22	2.65	47.86	85.5
4	22.87	607.08	360	33.66	3.50	84.70	81.24
5	22.87	691.8	370	33.66	3.50	84.70	62.98
6	50.71	1010.2	238	25.22	2.65	47.86	99.4
7	50.71	582.21	285	33.66	3.50	84.70	69.55
8	50.71	999.18	295	33.66	3.50	84.70	62.37
9	50.71	691.8	370	5.97	5.44	0.24	122.92
10	106.11	1010.2	238	33.66	3.50	84.70	121.76
11	106.11	908.03	245	33.66	3.50	84.70	193.05
12	106.11	691.8	370	25.22	2.65	47.86	174.44
13	106.11	561.2	412	25.22	2.65	47.86	204.51
14	106.11	999.18	295	25.22	2.65	47.86	171.97
15	106.11	582.21	285	25.22	2.65	47.86	153.35
16	22.87	1010.2	238	25.22	2.65	47.86	84.71
17	22.87	691.8	370	25.22	2.65	47.86	94.13
18	106.11	1010.2	238	25.22	2.65	47.86	141.3
19	106.11	582.21	285	33.66	*3.50*	84.70	86.3
20	106.11	999.18	295	33.66	3.50	84.70	121.33
21	50.71	1010.2	238	33.66	3.50	84.70	50.91
22	106.11	691.8	370	5.97	5.44	0.24	115.8
23	22.87	691.8	370	5.97	5.44	0.24	59.52
24	22.87	881.5	234	25.22	2.65	47.86	95.46
25	22.87	908.03	245	25.22	2.65	47.86	97.23
26	50.71	582.21	285	25.22	2.65	47.86	80.1
27	22.87	881.5	234	33.66	3.50	84.70	49.47
28	106.11	908.03	245	33.66	3.50	84.70	193.05
29	106.11	691.8	370	33.66	3.50	84.70	141.48
30	106.11	1010.2	238	5.97	5.44	0.24	96.07
31	106.11	561.2	412	33.66	3.50	84.70	176.02
32	106.11	1010.2	238	25.22	2.65	47.86	133.97
33	50.71	999.18	295	25.22	2.65	47.86	98.85
34	22.87	1010.2	238	33.66	3.50	84.70	57.65
35	50.71	691.8	370	25.22	2.65	47.86	117.95
36	106.11	1010.2	238	25.22	2.65	47.86	171.99
37	22.87	1010.2	238	25.22	2.65	47.86	152.3
38	50.71	1010.2	238	33.66	3.50	84.70	50.91
39	106.11	1010.2	238	25.22	2.65	47.86	133.97
40	22.87	908.03	245	33.66	3.50	84.70	57.29
41	22.87	881.5	230	5.97	0.24	0.24	47.82
42	22.87	582.21	285	25.22	2.65	47.86	87.40
43	22.87	691.8	360	33.66	3.50	84.70	65.62
44	50.71	881.5	230	25.22	2.65	47.86	94.39
45	50.71	582.21	285	33.66	3.50	84.70	67.14
46	50.71	691.8	360	5.97	0.24	0.24	152.69
47	106.11	881.5	230	33.66	3.50	84.70	147.21
48	106.11	582.21	285	5.97	0.24	0.24	122.61

Table 3 (continued)

Sl no	Warp way Flexural Rigidity (dyne.cm) of the base fabric	Embroidery thread breaking load (gf)	Embroidery Thread Denier	Stitch Density in no. of stitches per sq cm	Average Stitch Length in mm	Average angle between embroidery stitch and the warp direction of the base fabric	Longitudinal Flexural rigidity of embroidered fabric in dyne.cm
49	106.11	691.8	360	25.22	2.65	47.86	184.35

Testing of thickness of base fabric

Testing of Thickness of all the three base fabrics is done on DigiThick digital thickness tester, as per ASTM-D1777 standards.

Testing of denier of the embroidery threads

In case of the measurements of the Denier of embroidery threads, total ten readings have been taken for each of the embroidery threads. Denier measurement is done according to the standard procedure as per ASTM D1907.

Testing of tensile properties of the embroidery threads

Tensile properties of embroidery threads are determined on Instron 3366 constant rate of extension tensile tester, as per ASTM D2256 method.

Testing of embroidered fabric

The stitch density and stitch length on the embroidered fabrics are not uniform and they vary from segment to segment within the same repeat according to the nature of the designs. Therefore, embroidered fabrics are anisotropic and heterogeneous in nature so far as the areal density, stitch density and other stitch properties are concerned. Also unlike sewing process, in case of embroidery design, stitch lengths and stitch angles are not constant throughout the design repeat. They vary as the design silhouette and stitch direction vary frequently. Due to this heterogeneous and anisotropic nature of embroidered fabric, it is necessary to modify the traditional fabric testing techniques. Special measuring techniques have been adapted here for the testing of different properties of embroidered fabric.

Determination of average stitch angle of the embroidery designs Unlike regular stitching of seams, embroidery stitches are for decorative purpose and hence do not follow any fixed stitch direction. Embroidery stitches in one repeat can run in many different directions according to the silhouette and construction of the design. The scanned image of one full repeat of the design is imported in the CorelDraw-X3 software and magnified up to 400%. Different graphic tools are used to find the stitch angles w.r.t. the warp direction of the fabrics, for different segments of the design. The following scientific and sequential steps have been adopted in this study to determine the average stitch angle, frequency distribution of stitch angles etc. for each of the embroidery designs used in this study.

1. The one full repeat is virtually divided by imaginary lines into two or more than two segments which are distinctly separable form each other in the design.
2. Photo-image of each of the segments are taken and imported into the CorelDraw-X3 graphic-software.
3. The direction of Warp/Weft of the base fabric is indicated by arrow-headed lines on the image of the design.
4. Individual or Groups of stitches of different angles w.r.t warp or weft directions are identified.
5. Stitch angle for each stitch or group of stitches is measured with the help of 'line tool' or 'dimension tool' of the software.
6. Frequency or the no of repetitions, i.e. number of stitches corresponding to each of the stitch angles determined is calculated after 2 times or 4 times magnification of the image, as per requirement within the software.
7. The weighted average is calculated from the stitch angles and their corresponding frequencies.

The method adopted in this study to determine the average stitch angle is sequentially illustrated through the Figs. 3 to 4 and Figs. 5 to 6, taking the examples of design ED1 and ED2 respectively.

Determination of the average stitch length of the embroidered samples Unlike in case of Sewing, In the case of embroidery, there is no fixed stitch length for a particular design. Since the stitch length varies according to the design pattern. Therefore, there are a multiple values of stitch lengths with corresponding frequency values in case of embroidery design. Hence, the weighted average method has been adapted in this case to calculate the average stitch length for each of the designs. The following formula is used to determine the average stitch length for a particular embroidery design. Average

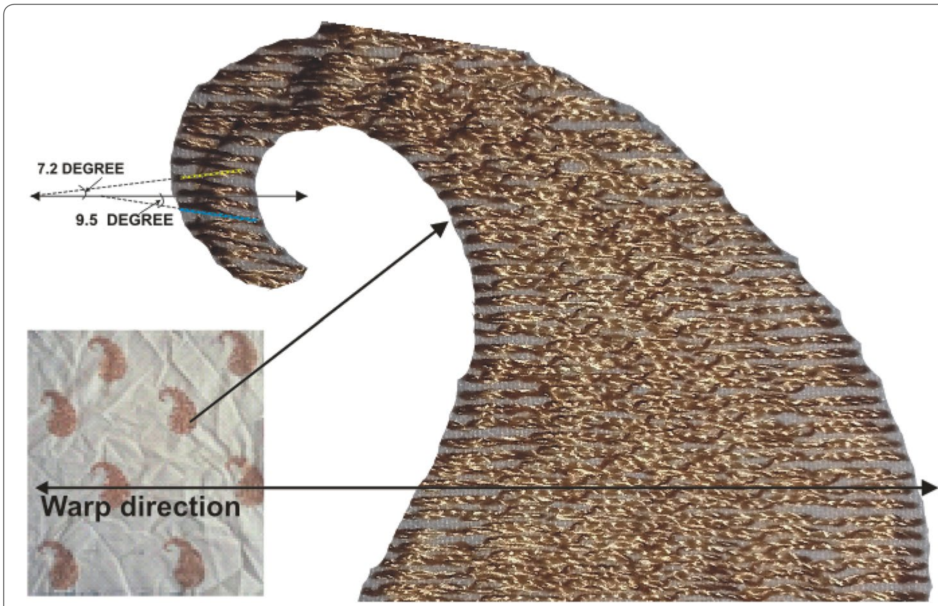

Fig. 3 Selection of independent repetitive segment from the design ED1

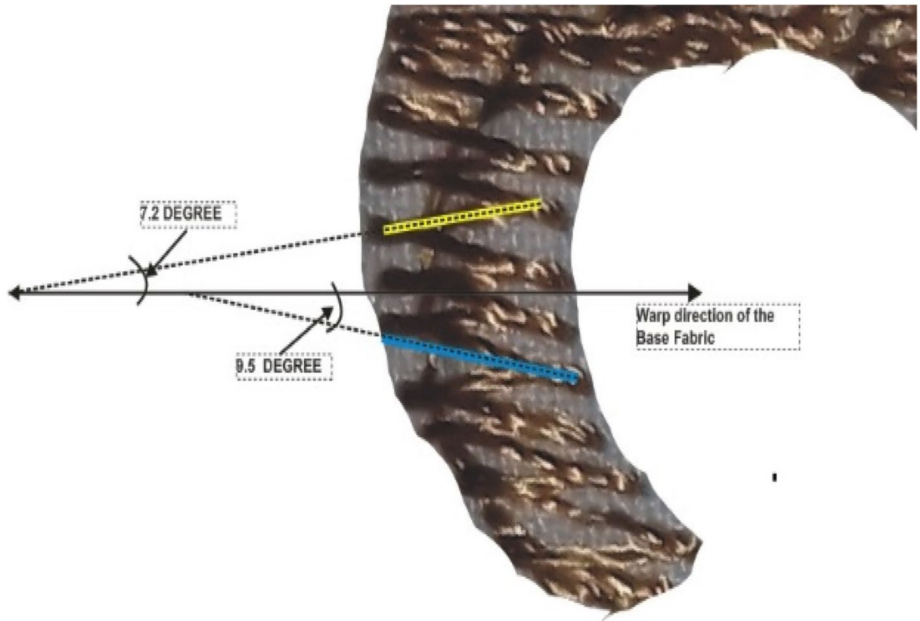

Fig. 4 View of the upper portion of the individual segment of the design ED1, after 400 percent magnification

Stitch length (L) = 1/N. ($\sum l_i . f_i$), Where, l_i = ith value of stitch length, f_i = frequency of occurrence of the i^{th} value of stitch length, N = total number of stitch per repeat = $\sum f_i$..

The principle adopted in this paper for determining the average stitch length of one full repeat of the embroidery design is illustrated through the design represented by Fig. 7. The Design ABCD in Fig. 7 has multiple segments like leaves (L1, L1'), Flower (F1), main stem (T) and branch stem (V). Each of the segments consists of multiple stitches of variable stitch lengths. For example, each of the two identical big leaves L1 & L1' have the stich length distribution measured as 2 mm × 4 stitches, 3 mm × 5 stitches, 4 mm × 7 stitches and 5 mm × 16 stitches. Similarly stitch distribution for each of the smaller leaves, each of the 11 Flowers (F1), each of the 10 side-branches (V) and the main stem (T) are determined with the help of calibrated millimeter scale and a magnifying glass.

Testing of bending length and flexural rigidity of embroidered fabric Due to the variations in stitch density and stitch direction between different design segments of a repeat, embroidered fabrics are anisotropic in nature so far as the areal density and hence the bending length of the embroidered fabric are concerned. Hence, it is obvious that the traditional cantilever method of testing of bending length of unembroidered fabrics cannot be fully applied in case of testing the bending length of embroidered fabrics, as the narrow strip of fabric can represent only a section of design repeat. In this context, a special method which includes cutting a number of fabric strips from all the different segments of the design repeat either in warp and weft way for warp-way bending length and weft way bending length respectively, in such a way that every segment of the design repeat is equally represented.

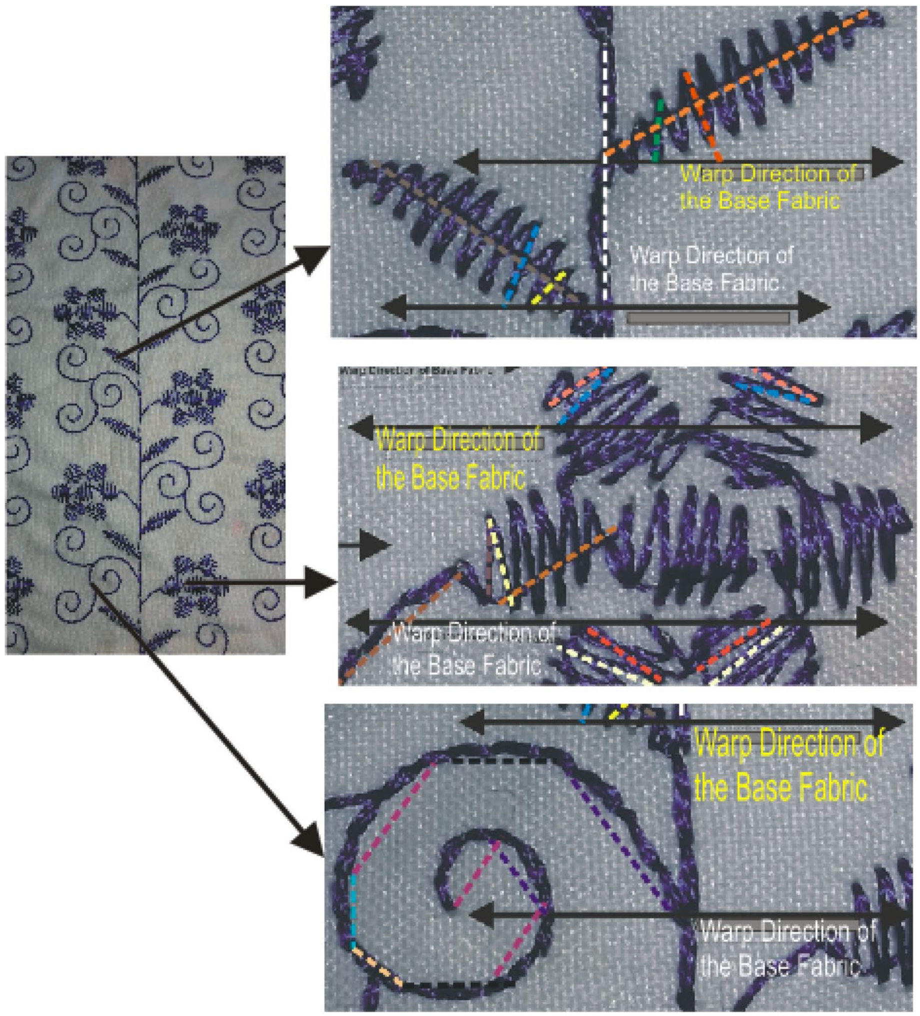

Fig. 5 Determination of Stitch angle for different sub-parts of the 1st segment of design ED2

The principle followed for the distribution of one full repeat of the embroidery design into different segments is illustrated by the Fig. 8.

The entire repeat of the embroidery design is represented by the rectangle ABCD. This one full repeat is divided into two segments PQRS (indicated by Segment-1 in the figure) and ABFE (indicated by Segment-2 in the figure) in the Fig. 3, which are distinctly separable from each other and set apart by a reasonable amount of unembroidered portion. Among those two segments, the frequencies of segment-1 and segment-2 can be counted as 3 and 1 respectively (Fig. 8).

Every sample strip is tested as per traditional cantilever method based upon the principle of Shirley stiffness tester as per ASTM-D1388 standard. Finally the average bending length is Calculated. A very scientific method has been followed while cutting the strips for the test of bending length. Starting from one end of the repeat subsequent parallel strips have been drawn in regular interval till the other end of the repeat is reached. Also, the strips are drawn in such a way that every sub-segments in one full repeat is represented. The method is illustrated by the Figs. 9 and 10.

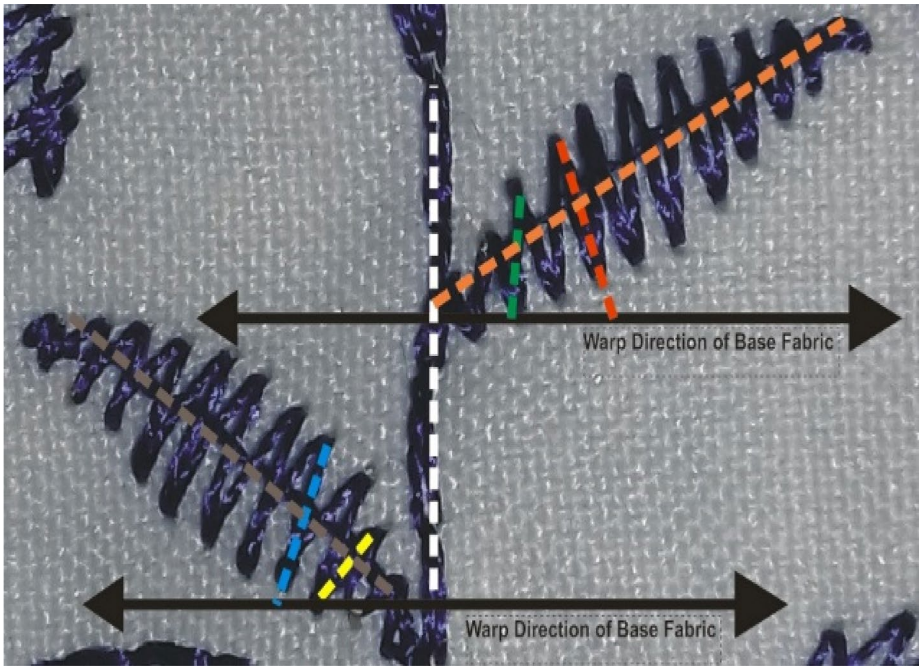

Fig. 6 Determination of stitch directions and stitch angles of the leaf and stem portion of segment 1 for design ED2

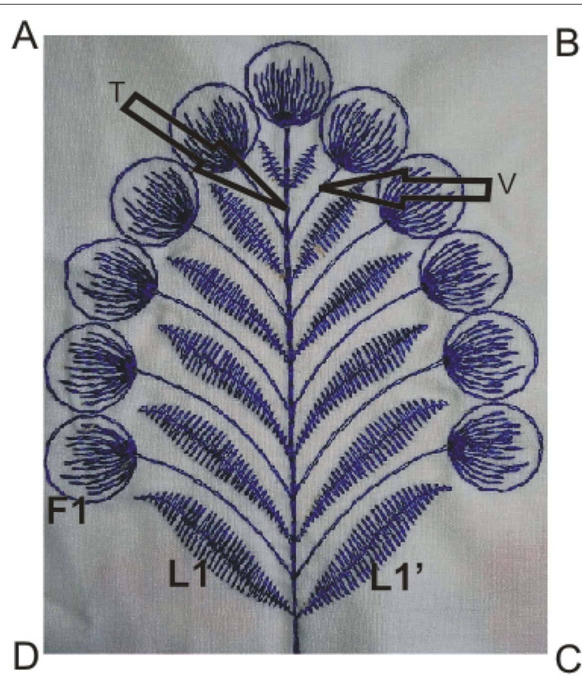

Fig. 7 Determination of stitch length for embroidery motif

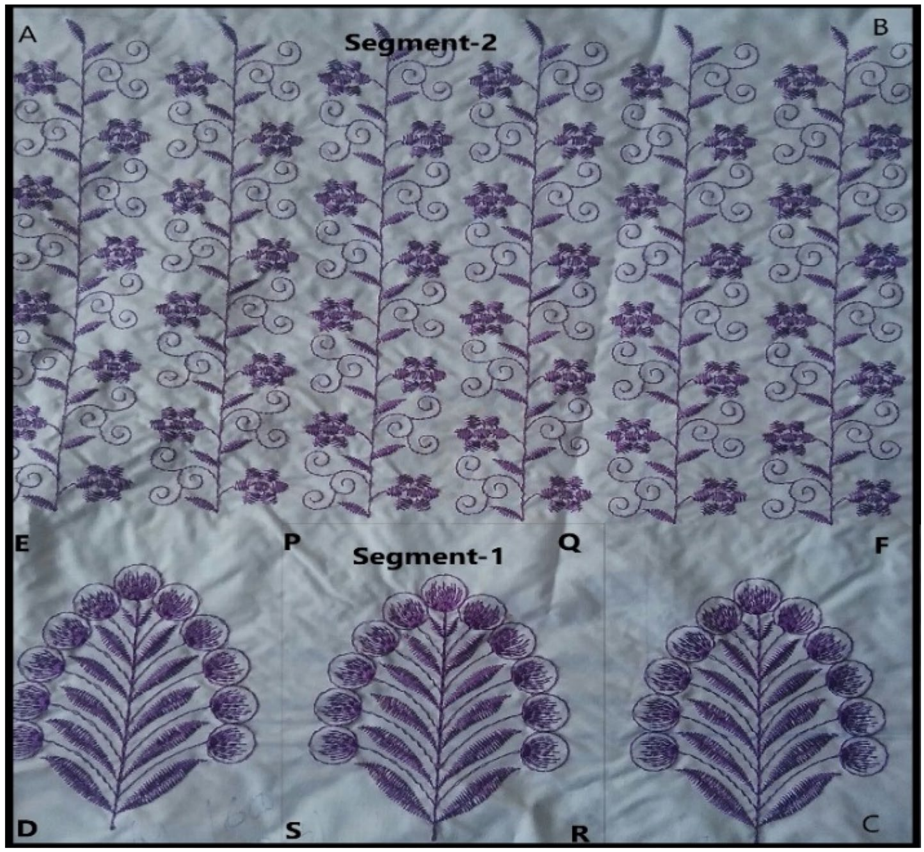

Fig. 8 Division of one full repeat of the embroidery design into multiple segments

Similarly, the average areal density (GSM) of embroidered fabric is also calculated by the weighted average of the areal densities of different segments. Longitudinal (warp-way) flexural rigidities of embroidered fabrics are determined by the same formula used for determining flexural rigidity of base fabric, using the average longitudinal bending length and GSM.

Result and discussion

Experimental results

Test results for all the 49 embroidered samples are represented by the Table 3.

The regression coefficients for all the input parameters to form the linear multiple regression equation are determined through advanced data analysis tools of MS-Excel 2013. Statistical details for the goodness of are also determined. The regression coefficients and values indicating the goodness of fit are shown in the Tables 4 and 5 respectively.

Based upon the coefficients obtained, the following prediction equation can be written.

$$E_{wp} = 0.872 * BF_{wp} + 0.032 * P + 0.248 * D + 6.967 * S - 6.176 * L - 2.246 * \theta_{wp} - 79.248 \quad (1)$$

Where, E_{wp} = Longitudinal (warp way) flexural rigidity of the embroidered fabric in dyne.cm, BF_{wp} = Longitudinal (warp way) flexural rigidity of the base fabric in dyne.

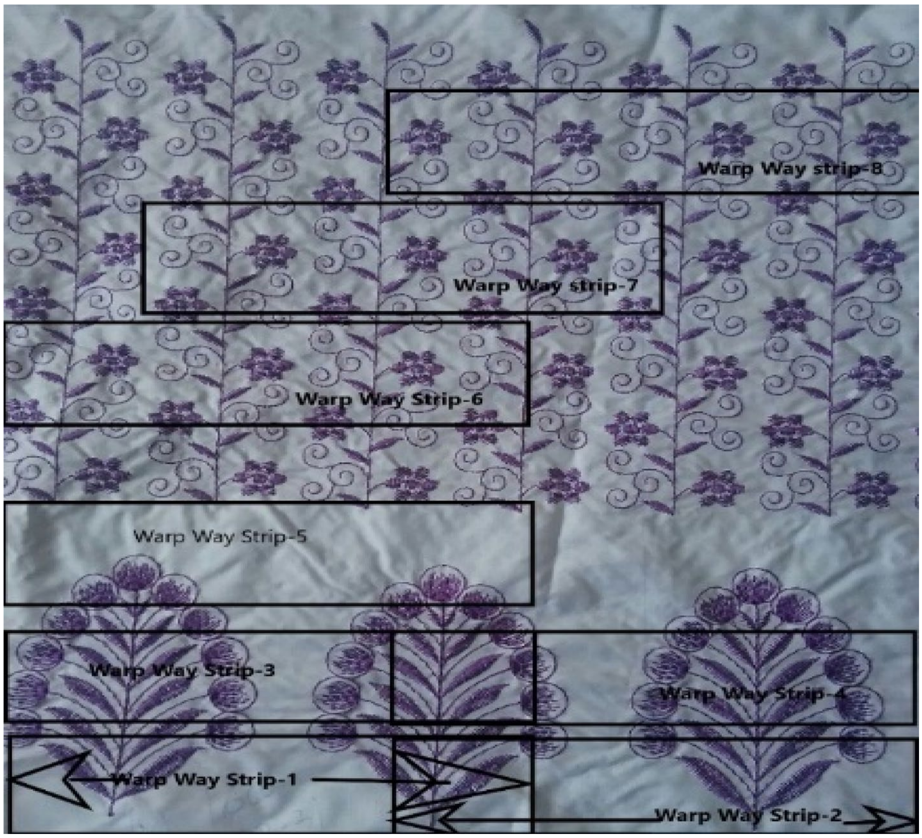

Fig. 9 Distribution of warp-way strips for the measurement of bending lengths for embroidery sample in case of embroidery design ED2

cm, P = Breaking load of embroidery thread in gram-force, D = Denier of the embroidery thread, S = Stitch Density (No of Stitches per sq.cm) of the embroidery design, L = Average stitch length in mm, θ_{wp} = Average stitch angle (in degree) of the embroidery design w.r.t. the warp direction.

From the coefficient values in all the three cases, it is evident that the stitch density of the embroidery design, followed by stitch length and stitch angle are the most influential input parameters so far as the flexural rigidity of the embroidered fabric is concerned. It is also found that the coefficient of the stitch angle w.r.t. warp direction is negative. That means the flexural rigidity of the embroidery fabric has a negative correlation with the stitch angle. Which indicates that the longitudinal stiffness of the embroidered fabric increases as the stitch angle w.r.t. warp direction (θ_{wp}) decreases. This phenomenon can be explained by the fact that as the value of θ_{wp} decreases, more and more number of stitches in a repeat trends to be almost parallel to the longitudinal i.e. the warp direction of the fabric. Hence the component of the binding force imparted by the embroidery stitches along warp direction increases, which in turn contributes in increasing the stiffness along warp direction. It is also noticed that average stitch length too has the negative coefficient value in the prediction equation, which also indicates that higher the value of stitch length in the design, lower

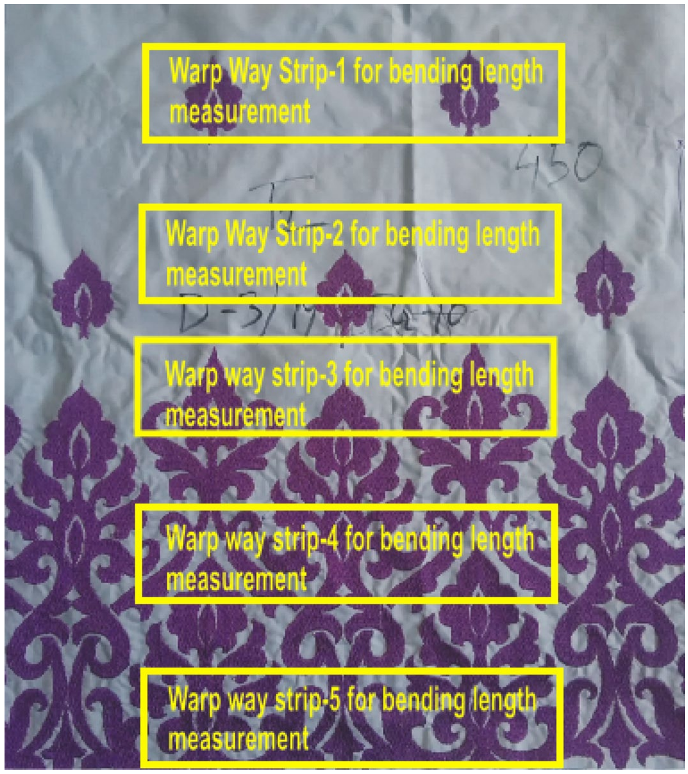

Fig. 10 Distribution of warp-way strips for the measurement of bending lengths for embroidery sample in case of embroidery design ED3

Table 4 Coefficients of the linear multiple regression equation for the longitudinal flexural rigidity of the embroidered fabric

Name of the input parameter	Coefficient
Constant (Intercept)	−79.248
Longitudinal Flexural Rigidity (dyne.cm) of the base fabric (BF_{wp})	0.872
Breaking load of Embroidery Thread in gram-force (P)	0.032
Denier of Embroidery Thread (D)	0.248
Stitch Density in no stitches per Sqcm (S)	6.967
Avg Stitch Length in mm (L)	−6.176
Average Stitch Angle of Embroidery Stitch w.r.t. the warp direction of the base fabric (θ_{wp})	−2.246

Table 5 Values of the Goodness of Fit parameters for the regression equation

Regression statistics	
Multiple R	0.84
R Square	0.70
Adjusted R Square	0.66
Standard Error	25.84

Table 6 Experimented results for the validation of prediction model

Sanple no	Warp way Flexural Rigidity (dyne.cm) of the base fabric	Breaking load of embroidery thread (gf)	Embroidery Thread Denier	Stitch Density in no stitches per sq cm	Average Stitch Length in mm	Average angle between Embroidery Stitch and the warp direction of the fabric	Actual Longitudinal Flexural Rigidity of Embroidered Fabric in dyne.cm	Predicted Longitudinal Flexural Rigidity of Embroidered Fabric in dyne.cm	Coeff.. of correlation
1	50.71	691.8	370	25.22	2.65	47.86	135.91	130.71	0.98
2	106.11	1010.23	238	5.97	5.44	0.24	109.92	112.07	
3	22.87	691.8	370	5.97	5.44	0.24	59.52	62.03	
4	106.11	1010.23	238	33.66	3.50	84.70	127.39	127.31	
5	106.11	691.8	370	33.66	3.50	84.70	141.48	149.86	
6	106.11	582.21	282	25.22	2.65	47.86	153.35	153.69	
7	106.11	999.11	295	25.22	2.65	47.86	171.97	170.25	
8	22.87	881.5	235	25.22	2.65	47.86	85.46	79.02	
9	22.87	1010.23	238	25.22	2.65	47.86	93.46	83.88	
10	22.87	908.026	250	25.22	2.65	47.86	97.23	83.59	
11	50.71	582.21	282	25.22	2.65	47.86	102.13	105.38	
12	106.11	582.21	282	33.66	3.50	84.70	121.4	124.53	
13	106.11	1010.23	238	25.22	2.65	47.86	142.13	156.47	
14	106.11	999.11	295	33.66	3.50	84.70	141.5	141.09	
15	22.87	607.08	360	33.66	3.50	84.70	81.24	72.08	
16	22.87	1010.23	238	25.22	2.65	47.86	74.71	83.88	
17	22.87	691.8	370	33.66	3.50	84.70	62.98	77.27	
18	22.87	881.5	235	5.97	5.44	0.24	42.46	34.62	
19	22.87	881.5	235	5.97	5.44	0.24	36.29	34.62	
20	50.71	582.21	282	5.97	5.44	0.24	75.16	60.97	
21	22.87	607.08	360	33.66	3.50	84.70	73.06	72.08	
22	50.71	607.08	360	25.22	2.65	47.86	127.95	125.52	
23	106.11	1010.23	238	25.22	2.65	47.86	163.81	156.48	
24	22.87	1010.23	238	5.97	5.44	0.24	43.1	39.48	
25	22.87	582.21	282	25.22	2.65	47.86	85.07	81.11	

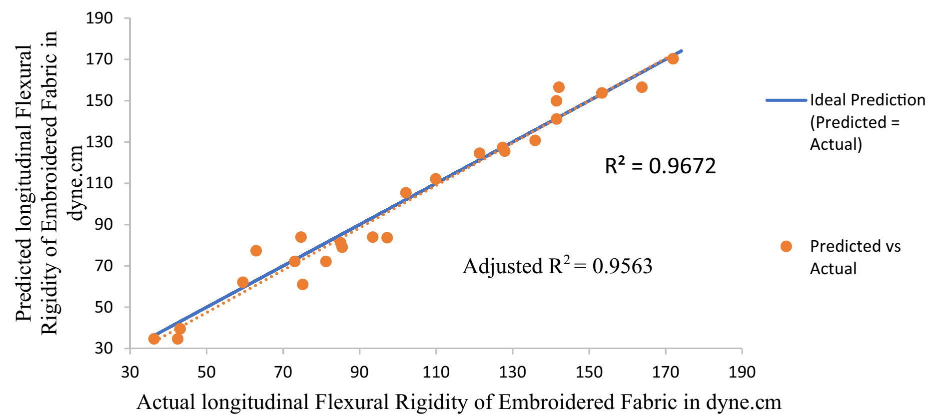

Fig. 11 Scatter diagram for comparison between predicted and actual values of longitudinal stiffness

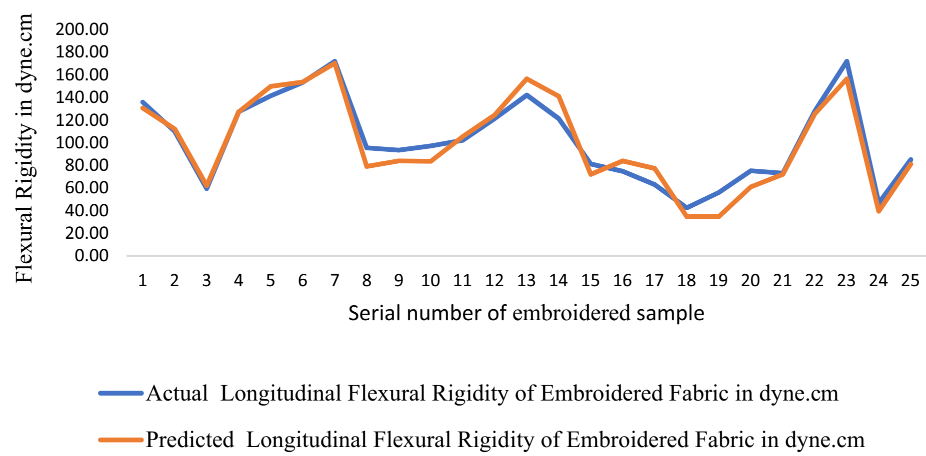

Fig. 12 Line diagram for comparison between predicted and actual values of longitudinal stiffness

Table 7 F-test results for the validation of prediction model of longitudinal stiffness of embroidered fabric

	Predicted Longitudinal Flexural Rigidity of Embroidered Fabric in dyne.cm	Actual Longitudinal Flexural Rigidity of Embroidered Fabric in dyne.cm
Mean	100.719	101.947
Variance	1679.821	1543.253
Observations	25	25
df	24	24
F	1.0885	
$P(F \leq f)$ one-tail	0.4186	
F Critical one-tail	1.9838	

is the stiffness of the embroidered fabric. As the stitch length increases, the distance between two consecutive needle-penetration points i.e. distance between two adjacent points of the thread insertion inside the base fabric also increases. This means the binding force imparted by a single stitch acts on a longer fabric length in case of higher stitch length, which ultimately reduces the effect. Whereas in case of smaller stitch lengths, the needle penetration points occur more frequently and close to each other in a more congested way. This ultimately enhances the effect of embroidery thread on the stiffness of embroidered fabric,

Statistical details for the goodness of fit test for all three regression equations are also determined. Details are given in the Table 5.

It is evident that a satisfactory value of multiple R, R-square (i.e. the coefficient of determination) and adjusted R-Square value have been obtained for the prediction equation developed.

Validation of multiple regression equation with new samples

Twenty-five new samples with varieties of base fabrics, designs and threads have been used to verify the prediction model developed.. The summarized test results are as shown in the Table 6.

Very high and positive value of correlation coefficient is obtained between actual and predicted values of the longitudinal flexural rigidity of embroidered fabrics. Also, the graphical representations of the comparison between actual and predicted flexural rigidity is represented by the Figs. 11 and 12.

It is prominently evident that the prediction equation can predict the longitudinal stiffness of embroidered fabric effectively and with a very close proximity to the actual value. In addition to the above validation test, F-test analysis has been made to test whether any significant difference exists between the predicted and actual values. The results of F-test analysis as obtained for the prediction model are as given in the Table 7.

It is clearly evident that the F-value obtained is less than the critical values of F at 95% confidence limit. Also, the P value is more than 0.05. Hence, it can be stated that the Null Hypothesis can be accepted, which means that no statistically significant difference has been found between the actual and calculated longitudinal stiffness values of the embroidered fabrics.

Propagation of error in the prediction model

Propagation of error in the prediction is calculated according the following standard formula.The formula for propagation of error of function $Y = f(X,Z,\ldots)$, i.e. a linear function of two or more than two independent variables (X,Z,…), can be expressed as the standard deviation of the response Y, given by the following relationship (Ku 1966).

$$SD_Y = \surd\left\{(dY/dX)^2 \cdot (SD_X)^2 + (dY/dZ)^2 \cdot (SD_Z)^2 + ——\right\} \tag{2}$$

Where, SD_Y is the propagation of error, i.e. the standard deviation of the measurements of the dependent variable Y, SD_X is the standard deviation of the measurements of the independent variable X, SD_Z is the standard deviation of the measurements of the independent variable Z and so on, dY/dX is the partial derivative of the function Y with respect to X i.e. the coefficient of the independent variable X in the function.

Applying the formula of propagation of error (Eq. 2) for the prediction model developed and verified (i.e. Eq. 1), the propagation of error for the prediction of the longitudinal stiffness of embroidered fabric can be calculated as below:

$$SD_{Ewp} = \sqrt{\{(0.872)^2 \cdot (SD_{BFwp})^2 + (0.032)^2 \cdot (SD_P)^2 + (0.248)^2 \cdot (SD_D)^2 + (6.967)^2 \cdot (SD_S)^2 + (-6.176)^2 \cdot SD_L^2 + (-2.246)^2 \cdot (SD_{\theta wp})^2\}} \quad (3)$$

Where, SD_{Ewp} is the propagation of error or the standard deviation of the predicted longitudinal stiffness of embroidered fabric and SD_{BFwp}, SD_P, SD_D, SD_S, SD_L, $SD_{\theta wp}$ are the standard deviations of the measurements of the longitudinal stiffness of base fabric, the breaking load of embroidery thread, the Denier of embroidery thread, the stitch density of the embroidery design, the average stitch length of the embroidery design and the average stitch angle of the embroidery design w.r.t. the warp direction respectively. The average values of SD_{BFwp}, SD_P and SD_D are obtained from the experimented data of base fabric stiffness and embroidery thread breaking loads and deniers respectively. The values of SD_S, SD_L and $SD_{\theta wp}$ can be considered as zero in case of computerised embroidery machine, as it is very unlikely that variation of stitch density, stitch length or stitch angle may occur between different design repeats in case of computerised modern embroidery machines. Using all the relevant standard deviations of the independent input parameters, the standard deviation of the prediction is obtained as 2.60. Hence more precisely, the upper limit and lower limit of the predicted value of longitudinal stiffness of embroidered fabric of the i^{th} data point can be expressed as $(E_{wp})_i + 2.60$ and $(E_{wp})_i - 2.60$ respectively. Therefore the prediction equation (i.e. Eq. 1) can be re-expressed as below.

$$E_{wp} = (0.872*BF_{wp} + 0.032*P + 0.248*D + 6.967*S - 6.176*L - 2.246*\theta_{wp} - 79.248) \pm 2.60 \quad (4)$$

After considering this propagation of error, the upper limit and lower limit of predicted longitudinal stiffness of embroidered fabric for each of the 25 embroidered samples (ref. Table 5) are calculated based upon the prediction model represented by Eq. 4. The graphical representation of all those upper and lower limits of predicted longitudinal

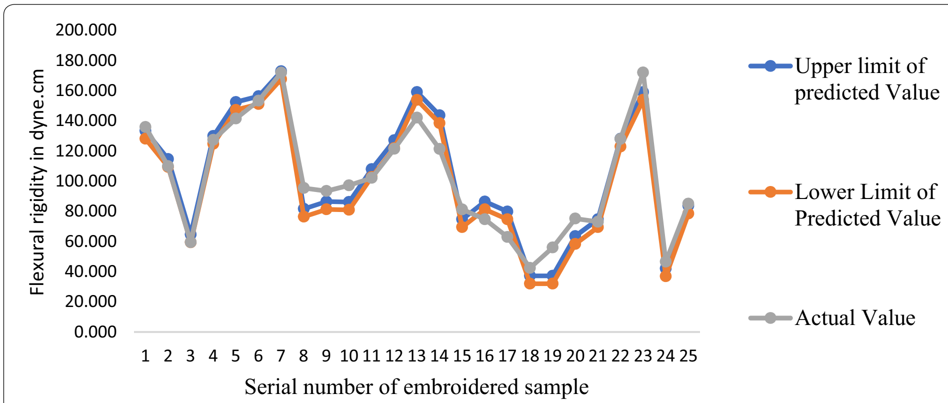

Fig. 13 Comparative illustration for actual longitudinal stiffness of embroidered fabrics with the predicted limits

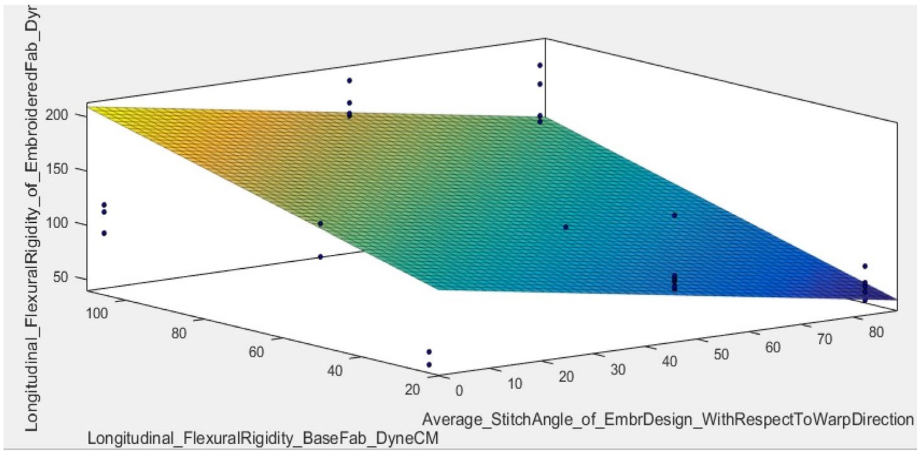

Fig. 14 Longitudinal stiffness of embroidered fabric vs longitudinal stiffness of base fabric and average stitch angle with respect to warp direction

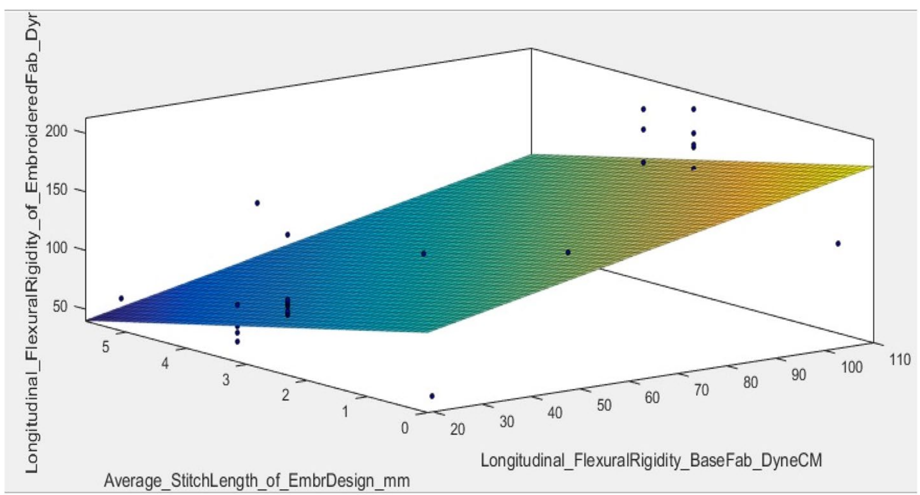

Fig. 15 Longitudinal stiffness of embroidered fabric vs longitudinal stiffness of base fabric and average stitch length

stiffness values along with the actual longitudinal stiffness values of embroidered fabrics are represented by the Fig. 13.

It is clearly evident that actual longitudinal stiffness of embroidered fabric for almost all the embroidery samples are either well within the predicted range or close to any of the two prediction limits. Hence, this analysis further ensures the prediction accuracy of the model developed in this work.

Three dimensional surface diagrams to illustrate the influence of input parameters on the longitudinal stiffness of embroidered fabric

Three dimensional surface diagrams are prepared through Matlab-R2019a software, keeping the longitudinal stiffness of embroidered fabric in the output axis i.e. Z-axis and

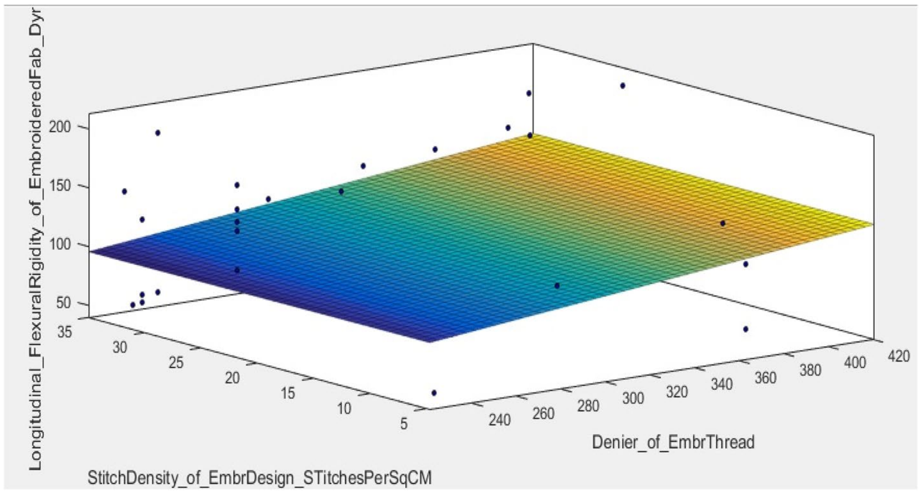

Fig. 16 Longitudinal stiffness of embroidered fabric vs stitch density and the Denier of embroidery thread

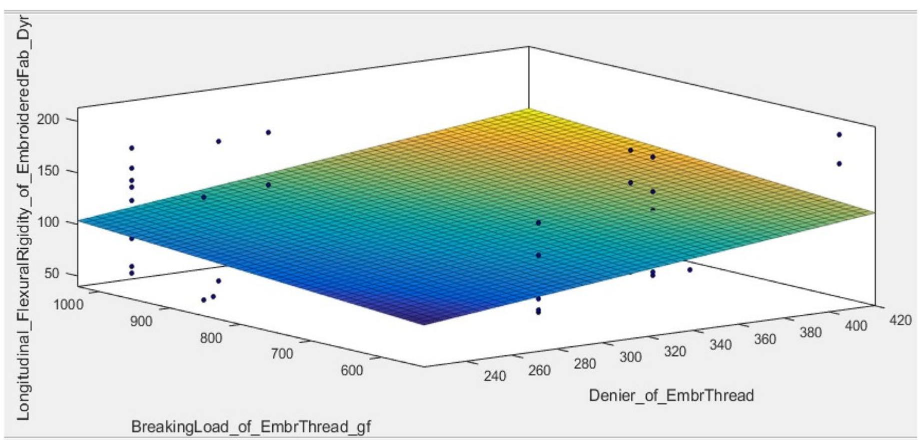

Fig. 17 Longitudinal stiffness of embroidered fabric vs breaking load and the Denier of embroidery thread

any two of the six input parameters in X and Y axes. Hereby total four such surface diagrams are prepared, represented by Figs. 14, 15, 16, and 17.

The prime objective of the 3D surface diagrams is to prepare the visual illustrations to have a lucid view of the influences of the input parameters on the stiffness property of embroidered fabric. Also, it is a graphical verification of the influences obtained in terms of the regression coefficients earlier.

It is clearly evident from the Fig. 14 that the longitudinal stiffness of embroidered fabric increases steadily as the longitudinal stiffness of the base fabric increases. Whereas, the negative impact of the stitch angle (w.r.t. warp direction) is also very prominent here, which reveals the fact that as the stitch angle w.r.t. the warp direction increases the longitudinal i.e. warp-way stiffness of the embroidery fabric decreases, as explained earlier in the "Design of experiment" section.

Figure 15 exhibits the negative influence of the average stitch length of the embroidery design. The graph clearly indicates the decrease in the longitudinal stiffness of embroidery fabrics with the increase in the average stitch length of the design. The explanation of this incident is provided in the "Experimental results" section.

As it is represented by the Fig. 16, the longitudinal stiffness of embroidered fabric increases as the linear density (expressed as denier here) of the embroidery thread increases. The higher the denier of the thread more is the addition of weight in the fabric and that ultimately results in higher stiffness in terms of flexural rigidity of the fabric. Also the longitudinal stiffness increases as the stitch density of the design increases.

Also the Fig. 17 conveys the fact that the tensile strength in terms of breaking load of the embroidery thread has a positive impact on the longitudinal stiffness of the embroidered fabric. Threads with higher breaking load result in enhancement of the binding force applied by the thread on the base fabric structure. This figure also substantiates the findings obtained in terms of regression coefficients that the stiffness of the embroidered fabric increases steadily as the denier of the thread increases.

Conclusions

A very significant increment of longitudinal stiffness of fabric due to embroidery process is noted in this study. Stiffness increases mainly due to the addition of embroidery threads in the fabric structure. The increment of longitudinal stiffness of embroidered fabric mainly depends upon the stitch density, stitch length, stitch angles and the physical and mechanical properties of the embroidery threads in terms of denier and breaking load. It is observed that the longitudinal stiffness increases as the stitch density of the design, denier and breaking load of the embroidery thread increase. On the other hand it is also noted that it decreases with the increment of stitch length and stitch angle w.r.t. the warp direction.

The prediction model through linear multiple regression has been developed based upon tested values of all the samples prepared representing different levels of base fabric stiffness, breaking load and linear density of embroidery threads and stitch properties like stitch density, stitch angle and stitch length. The prediction model is tested statistically with new set of embroidery samples and a very satisfactory level of prediction accuracy is obtained.

This prediction model can be used to assess the longitudinal stiffness of embroidered fabrics, even before the starting of actual embroidery process. The input parameters used here are very basic parameters related to design and materials, which can be easily available. And also, a simple linear multiple regression is used to make the prediction equation simple and user-friendly. So this model can help the embroidery designers or garment designers significantly to pre-estimate the longitudinal stiffness of the embroidered fabrics and in this way, the designers can be able to adjust the embroidery parameters and thread parameters accordingly in the planning and designing stage itself to ensure that the stiffness of embroidered fabrics remains within desirable range, depending upon the end-use of that fabric.

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