Influence of Stitching Pattern on Deformation Behaviour of Woven Fabric during Forming

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An experimental study of the influence of stitching pattern, direction, location and stitching step on fabric deformation behaviour has been carried out. Uniaxial tension test of bias fabric specimen combined with image processing was chosen to describe the formability and buckling of fabric by parameters: critical buckling load P_{cr}, critical elongation ε_{cr}, critical shear angle γ_{cr}. Different specimen response to the stitches made in warp, in weft and stitches oriented at 45° angle to the warp direction was observed. Stitches oriented perpendicularly and diagonally to the specimen tension direction have no significant influence on the parameters, which describe fabric formability. Stitching coincident with principal directions of a fabric has significantly restricted specimen deformation behaviour during bias tension. It was determined that proper selection of the stitching step and stitch location will warrant higher form stability of woven fabric when more uniform deformation distribution in a specimen can be obtained.

Keywords: woven fabric, stitching pattern, formability, bias tension, critical buckling parameters.

1. INTRODUCTION

Stitching of textiles is used in various industry sectors and products. The type and parameters of stitching are different and depend on purpose: commonly the aesthetical look of a product is changed [1 – 3], the strength and stability properties are controlled [4 – 10] or the functional properties are provided [3, 11 – 13]. Stitches as essential binding element of fibers or filaments are responsible for the strength of stitched products. Stitches are used to join multilayer materials, to increase stability and to gain special visual effects on clothing, furnishing, bedding, quilted products of traditional textiles [1 – 3]. For technical textiles stitching technology is conceded as the progressive technique intending to change fabric properties in proper direction and the goals of this can be different: to increase the damage resistance of composites for the ballistic protection of personnel [4, 9], to improve the interlaminar toughness and to increase the strength of laminate [7, 8]. Stitches are also used to fulfil sensing and responding activities thanks to embroidered interconnections and encapsulation for electronics in textiles for wearable electronics applications [3, 11].

In resent years stitching technology was applied to change the formability properties of woven fabric and to avoid appearing of instability defects [7, 8]. During forming process fabric is subjected to the complex of deformations: tension, compression, shear and bending. The formability of woven fabric is limited by shear rigidity and out-of-plane buckling or surface wrinkling rise when critical deformations are exceeded. The new idea to incorporate stitches just in localized sections of woven sample and to transfer shear forces to the unsheared zones was presented by P. Molnar et al [7]. The authors concluded that the seams applied at the highly deformable and predefined zones help to reduce fabric shearing or to transfer the shear forces into the unsheared areas during the thermoforming process. However more comprehensive analysis of mechanical properties of woven fabric as system of threads and deformation behaviour that has been changed by various stitching patterns would provide deeper understanding of possibility to validate forming process of a woven fabric by stitching.

The aim of this research is to study influence of stitching on formability of woven fabric.

2. MATERIALS AND METHODS

2.1. Material and specimen preparation

Plain woven cotton fabric of 137 g/m^2 area density, 23 cm^{-1} in warp (linear density 30 tex), and 22 cm^{-1} in weft (linear density 27.5 tex) was chosen for the investigations. The sewing thread of 100 % polyester, 21.25 tex × 2 was used as upper and lower threads to form 301 type lockstitch. The seam with stitch density 4 cm^{-1} (2.5 mm stitch length) was produced on a single fabric layer by industrial sewing machine Juki using needle No. 80 (size 12).

Considering the order, in which stitches were performed, two types of sewing patterns were distinguished: periodic order and symmetric order.

Periodic pattern is an order of stitches that repeat itself in a sequence of concrete step. 6 lengthwise periodic patterns and 3 patterns of stitched net (Table 1) were made at 5 mm or 10 mm step to study stitching pattern, pattern direction (warp, weft or 45° angle to the warp direction) and stitching step effect upon formability characteristics of a woven fabric.

The various periodic patterns include different count of stitches. Mechanical properties of the fabric are changed by the amount and direction of incorporated thread. The influence of stitching pattern on fabric surface density w, bending rigidity B, shear rigidity G, maximum force at break P_{max} and elongation ε_{max} at break are presented in Table 2.

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Table 1. Periodic stitching patterns

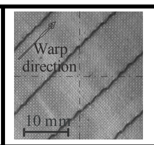
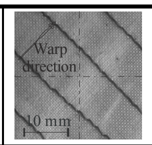
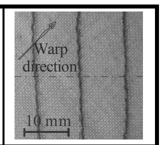
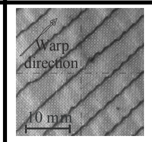
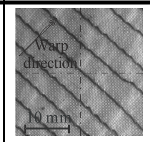
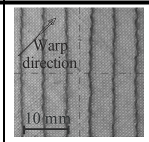
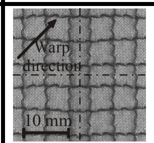
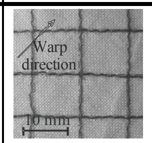
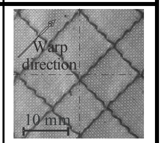
Stitching pattern			
Specimen code	L_warp_10	L_weft_10	L_bias_10
Stitching pattern			
Specimen code	L_warp_5	L_weft_5	L_bias_5
Stitching pattern			
Specimen code	Net_bias_5	Net_bias_10	Net_10

Table 2. The main mechanical parameters of tested specimens

Stitching pattern	w, g/m^2	B*, μNm	G*, N/m	ε_{max}, %	P_{max}, N
Unstitched	137.00	5.20	157.70	59.18	229.50
L_warp_10	142.84	6.93	236.54	57.00	250.40
L_weft_10		7.56	189.23	53.70	201.75
L_bias_10		9.58	372.73	30.00	137.20
L_warp_5	147.02	9.89	300.00	56.48	262.00
L_weft_5		8.59	307.50	58.80	262.00
L_bias_5		15.62	878.57	31.20	240.00
Net_10		9.58	286.05	56.40	291.20
Net_bias_10		10.21	820.00	29.78	138.80
Net_bias_5	152.61	15.36	1118.18	32.03	269.60

* Characteristics were obtained according FAST methodic.

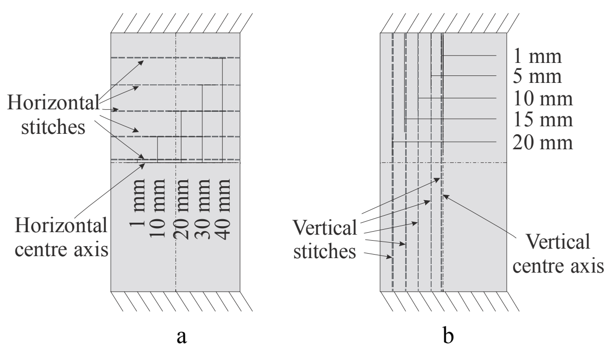


Fig. 1. The variation of symmetric stitching location considering the distance from specimen centre axes: a − horizontal stitching pattern, b − vertical stitching pattern

To study the influence of stitching location two parallel stitches were made symmetrically to the specimen centre axes (horizontal and vertical) with gradually increased distance between centre axis and stitches. In a case of vertical stitching the distance was 1, 5, 10, 15 and 20 mm (the specimens were coded as V_1, V_5, V_10, V_15 and V_20 respectively) and in a case of horizontal stitching – 1, 10, 20, 30 and 40 mm (the codes were H_1, H_10, H_20, H_30 and H_40 respectively) (Fig. 1).

2.2. Experimental methods

For the investigations rectangular fabric specimens with operating area of (50×100) mm^2 were cut at 45° angle to the warp yarn system. Three specimens with different stitching pattern were prepared for each test.

The uniaxial bias tension test until specimen break combined with the image analysis was carried out to study deformation behaviour of fabric-threads system. The special illumination arrangement was applied for image analysis evaluation in order to commit the moment when stretched specimen looses its stable form and starts to buckle. Images of a deformed specimen at every step of 0.5 mm were recorded. The buckling moment was defined from captured digital images of 256 grey scale values after image filtering and grey scale colour close contour separation (Fig. 2) [12, 13]. The critical form stability moment was described by parameters: critical load P_{cr}, critical elongation ε_{cr} and critical shear angle γ_{cr}.

Fig. 2. The principle of image analysis for specimen buckling moment evaluation (unstitched specimen elongation 4 %)

During tension test the stress and strain distribution along the direction of applied load is non-uniform because of the specimen yarns fixation in clamps: in the third zone (III zone) both yarns systems are clamped and no significant deformations are there, in the second zone (II zone) only one yarn system is clamped and in the first zone (I zone) in a centre part of a specimen both yarn systems are clamps free therefore the most significant deformations in this zone are obtained (Fig. 2). To study distribution uniformity of deformations the zones with different modes of deformation were identified in a specimen tracing the last clamped yarn and the angle θ between two yarns systems was evaluated in all specimen deformation zones until 20 % elongation of specimen was reached. From 5 up to 9 measurements of the angle θ were performed for each separated zone and mean value of angle θ was calculated. Shear angle γ was defined as $\gamma = \pi/2 - \theta$. The coefficient of variation of all tests varied up to 4.90 %.

3. RESULTS AND DISCUSSION

3.1. Periodic stitching patterns

The tensile curves (P–ε) of periodically stitched specimens are presented in Figure 3. The highest values of elongation at the same load were obtained for unstitched specimen. The close behaviour and similar tensile characteristics were observed for specimens where stitches were coincident with warp/weft yarns direction (diagonal in respect to the specimen tension direction). An exception was the specimen with stitched net pattern – Net_10. This specimen obtained lower elongation values under the same load and reached the highest value of load at break. This could be related with the restriction of specimen thread movement by crossing of the perpendicular stitches. It must also be noted, that no significant effect of stitching step upon specimen stitched in principal fabric directions behaviour was observed.

The stitches oriented at 45° angle (coincident with the specimen tension direction) have changed specimen behaviour significantly. The values of elongation at break decreased. This means that these fabric-threads systems could be used to obtain spatial shapes of significantly lower curvature, other way − the product breaks-up. The analysis of stitching step influence upon specimen behaviour has shown that specimens with denser stitching patterns will require higher values of load to obtain the same value of elongation comparing to specimens having rarer stitching density. This is related with additional strength of stitching thread [5]. It must be mentioned that no effect of perpendicularly to the specimen tension direction sewn stitches on the specimen behaviour and tension parameters was observed.

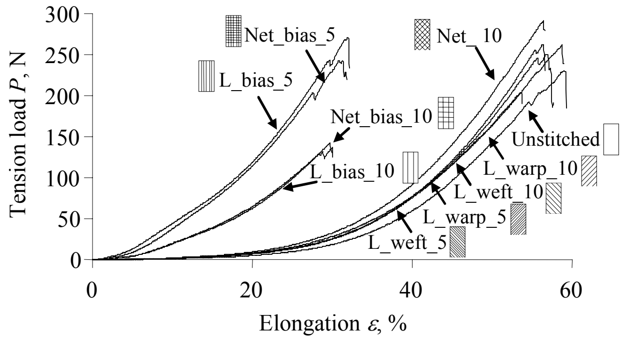


Fig. 3. The P–ε curves of specimen with periodic stitching patterns

To study the variation of shear angle γ in three zones of deformed specimen with different stitching patterns the typical tension load P – shear angle γ curves were drawn. The exponential equation $P = a + b\gamma^c$ was used to present obtained dependences (Fig. 4) and high values of coefficients of determination R^2 were obtained ($R^2 = 0.936 \div 0.999$).

The graphs in Figure 4 a show that the load required to reach specimen elongation of 20 % increases twice when stitches are sewn in warp direction of a fabric specimen, but the values of shear angle are obtained similar in all specimens: for unstitched specimen shear angles in I, II and III zones are respectively 34°, 25°, 6°; for specimen L_warp_10 – 35°, 23°, 5° and for specimen L_warp_5 – 35°, 21°, 5°. The same results were measured for samples with stitches made in weft direction of a fabric.

The behaviour of specimen Net_10 during deformation was close to discussed above (Fig. 4, b). But this specimen has reached the higher shear angle values at 20 % of specimen elongation at I and II zones – respectively 39° and 30°. This means that stitches coincident with warp and weft yarns increased shear deformations of a specimen. This result is coincided with results obtained by P. Molar et al. [7] where possibilities to apply stitching and to control shearing during product

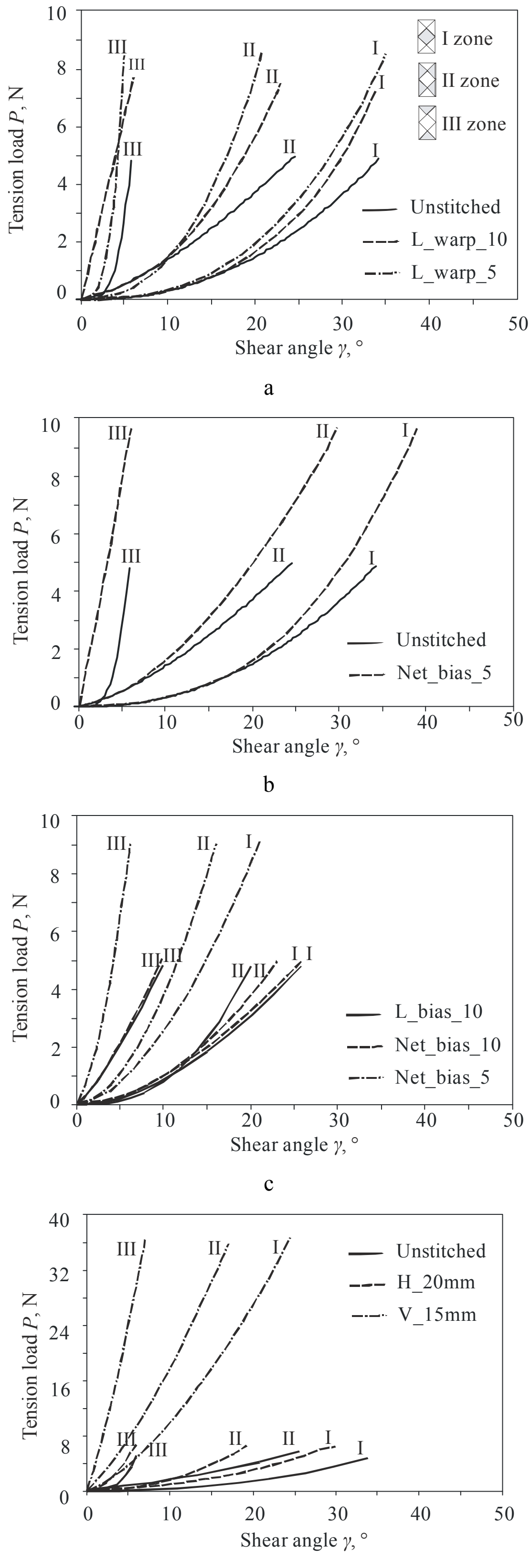


Fig. 4. Typical curves of shear angle γ variation in different zones of deformed specimen

forming were discussed. In our experiment it was found that with increase of shear deformations the uniformity of deformation distribution of a specimen decreased and led to the lower critical buckling elongation and critical buckling load values. The mechanism of fabric buckling because of deformation distribution uniformity is broadly discussed in our previous article [14].

The stitching oriented at 45° angle (L_bias_10, L_bias_5) as well as net stitching (Net_bias_10, Net_bias_5) have significantly changed behaviour of a fabric during deformation. Approximately 10 times higher tension load in a case of stitching step 10 mm and up to 25 times higher in a case of stitching step 5 mm (Fig. 4, c) was required to reach 20 % specimen elongation. Herewith lower shear angle values in I and II zones and higher in zone III were reached decreasing stitching step in a specimen. It evidence the increase of tension deformations and decrease of shear deformations of a deformed specimen when higher uniformity of deformation distribution in a specimen warrant higher form stability of a material. No effect of stitches sewn perpendicularly to the specimen tension direction was observed.

Buckling moment of a specimen was defined by image analysis and obtained parameters that describe form stability limit are listed in Table 3. The increase of critical form stability parameters was estimated when denser stitching step was applied up to fabric warp or weft yarns direction. This probably is related with increased bending rigidity B of a specimen (Table 2).

When stitches were applied to both yarn directions simultaneously specimen buckled under lower critical elongation $\varepsilon_{cr} = 2.75$ % but higher critical shear angle $\gamma_{cr} = 8°$ was reached. This confirms above mentioned notes [14] that decrease of uniformity of deformations distribution will cause the prior buckling of a material. Accordingly because of higher uniformity of deformation distribution no buckling was observed for the specimens reinforced by stitching at 45° angle.

Table 3. Critical buckling conditions of bias specimens with periodic stitching patterns

Stitching pattern code	Critical load (P_{cr}), N/m	Critical elongation (ε_{cr}), %	Critical shear angle (γ_{cr}),°
Unstitched	9.13	4.00	7
L_warp_10	13.03	4.00	7
L_weft_10	11.80	4.00	7
L_bias_10	–	–	–
L_warp_5	17.29	5.25	9
L_weft_5	17.79	4.75	8
L_bias_5	–	–	–
Net_10	13.05	2.75	8
Net_bias_10	–	–	–
Net_bias_5	–	–	–

The study of formability properties of stitched woven fabric behaviour has proved that additional thread systems warrant higher form stability but stitched fabric requires significant higher loads during forming process because of higher rigidity to tension and shear.

3.2. Symmetric stitching patterns

The study of symmetric pattern influence on woven fabric deformations has clarified different behaviour response when stitches are applied perpendicularly and coincident to the specimen tension direction. The effect of stitches added perpendicularly to the specimen tension direction was insignificant and stitches applied coincident with specimen tension direction have changed deformation behaviour of a specimen considerably (Fig. 5).

The study of influence of symmetric pattern location on the deformation behaviour of a specimen during tension has shown no relationship between deformation behaviour and order of stitches. The obtained P–ε curves and functions of approximation are presented in Figure 6.

The analysis of shear angle variation (Fig. 4, d) during specimen tension shows that specimens with horizontal stitching pattern have reached lower shear angle values in I and II zones ($\gamma = 30° \div 32°$ and $\gamma = 17° \div 20°$ respectively) then unstitched specimen at the same elongation of 20 % ($\gamma = 34°$ and $\gamma = 25°$). Because of higher uniformity of deformation distribution in a specimen the higher values of critical form stability parameters were recorded for these samples (Table 4).

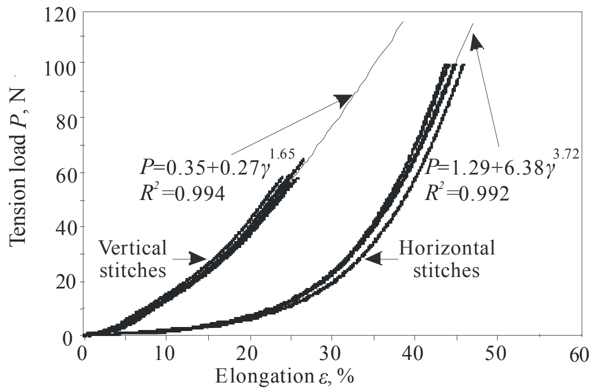
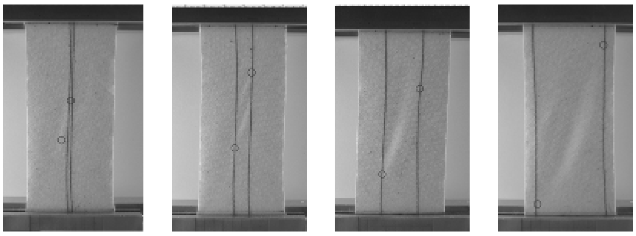


Fig. 5. The P–ε curves of specimens with symmetric patterns

Table 4. Critical buckling conditions of bias specimens with symmetric stitching patterns

Stitching pattern code	Critical load (P_{cr}), N/m	Critical elongation (ε_{cr}), %	Critical shear angle (γ_{cr}),°
Unstitched	9.13	4.00	7
H_1	15.00	5.00	6
H_10	13.50	4.50	6
H_20	13.07	4.50	6
H_30	12.67	5.00	6
H_40	13.38	5.00	6
V_1	128.00	5.50	4
V_5	57.60	4.00	3
V_10	28.80	3.50	3
V_15	33.00	3.50	3
V_20	28.80	3.00	3

Approximately 8 times higher tension load was required to obtain 20 % elongation for specimens with vertical stitches. The lower shear angle values in I and II zones were reached ($\gamma = 22° \div 23°$ and $\gamma = 17° \div 19°$ respectively). This means that applying stitches tension deformation increased and shear deformations decreased, so the higher uniformity of deformation distribution in specimen was obtained. However, buckling behaviour is related with stitching pattern location in a specimen. As nearer the centre of a deformed specimen stitches were made the higher values of critical form stability were determined. This phenomenon can be explained analysing the form and place of revealed buckling wave. During fabric tension the stress concentrators are formed at intersection of distinct deformation zones (Fig. 6). As it is shown in Figure 6 stitches have restricted specimen movements in certain zones and stress concentration points are formed in different locations.



a b c d

Fig. 6. The buckled horizontally stitched specimens (a) H_1 mm, (b) H_10 mm, (c) H_20 mm, (d) H_40 mm with different location of stress concentration points

Comparing deformation behaviour of specimens with vertically stitched symmetric patterns (V_1 mm, V_5 mm, V_10 mm, V_15 mm and V_20 mm) with in the same direction oriented lengthwise stitching patterns (L_bias_10, L_bias_5) was observed the importance to apply stitches not only in a zone where fabric wrinkling occurs, but also in neighbouring zones. This must be benefit to obtain more uniform deformation distribution in whole fabric during forming.

4. CONCLUSIONS

The study of fabric bending, shear, tension and buckling properties when specimens were reinforced by stitching shows that formability parameters of a fabric can be changed by performing seams.

The most significant influence on the deformed fabric form stability as well as load – deformation response has been determined for the specimens with stitching patterns applied coincident with fabric tension direction. These fabric – thread systems require higher values of load to obtain certain value of elongation and the degradation of forming properties are observed. Proper selection of stitching step and stitch location warrant higher form stability of woven fabric when more uniform deformation distribution in a specimen is obtained because of restricted shear deformation during bias uniaxial tension.

Acknowledgments

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