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New Funnel Shaped Nozzle for Evaluation of the Mechanical Properties of Woven Fabric by the Extraction Method

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Abstract
Current methods of mechanical property evaluation of fabrics such as the KESF and FAST systems employ several testing devices for measuring tensile, shearing and bending characteristics separately. In this research a new facile and efficient extraction method for simultaneous estimation of different mechanical properties using a funnel-shape nozzle is introduced. The tensile, shearing and bending properties of 84 woven fabric samples were measured using standard methods and subsequently circular specimens of these fabrics were extracted through the funnel shaped nozzle. Sixteen different parameters were graphically selected from the force-displacement curves obtained, and the correlation between these parameters with the experimental mechanical properties was calculated. Finally stepwise multiple linear regression analysis was applied to acquire the best equation for predicting the mechanical properties of the fabrics. Our findings revealed that the shear stiffness and tensile strength can be objectively evaluated by measuring the initial slope (S1) and maximum load (P_{max}) on the load-displacement curve. The maximum load in the 4th zone (F_{max}) of the graph was introduced as an objective measure of the bending rigidity and tensile module in the warp direction. The area of curve (A) can be used for objective evaluation of bending rigidity in the weft and bias directions.

Key words: *extraction method, force–displacement curve, mechanical properties, woven fabrics.*

Introduction

The mechanical properties of fabrics govern many aspects of fabric performance, such as hand and drape [1]. Objective measurement of these properties, including bending, tensile, shear, compression and surface characteristics, is necessary in selecting appropriate fabrics in order to minimise tailoring problems and improve the quality of the finished garment. The bending properties of a fabric are determined by fabric and yarn parameters such as thread spacing and crimp, yarn geometry and flexural rigidity, etc. [2, 3]. In practice, the tools which are used to measure bending properties are the KES-FB2 pure bending tester, which measures bending rigidity per unit width and the hysteresis of the bending movement [4]; and the FAST-2 bending meter [5], based on Peirce's bending length [6], which can measure the fabric bending length and bending rigidity.

Shearing behavior is also very important for designing automated processes to evaluate fabric handle [7] and drape [1]. The shear rigidity of a fabric depends on the mobility of cross-threads at the intersection point, which again depends on the weave, yarn diameter and surface characteristics of both fibre and yarn [8]. The KES-FB1 shearing tester [4] and FAST-3 extensibility meter [5] are used for the evaluation of fabric shearing properties.

Tensile strength is another important attribute of woven fabrics that distinguishes them from non-woven and knitted fabrics. The strength of a fabric depends not only on the strength of constituent yarns but also on the yarn material, yarn fineness, the number of ends and picks per unit length and the weave design [9, 10]. The KES-FB1 tensile tester [4] and FAST-3 extensibility meter [5] are used for measuring fabric tensile properties.

Previous researchers have used a known method based on pushing a fabric sample through a slot or pulling it through a ring (***Figure 1***) to measure resistance forces in the push-through or pull-through mechanisms [11 - 14]. It is claimed that these methods could also be beneficial in evaluating fabric mechanical properties and handle [12, 15 - 18]. But in this research work a new funnel shaped nozzle was developed and used to measure the mechanical properties of fabrics by extraction of circular fabric samples through it. As a result a new force–displacement graph gave new and accurate extracted parameters to evaluate fabric properties.

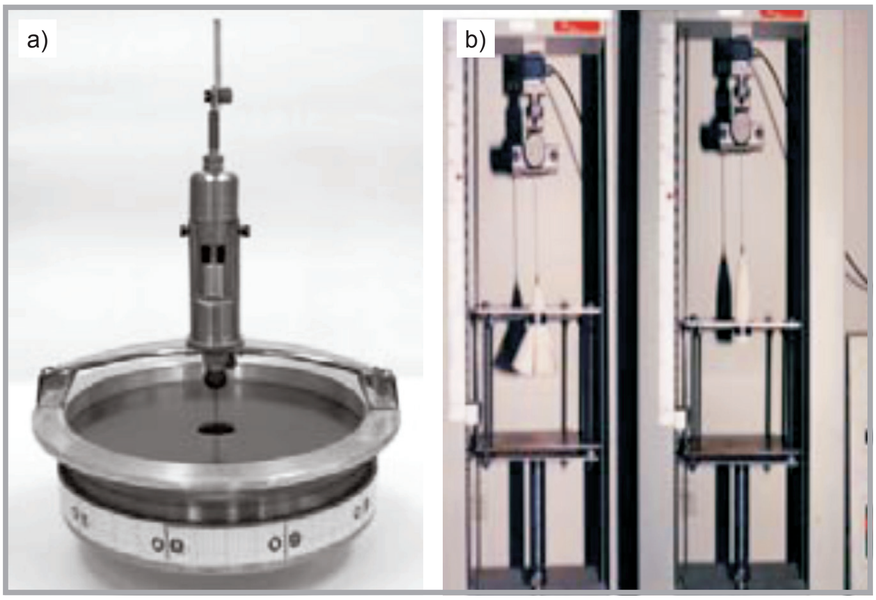

Figure 1. *a) pushing through and b) pulling through a ring [11 - 14].*

Table 1. Woven fabrics' characteristics.

Fabric code	Warp			Weft			Fabric	
	Fibre content, %	Density, End/cm	Count, tex	Fibre content, %	Density, Pick/cm	Count, dtex	Area weight, g/m^2	Structure
A1	70/30 Polyester/Cotton	30	19.7	70/30 Polyester/Cotton	13	19.7	89.5	Twill
A2						22.7	96.9	
A3		31			19	19.7	107.9	
A4						22.7	115.0	
A5					25	19.7	120.5	
A6						22.7	127.2	
B1	100 Card Cotton	40	39.3	Cotton/Filament	19	8/19.7	344.5	Mix
I2	50/50 Polyester/Cotton	10	29.5	50/50 Polyester/Cotton	8	29.5	45.9	Plain
D4	100 Cotton	24	29.5	100 Cotton	13	29.5	111.6	Plain
D5					18		127.1	
D6					23		151.2	
D7					18	59.0	194.8	
D8					13		158.2	
H1	70/30 Polyester/Cotton	28	19.7	70/30 Polyester/Cotton	33	14.8	131.2	Plain
H2							126.0	
K1	100 Cotton	28.5	29.5	100 Cotton	15	29.5	136.2	Plain finish
K2		24			16		130.4	Plain gray
M1	70/30 Polyester/Cotton	40	14.8	70/30 Polyester/Viscose	27	16.4	123.1	Plain
M4						19.7	130.2	
M7				100 Cotton			127.6	
M9				70/30 Polyester/Cotton	20		112.1	
N4		46					123.2	
N6						16.4	117.1	
N8						19.7	121.5	
N12				100 Cotton	27		135.2	
P4	100 Polyester	30	19.7	100 Polyester	23.5	19.7	113.5	Plain
P5					20.0		107.5	
P6					17.0		96.4	
P7					23.5		109.3	Twill
P8					20.0		100.9	
P9					17.0		94.8	

Materials and methods

In this work 84 woven fabric specimens were made using a Sulzer-Rapier G6100 loom under the same conditions. The specimens were produced with different fibre types, yarn counts, warp and weft densities and weave types, some of which are listed in ***Table 1***. In all the experiments, each measurement was made for three separate samples cut from different parts of woven fabrics not sharing similar warps or wefts, and the resulting values were averaged. All measurements were conducted in standard atmospheric conditions of 20 ± 2 °C temperature and 65 ± 2% relative humidity.

First the bending rigidity of three separate standard samples of 25 mm width × 200 mm length in the warp, weft and bias (45°) directions were measured by a Shirley stiffness tester, which measures the bending length of fabrics using the cantilever bending principle. From the bending length values obtained, the bending rigidity of the fabrics was calculated using ***Equation 1***.

$$B = W\, C^3\, 9.8 \times 10^{-3} \qquad (1)$$

where: B - bending rigidity in mN·mm, C - bending length in cm, W - fabric weight in g/m^2.

Mean values for the bending rigidity of some selected samples are shown in ***Table 2***.

Table 2. Experimental mean values of bending rigidity of fabric samples.

Parameter	Weight, g/m^2	Bending length, cm			Bending rigidity, mN·mm		
		warp	weft	bias	warp	weft	bias
Mean	123.8	4.00	2.76	3.35	89.6	33.98	54.75
Max (Sample B1)	344.5	6.13	4.74	5.18	791.6	366.3	477.44
Min (Sample I2)	45.9	1.92	1.36	1.60	3.24	1.16	1.88

In the second set of experiments, an Instron tensile tester was used to measure the tensile module in the warp and weft directions. The standard fabric samples of 60 mm width × 200 mm length were prepared. A gauge length of 50 mm was maintained for all samples. The test was conducted at a crosshead speed of 10 mm/min using a 10 kg load cell. After drawing the stress-strain curves of the samples, the tensile module was calculated graphically from the initial slope of the curve.

Finally the shear rigidity was calculated from the extension of the fabric samples in the bias (45°) direction using ***Equation 2***.

$$G = 123 / EB5 \qquad (2)$$

where: G - shearing rigidity in N/m, $EB5$ - sidelong fabric elongation measured at a pressure of 0.49 kPa.

Mean values of the tensile module and shear rigidity of some selected samples are shown in ***Table 3***.

Figure 2 shows basic components of the new method of extraction based on pulling (extracting) fabric through a funnel of appropriate diameter using an Instron tensile tester. This method shares some common features with previous ones including a ring and slot. Fabrics were drawn through a newly designed plexiglass funnel with the following dimensions: d_{min}= 25 mm, d_{max}= 150 mm, 55 mm conical and 20 mm cylindrical height (***Figure 2***). This funnel shape nozzle was placed above two horizontal plates: the upper adjustable „distance plate" with a hole of 150 mm diameter in the centre, and a "base plate" placed at a specified distance from the distance plate. The distance between the base plate and distance plate was adjustable (***Figure 2***). Circular samples of 250 mm diameter were cut from the center of each fabric specimen and marked in the warp, weft and bias directions, as indicated in ***Figure 3***. Samples were extracted through the funnel and the pulling force required was measured with respect to the displacement of the specimen, which is recorded as a force-displacement curve. The tension rate was 10 mm/min, and fabric behaviour over the entire extraction period was captured by a digital camera installed in an appropriate position under the funnel.

During this extraction process, a circular fabric sample behaves in the following sequential manner;

- At the beginning, the sample is in a flat horizontal position
- Then the sample begins to touch the inside wall of the conical part of the funnel when it is pulled through the funnel using an Instron tensile tester. Contact between the fabric sample and inside wall of the funnel forces the fabric to fold up in some positions.
- As the sample attempts to enter the narrowest part of the funnel, tension builds and reaches a peak as a result of a combination of stretching, compression, shear and bending effects. During this process, more constrained folding and surface reconfiguration is applied on the sample to accommodate its alignment with the conical part of the funnel. By using the distance plate, fabric bending and shearing occurs more intensively since this plate multiplies the number of creases.

Table 3. *Experimental mean values of tensile module and shearing rigidity of fabric samples.*

Parameter	Modules tensile, N/mm^2		Shearing rigidity, N/m
	warp	weft	bias (45˚)
Mean	0.3838	0.354	1436.
Max (Sample B1)	0.7625	1.189	4920
Min (Sample I2)	0.0081	0.010	11.64

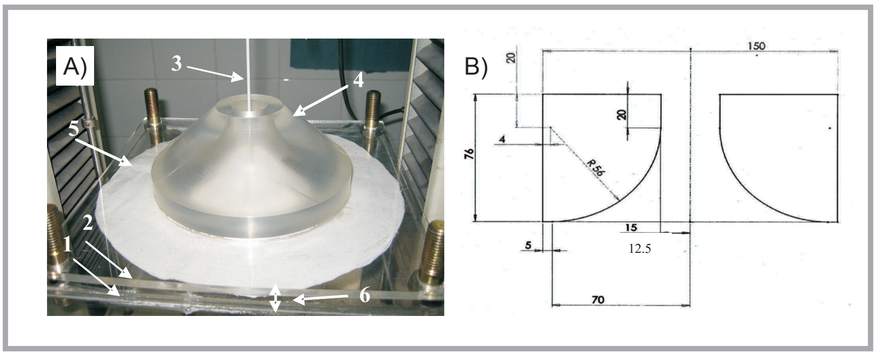

Figure 2. *A) Pulling through newly designed funnel; 1) base plate, 2) distance plate, 3) pulling axle, 4) funnel, 5) fabric sample, 6) adjustable space. B) Funnel dimensions.*

- After that, the tension begins to drop and then rises again because of frictional forces. The friction mechanism in the cylindrical portion of the funnel is largely determined by the internal lateral pressure created by pressing the sample inside the funnel and by the extent of pre-folding. A stiff sample will result in high lateral pressure, and a flexible sample will result in low lateral pressure.
- As the fabric sample exits the funnel, continuous reduction in extracting force will be observed. This pressure release results in internal stress relaxation, unfolding, and some forms of crease recovery.

Whole fluctuations of the extracting force against the displacement of the fabric during its passage through the funnel shaped nozzle is recorded as a force–displacement graph (***Figure 4***). A comparative analysis of the resulting curves for all fabric specimens led to introducing sixteen essential parameters which can be related to the mechanical properties of each fabric sample. These parameters are shown in ***Figure 4*** and listed in ***Table 4***.

The range of parameters extracted from the force displacement curves of the fabric specimens tested is shown in ***Table 5***.

Result and discussion

It has been theoretically proven that there is a logical relation between the mechanical properties of fabrics and the shape of the force-displacement graph of each sample. Due to the lack of any direct method to identify specific parameters on the graph corresponding to the actual fabric properties, a Pearson's correlation analysis was made using bending, tensile and shearing properties of the fabrics as the dependent variables. To establish an empirical model for prediction of the above-mentioned fabrics mechanical properties from the graph features, the data was analysed using the multiple linear regression technique. The stepwise method was used for the regression analysis, and the parameters were analyzed at a 95% confidence level, i.e. $\alpha = 0.05$.

Predicting the bending rigidity

Table 6 shows correlation coefficients between features extracted from the pulling-through curves and bending rigidities

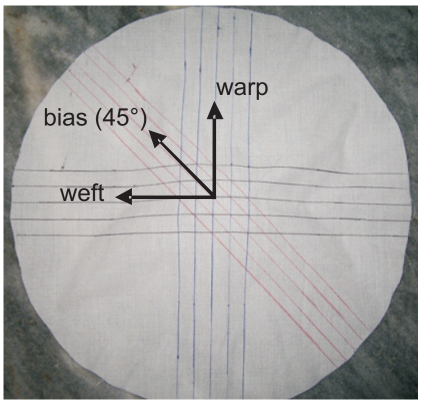

Figure 3. *Markings on fabric sample in warp, weft and bias directions.*

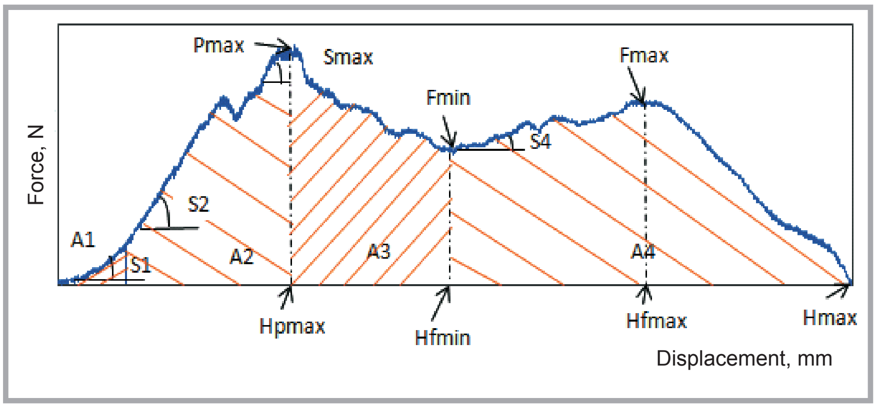

Figure 4. *Force-displacement graph.*

Table 4. *Parameters extracted from the force displacement curves.*

Symbol	Parameter	Symbol	Parameter
A_1	1st area of curve	F_{min}	Minimum load in 3rd area
S_1	Initial slope in 1st area	H_{Fmin}	Displacement at minimum load (F_{min})
A_2	2nd area of curve	A_4	4th area of curve
S_2	Initial slope in 2nd area	S_4	Initial slope in 4th area
P_{max}	Maximum load	F_{max}	Maximum load ini 4th area
S_{Pmax}	Slope at maximum load (P_{max})	H_{Fmax}	Displacement at maximum load (F_{max})
H_{Pmax}	Displacement at maximum load (P_{max})	A	Area of curve
A_3	3rd area of curve	H_{max}	Maximum displacement

Table 5. *Range of the extracted parameters from the force displacement curves.*

Symbol	Max (Sample B1)	Min (Sample I2)	Symbol	Max (Sample B1)	Min (Sample I2)
A_1	0.5578	3.2404	F_{min}	14.64	0.32
S_1	0.0025	.00004	H_{Fmin}	96.72	118.33
A_2	720.8572	15.5915	A_4	1741.5	49.4342
S_2	.0133	0.0001	S_4	0.015	0.00006
P_{max}	18.15	.04	F_{max}	31.32	0.4
S_{Pmax}	0.0046	.0001	H_{Fmax}	163.25	180.96
H_{Pmax}	67.58	100.40	A	2922.6	74.5
A_3	459.6850	6.2416	H_{max}	190.8	274.5

Table 6. *Correlation coefficients (R) between curve parameters and actual values of samples' mechanical properties*

Parameter	Bending rigidity, mN mm			Tensile module, N/mm²		Shearing rigidity, N/m
	Warp direction	Weft direction	Bias (45°) direction	Warp direction	Weft direction	Bias (45°) direction
S_1	0.62	0.78	0.75	0.54	0.79	**0.84**
A_1	0.16	0.13	0.11	0.28	0.05	0.23
S_2	0.77	**0.91**	**0.89**	0.51	**0.82**	0.74
A_2	**0.85**	**0.91**	**0.92**	0.46	0.76	0.66
S_{Pmax}	0.31	0.48	0.43	0.53	0.58	0.55
P_{max}	0.78	**0.92**	**0.91**	0.52	**0.86**	0.75
H_{Pmax}	0.03	0.10	0.05	0.29	0.24	0.25
A_3	0.68	**0.83**	**0.80**	0.47	0.77	0.63
F_{min}	**0.87**	**0.95**	**0.95**	0.52	**0.83**	0.73
H_{Fmin}	0.11	0.15	0.15	0.29	0.28	0.38
S_4	**0.84**	**0.84**	**0.86**	0.44	0.69	0.48
F_{max}	**0.93**	**0.94**	**0.95**	0.47	0.77	0.62
H_{Fmax}	0.14	0.15	0.11	0.27	0.05	0.22
A_4	**0.91**	**0.95**	**0.96**	0.49	**0.82**	0.69
H_{max}	0.54	0.21	0.33	0.34	0.20	0.26
A	**0.89**	**0.96**	**0.96**	0.50	**0.83**	0.70

in the warp, weft and bias directions of a typical sample.

As depicted in ***Table 6***, a strong correlation exists between the S_2, A_2, P_{max}, F_{min}, A_3, F_{max}, A_4 and A parameters and the bending rigidity of the experimental fabrics in different directions ($\alpha = 0.05$). The regression analysis results have been summarised in ***Table*** *7*. Equation models for predicting fabric bending rigidity are shown in this table too. All the remaining parameters in these models were significant at the 0.05 confidence level.

As shown in ***Table*** *7*, there is a strong correlation (R) between the experimental and predicted values of fabric bending rigidity for all models (higher than 0.8); therefore this new extraction method using a funnel can be proposed as a simple tool to estimate fabric stiffness.

Predicting the tensile module

As listed in ***Table 6***, there is a strong correlation between the S_2, P_{max}, F_{min}, A_4 and A parameters and experimental tensile module values in the weft direction ($\alpha = 0.05$). The regression analysis results have been summarised in ***Tables*** *7*. All parameters employed in the simplified equation models for predicting the fabric tensile module were significant at the 0.05 confidence level.

As shown in ***Table*** *7*, there is a strong correlation (R) between the experimental and predicted values of the fabric tensile module for all models (higher than 0.8); therefore this new extraction method can also be used to objectively evaluate fabric tensile strength.

Predicting shearing rigidity

As indicated in ***Table 6***, the S_1 parameter has a strong correlation with the shearing rigidity of the experimental fabrics ($\alpha = 0.05$). The regression outcome, written in ***Table*** *7*, shows this parameter (S_1) in the equation model for predicting fabric shearing rigidity, significant at the 0.05 confidence level. There is a strong correlation (R) between the experimental and predicted values of fabric shearing rigidity for the model (higher than 0.8), and this equation can be used to reliably estimate fabric shearing rigidity (***Table*** *7*).

During the fabric pulling out process through the funnel shaped nozzle, a force–displacement curve will be generated that, as seen in ***Figure 4***, can be divided into four primary zones identified as areas under the curve: A_1, A_2, A_3 and A_4. In the first zone (A_1) the initial slope (S_1) corresponds to the shearing movement in bias (45°), as this slope for light and soft fabrics is less than for heavy and stiff fabrics (***Figure 5***). The findings revealed that the influence of shearing rigidity (G) on the initial slope (S_1) is more than other pulling-through graphical features. Also the initial slope has the highest correlation with the shear stiffness.

The second zone (A_2) begins at the moment the fabric touches the inside wall of the conical part of the funnel and ends at the point of maximum force (P_{max}). This maximum point reflects a combination of tensile, shearing and bending stiffness. The strong correlation between experimental and predicted tensile module values in the weft direction is in agreement with this claim.

The first change in the curve slope (S_2) in zone A_2 is caused by the bending of yarns in the weft and 45° directions. The size and number of folds at this stage is largely determined by a combination of fabric stiffness and inter-fold friction.

Table 7. *Regression equations between parameters extracted from the force displacement graph and experimental values.*

Regression equation		Correlation	ANOVA	
		R	F	Sig
Bending rigidity, mN mm	Bending rigidity $_{warp}$ = 23.04F_{max} + 3.826	0.935	569.86	0.000
	Bending rigidity $_{weft}$ = 0.126A – 21.698	0.960	998.67	
	Bending rigidity $_{bias}$ = 0.157A – 14.812	0.958	912.38	
Tensile module, N/mm2	Tensile module $_{warp}$ = 0.109F_{max}	0.862	523.97	
	Tensile module $_{weft}$ = 0.1P_{max}	0.938	609.80	
Shearing rigidity, N/m	Shearing rigidity = 2.029E6S_1	0.941	646.84	

This slope has the highest correlation with the bending stiffness.

The third zone (A_3) begins at P_{max} and ends with a consequent fall in tension (F_{min}). This zone reflects bending stiffness. The fourth zone (A_4) of the curve begins at F_{min} and ends at the end of the extraction process. Two parameters can be highlighted in this zone: slope S_4 and the peak resistance of this zone (F_{max}). The point of maximum force (F_{max}) has a strong correlation with bending stiffness in all directions and with the tensile module in the warp direction.

Conclusions

Mechanical properties of woven fabrics were evaluated in an extraction experiment through a newly developed funnel shaped nozzle. This new combined apparatus, with a transparent funnel above two horizontal plates, was used to draw fabric samples. Observations showed that the passing behaviour of the fabric in the new device is different from the passing conditions through known nozzles [11 - 14], because the fabric movement behavior while passing through the funnel was under the control of those two adjustable plates. This movement is comparable with the figuration style of long-trail and floor-length wedding dresses. Accordingly a new different force-displacement graph was obtained including two new extra zones (A_2 & A_3) in comparison with known curves (***Figure 5,*** see page 52). Sixteen parameters

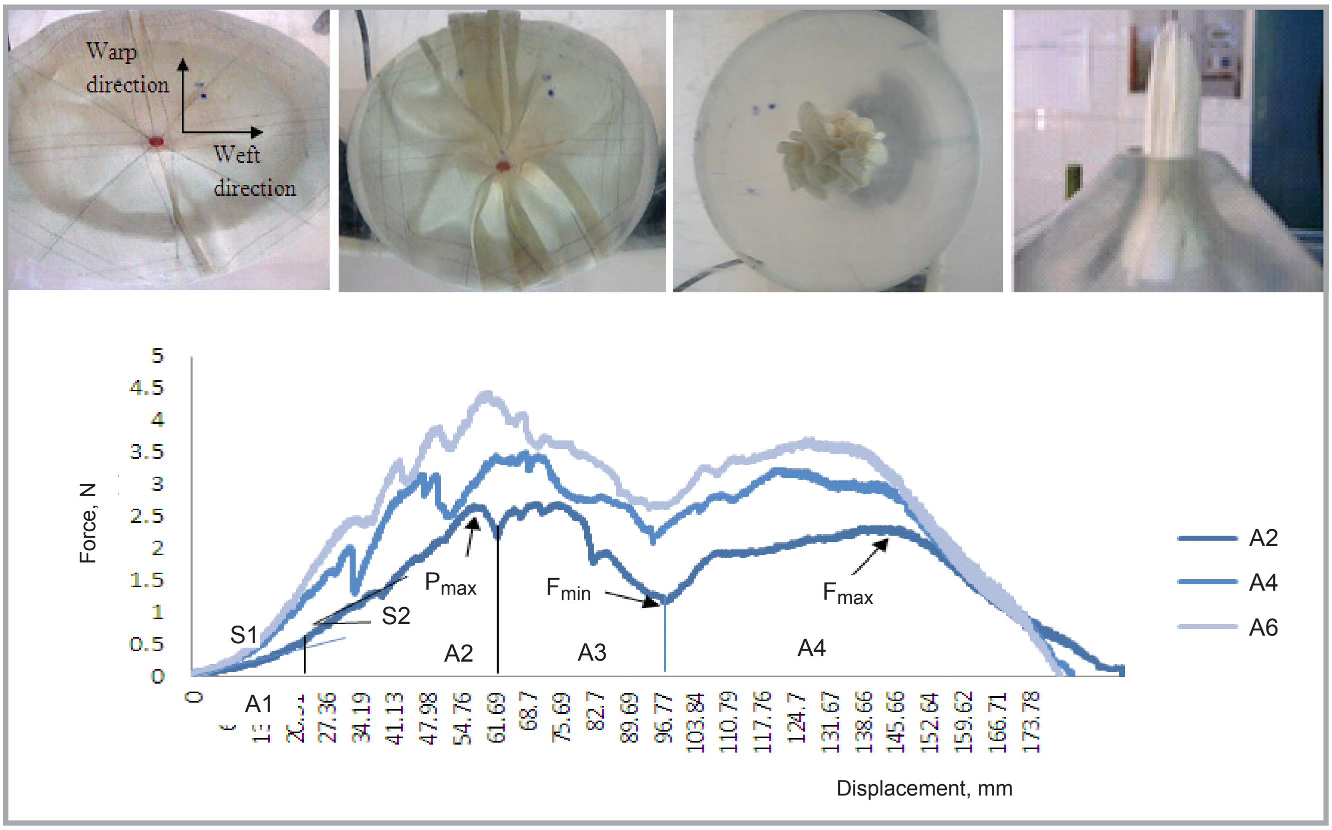

Figure 4. *Fabric behavior corresponding to different parts of force-displacement curves. A2, A4 and A6: three fabric samples with different weft densities.*

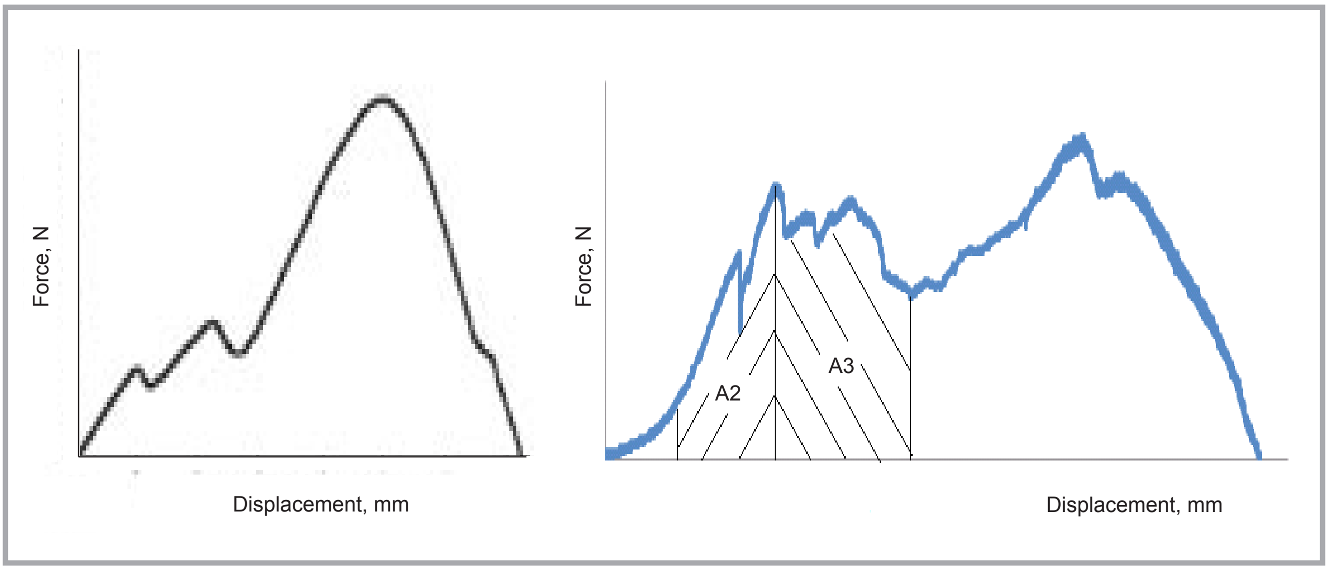

Figure 5. *Comparison between a known force-displacement curve (A) and that obtained from the new apparatus (B).*

were chosen from the pulling out force displacement curves for 84 different woven fabrics. Correlation coefficients between features extracted from the pulling out curves and the bending rigidity, tensile module and shearing rigidity were calculated. Based on our findings and calculations, there is a significant correlation between the experimental mechanical properties and features extracted from the pulling-out curves. From the experimental findings, we can draw the following conclusions:

1. The initial slope of the curve (S_1) can be used to objectively evaluate fabric shearing rigidity.
2. The maximum force in the fourth zone (F_{max}) can be reflected by the bending rigidity and tensile module in the warp direction.
3. The area of curve (A) can be used for objective evaluation of bending rigidity in the weft and bias directions.
4. The maximum force in the first zone (P_{max}) can be used to objectively evaluate the tensile module in the weft direction.

We found very strong correlations (R) between the predicted and experimental values of the fabric bending rigidity, tensile module and shear rigidity by simply using a funnel shape nozzle. As seen, significant parameters S_2, A_2, P_{max}, A_3 & F_{min} , which had the best correlations with fabric stretching, shear and bending properties, were extracted from the above-mentioned zones (A_2 & A_3). Comparing our results with the findings of known reports on objective evaluations using normal rings as a nozzle [13, 15 - 17, 19, 20], it strongly proves that we achieved the highest accuracy and capability of the newly introduced funnel shaped nozzle for objective evaluation and prediction of fabric mechanical properties.

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