Proceedings Paper:

Wang, Y and Mao, N (2015) The influences of pre-tensions on the deformations of woven fabric shells during cyclic axial compression buckling processes. In: Proceedings of the 8th Textile Bioengineering and Informatics Symposium. The 8th Textile Bioengineering and Informatics Symposium, 14-17 Jun 2015, Zadar, Croatia. .

The influences of pre-tensions on the deformations of woven fabric shells during cyclic axial compression buckling processes

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Abstract

The influences of pre-tensions on the deformations of cylindrical shells made of various woven fabrics undergoing axial compression buckling process were studied. The fabric deformations were differentiated and quantified using the energy consumed to produce and recover them. Various types of deformation including elastic deformation, recoverable deformation and permanent deformation produced in the cyclic compression buckling-recovery processes were associated with their corresponding energy consumed to either form the fabric deformations or recover the deformations. It was found that the fabric shells having greater pre-tensions in the compression buckling process consumed greater amount of energy to deform the fabrics and requires less energy to recover the deformed fabrics, and that deformed fabrics released greater amount of strain energy to self-recover their elastic deformations. It was also found that the effect of pretension on the energies consumed to deform a fabric varies with the fabric areal density, the minimum pre-tension of 2N/m is required to enable the energies consumed to deform the fabrics of light, medium and heavy weight less sensitive to the changes of pre-tension.

Keywords: pre-tension, fabric, cylindrical shell, compression buckling, quantification, energy

1. Introduction

Fabric compression buckling and recovery characteristics are known to influence fabric's performance during design, manufacture process and daily uses of garments [1]. Fabric compression buckling is found [1] related to the fabric bending stiffness, fabric torsion, and fabric shear modulus, and is found related to the fabric handle [2], drape and widely used in fabric simulation [24], a series of indices based on the fabric compression buckling behaviour were identified by Lindberg et al [2] and subsequently linked with fabric softness.

The characteristics of the compression buckling of different fabric plates including buckling curves, cyclic buckling and the recovery behaviour were studied by Lindberg et al [2]. It was shown in previous research [3-10] that the fabric plate compression buckling was related to fabric stiffness. Lindberg et al [1, 10] investigated the characteristics of plate and shell compression buckling of various fabrics and defined the fabric formability in garment technology. The critical fabric buckling force for the buckling of a fabric plate, P_{CR}, by using Euler's equation for buckling of a bar is expressed as follows[11]:

$$P_{CR} = \frac{4\pi^2 EI}{L^2} \quad (1)$$

where E is the modulus of elasticity of the fabric, L is the length of the fabric plate subjected to buckling deformation and I is the moment of inertia based on the geometrical dimensions of the fabric and is given by the equation[11]:

$$I = \frac{Lt^2}{12} \quad (2)$$

where L and t are the length and thickness of the fabric plate, respectively.

Fabric buckling wrinkle of knitted and woven fabric were also investigated [11], and the width of the buckling wrinkle patterns in the circumference directions in a fabric shell compression buckling were given [12] in a semi-empirical equation as follows:

$$w = 3.38\sqrt[4]{\frac{E_1}{E_2}}\sqrt{Rt} \tag{3}$$

where E_1 and E_2 are the Young's modulus of the fabric in the axial and circumferential directions of the fabric shell respectively, R is the radius of the cylindrical fabric shell and t is the fabric thickness.

It is noticed that the system for the measurement of the compression buckling of thin and soft fabric plates is complex and difficult to operate [2], while the reproducibility of the measurement of axial compression buckling deformations of circular cylindrical shells made from thin and elastic materials is quite well and the analytical models of the compression buckling deformations of the cylindrical shells [13] are well studied. The semi-empirical solution of the upper critical buckling stress [14] for a thin shell made of elastic materials with clamped two ends in axial compression buckling deformation is determined as follows [15]:

$$\sigma_{cr} = \frac{k_X \pi^2 D}{L^2 t} \tag{4}$$

Where t is the thickness of the thin shell materials and L is length of the shell subjected to buckling deformaiton, and the bending parameter, D, is defined as:

$$D \equiv \frac{Et^3}{12(1-v^2)} \tag{5}$$

the empirical critical stress coefficient, k_x, is $k_x = 4$ for short shells ($Z < 0.5R/t$) and $k_X = 1.15CZ$ for long shells ($L/R>0.75$, and $Z > 0.5R/t$). Where C is an empirical constant, v and E are the Poisson's ratio and Young's modulus of the fabric material respectively, and R is the radius of the thin shell subjected to buckling deformation; and the curvature coefficient, Z, is defined as

$$Z = \frac{L^2}{Rt}\left(1-v^2\right)^{1/2} \tag{6}$$

More accurate compression buckling behaviours of the cylindrical thin shells made from elastic materials can be described by Donnel [16]–Mushtari [17]–Vlasov [18] (DMV) theory, and Lur'e [19] showed that the analysis of not too long cylindrical shells, based on this DMV theory also gives sufficiently accurate results even for slowly varying loads (e.g. pure bending deformations).

However, textile fabrics usually do not perform as pure elastic materials during greater deformations such as compression buckling process, as it frequently demonstrates characteristics of hysteresis in tensile, shear and compression buckling processes [25-27]. In addition, various fabric structural parameters such as fabric tightness, fabric density, and fabric thickness affect the Young's modulus of the fabrics and thus their buckling properties. Therefore, the fabric buckling behaviour is difficult to be predicted by directly using the above models. In order to study the characteristics of fabric buckling properties, Mao et al [22, 23] proposed a method to differentiate and quantify the fabric deformations using the energy consumed to either produce or recover such fabric deformations. Various types of deformation including elastic deformations, recoverable deformations and permanent deformations produced in the cyclic compression buckling-recovery processes were associated with their corresponding energy consumed to deform the fabrics.

It is known that the testing conditions such as pre-tension applied on the fabric affects fabric's tensile, shear and bending behaviour. Wei and Chen [20] studied the influence of pre-tension on tensile extension and recovery property of knitted fabrics, and found that pre-tension had significant influence on initial elongation of different retractility knits. For little retractility knits, pre-tensions do not significantly affect their elongation percentage, but for well retractility knits, the greater the pre-tension is, the more significant the influence is. Glaser and Caccese [21] studied the effect of pre-tension on shear buckling properties of polyurethane-coated nylon fabric, and found that pre-tension force influenced material behaviour during the initial bucking deformation region, the post-buckling diagonal fold region, and also the final state and cumulative damage.

However, there is little research reported on how the testing conditions such as pre-tensions applied on the fabric cylindrical shell influence the fabric deformations in its compression buckling process. In this paper, the influences of pre-tensions on the deformation of the fabric shells in compression buckling and recovery processes are investigated.

2. Experiment

2.1 Materials

Six woven fabrics are studied in this research. These fabrics have a wide range of mass per unit area and thickness, and the structural parameters are shown in Table 1.

Table 1 Specifications of the six woven fabric samples

Sample Name	Structure	Fibre type	Thickness (mm)	Mass per unit area (g/m^2)	Bulk density (Kg/m^3)
W1	Rib stop	polyamide	0.1	57.8	578.0
W2	Plain	wool	0.62	211.3	340.8
W3	Plain	Cotton/polyester	0.33	118.5	359.1
W4	Twill 1/2	wool	1.08	263.5	244.0
W5	Twill 2/2	Wool/viscose	0.99	358.0	361.6
W6	Twill 1/3	cotton	1.10	426.7	387.9

Sample Name	Count (number/10cm)		Yarn linear density (tex)		Yarn twist (turns/m)	
	warp	weft	warp	weft	warp	weft
W1	463	507	5	5	Low twist filament	Low twist filament
W2	183	130	60	72	(S)336	(S)227
W3	480	310	13	13	(Z)1317	(Z)932
W4	183	130	68	66	(Z)608	(Z)549
W5	250	280	58/65	58/65	(S)492/ (S)428	(S)432/ (S)421
W6	160	260	100	80	(Z)366	(Z)471

2.2 Equipment

The axial compression buckling deformations of the cylindrical shells made from the above fabric materials were performed in a system designed for the objective evaluation of fabric handle properties [22].

Each of the six fabrics was tested in both warp and weft directions. Each fabric specimen was formed into a circular cylindrical shell of 80mm in diameter and 110mm in length and its two ends were fixed in a pair of sample holders in such a way that a certain level of pre-tension force was exerted on the body of cylindrical shell in its longitudinal direction to maintain the cylindrical shell straight and stable; the gage length between the two fixed ends of the fabric shell was fixed at 50mm. During the compression-recovery process, the upper end of fabric shell was compressed axially in 15mm then forced recovering back axially to its original position at a speed of 1mm/s. The dynamic forces required to compress and recover the fabric shell were measured, and the corresponding force-displacement curve was obtained. In a complete cyclic compression buckling test, each fabric shell specimen was deformed and recovered in five cycles.

In this research, the characteristics of the axial compression buckling deformations are analyzed, and the energies consumed to generate each type of deformation are discussed. Also, the influences of the pre-tensions on the axial compression buckling deformations are studied. Five pre-tensions (pre-tension force per unit circumference length of the fabric shell) including 0.8N/m, 1.2N/m, 1.6N/m, 2N/m and 4N/m, were applied on the fabric shells before compression buckling. The results under different pre-tensions were analysed to explore the effect of pre-tension on fabric's compression buckling and recovery properties.

3. Results and discussions

3.1 The characteristics of the fabric deformation in the force-displacement curve of cyclic compression buckling-recovery processes

A typical force-displacement curve of cyclic compression-recovery processes is shown in Fig. 1

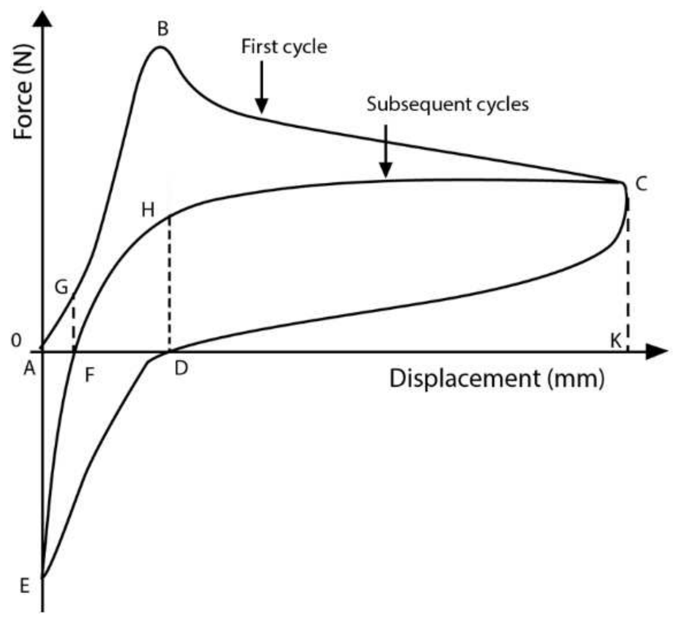


Fig.1. A typical force-displacement curve of the cyclic axial compression buckling -recovery process of a circular cylindrical thin fabric shell

In the monotonic compression buckling process (first compression-recovery cycle), there are a compression phase and a recovery phase. In the compression phase, the fabric shell is gradually compressed axially by an external compression force and the fabric shell is deformed, the compression force usually increases rapidly with the increase of the compression displacement and reaches a peak force at the point B, the buckling force (shown as line AB in Fig.1). With the further increases of the compression displacement, the compression force might decrease slightly and then become steady (shown as the line BC in Fig.1). The compression phase of the first compression-recovery cycle is represented by the line AGBC when the fabric reaches to the point C which corresponds to the maximum displacement in point K in the X-axis) before its recovery.

In the recovery phase of the monotonic compression-recovery process, the deformed fabric shell starts to return towards its original shell length from the maximum displacement point C, and the strain energy stored in the deformed fabric is released to produce an elastic force to help the fabric recover to a certain displacement point D (shown as line CD in Fig.1). While the deformed fabric shell does not recover completely to its original length by this elastic force, an external extension force is applied to recover the deformed fabric back to its original full shell length at the point E which corresponds to the zero displacement. The recovery phase of the first compression-recovery cycle is represented by the line CDE in Fig.1 when the fabric shell is recovered reaching to its original shell length in point E.

In the compression phase of the second compression-recovery cycle, the recovered fabric shell being stretched at point E is gradually compressed to a state of zero tension at point F (shown as line EF in Fig.1), because the deformed fabric shell is not returned to the original shell length when the tension of the fabric shell is zero, this means that part of the deformation of the deformed fabric shell cannot be recovered by the extension force. With further compression of the recovered fabric shell in the second cycle from point F, the compression of the fabric shell in the second cycle terminates at point C when the compression displacement reaches to its maximum (shown as line FHC in Fig.1). During this process, the compression force applied to compress the fabric shell gradually reaches to its peak.

In the recovery phase of the second compression-recovery cycle, the deformed fabric shell starts to recover from the point C of the maximum displacement towards its original shell length; it is noticed that the recovery phase in the second (and other consecutive) compression-recovery cycles is, for most of the textile fabrics, represented by the identical line CDE in Fig. 1 although they might have small differences to the recovery phase of the monotonic compression-recovery process, because the differences are relatively small for most of textile fabrics.

While the compression and recovery phases of the subsequence cyclic compression-recovery cycles, are slightly different from the corresponding phases of the second cycle, the differences are relatively small for most of textile fabrics in this research, they are thus represented by the identical lines EFHC and CDE in Fig 1 respectively.

3.2 The energy consumed for different types of deformation

As indicated in previous research [22, 23], the areas in the curves shown in Fig.1 represent the energies consumed to deform the fabric shell, to recover the deformation of the deformed fabric shell and to form the unrecoverable fabric deformations during the compression buckling-recovery processes. They are summarised as follows [22, 23]. The area ABCKA is the energy consumed to deform the virgin fabric shell in the monotonic compression buckling process, and denoted as A1cp1. The area FHCKF is the energy consumed to deform the recovered fabric shell in the second and subsequent cyclic compression cycles, denoted as A1. The area DCKD is the work done by the elastic force produced by the deformed fabric to recover the compression deformation, denoted as A2; The area AFEA is the energy consumed to recover permanently deformed fabric, denoted as A3; The area DEFD is the energy consumed to recover the recoverable deformation through stretching and extension, denoted as A4. Area FHCDF is the energy consumed to form plastic deformation; it consists of two component areas: the area FHDF, denoted as A5, is the energy consumed to form recoverable deformations in association with the deformations recovered by extension forces; the area HCDH, denoted as A6, is the energy consumed to form the recoverable deformations associated with self-recoverable deformations .

Based on the analysis above, some of the deformations corresponding to the energies (A1cp1, A1, A2, A3, A4, A5 and A6) consumed in the compression buckling-recovery process are discussed below. The values of these seven energies for the six fabric samples under different pre-tensions are compared and shown in Fig. 2~8. In these Figures, the suffixes '-p' and "-t" of each name of the woven fabric sample represents the testing in the warp and weft directions respectively. For example, the notation of w1-p means the testing results of the woven fabric 1 in the warp direction.

3.2.1 The energy consumed to produce the whole deformation in the fabric (A1cp1)

The area A1cp1 represents the energy consumed to deform the virgin fabric shell in the monotonic compression buckling process (see Fig. 2(a)), it increases linearly with the increase of the pre-tensions, it has an apparent linear relationship with pre-tensions ($A1cp1 = 0.00343x + b$, where x is pre-tension) (see Fig. 2(b)). It is also found that a fabric which consumes greater energy in the warp direction always has greater energy consumption in the weft direction; for example, fabric W6 having the greatest mass per unit area among all of the six woven fabrics, consumes the greatest amount of energy to form deformations in both warp and weft directions.

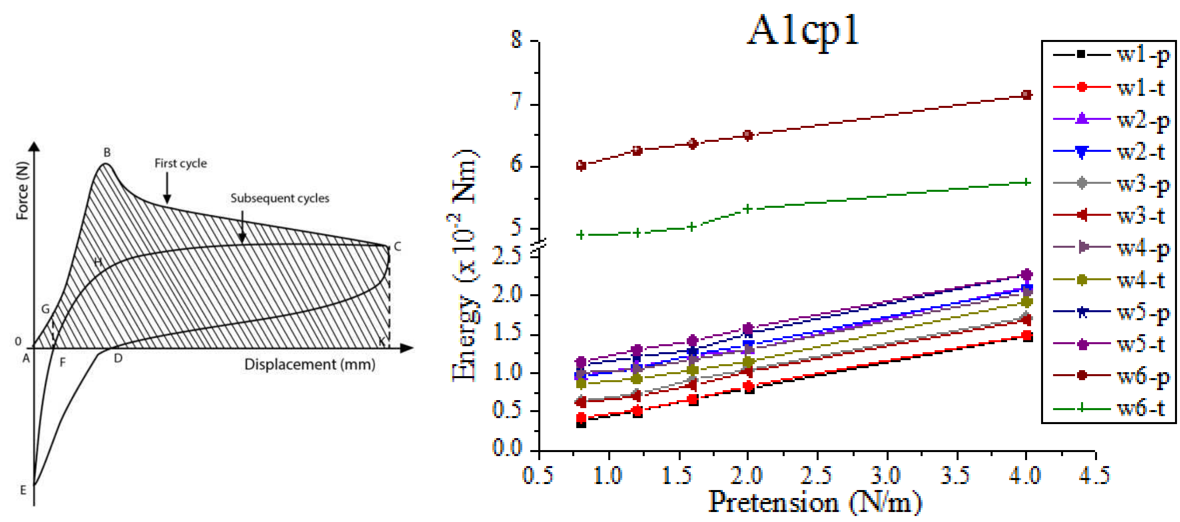
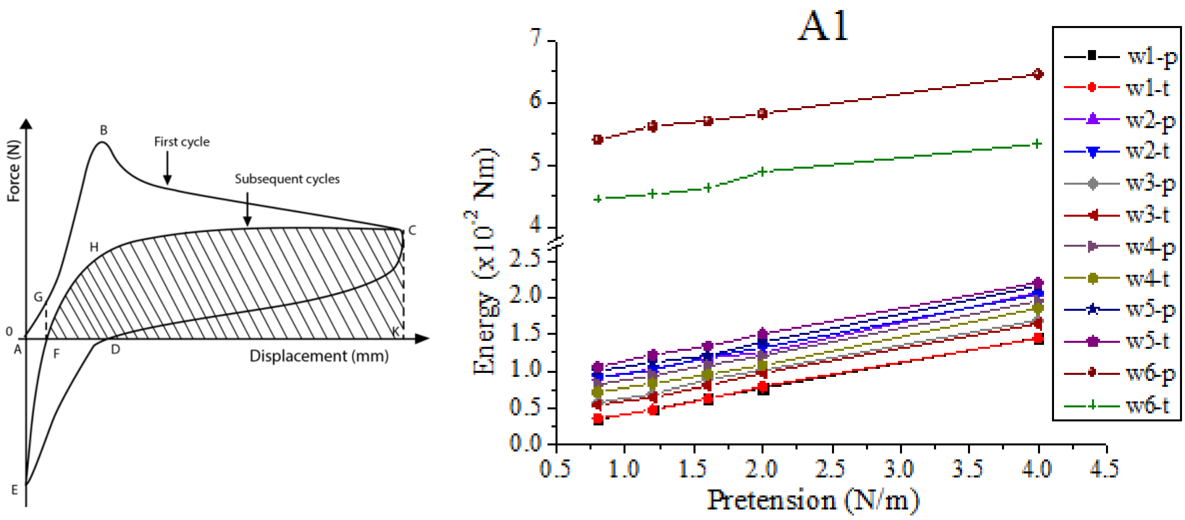


Fig. 2. Energy consumed to produce overall deformations (A1cp1)

3.2.2 The energy consumed to deform recovered fabric (A1)

A1 is the energy consumed to deform the recovered fabric in the second compression-recovery cycle (see Fig. 3(a)), it also increases linearly with the increase of the pre-tensions ($A1 = 0.00346x + b1$, where x is the pre-tension) (see Fig. 3(b)); there is little apparent differences in the values of A1 between warp and weft directions for these six fabrics. The greater pre-tensions lead to greater energy consumed to deform the recovered fabrics. The fabrics having greater mass per unit area (e.g., fabric W6) have greater values of A1 than other five fabrics.

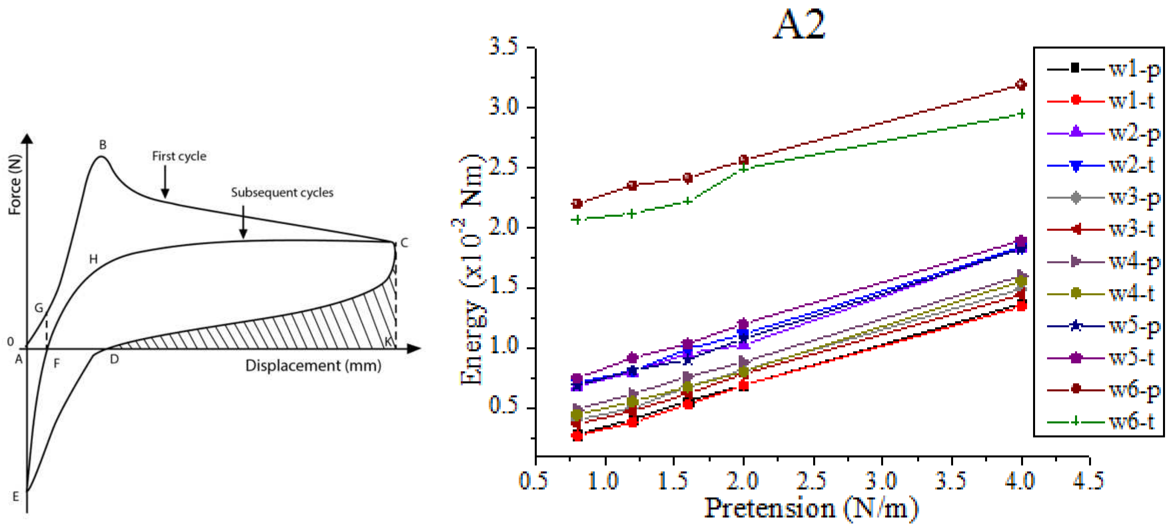


(a) (b)

Fig. 3. Energy consumed to produce deformations in recovered shell (A1)

3.2.3 The energy consumed to self-recover deformed fabrics (A2)

A2 represents the internal strain energy produced by deformed fabrics to self-recover their elastic deformations (see Fig. 4(a)) and it represents the fabrics' self-recovery capability. It increases linearly with the increase of the pre-tensions ($A2 = 0.00343x + b2$, where x is the pre-tension) (see Fig. 4(b)); that is, the strain energy released by deformed fabrics to self-recover its deformations increases with the increases of the pre-tensions. It is found in Fig. 4(b) that fabrics having greater mass per unit area (e.g., fabric W6) have much greater value of A2 than other fabrics.

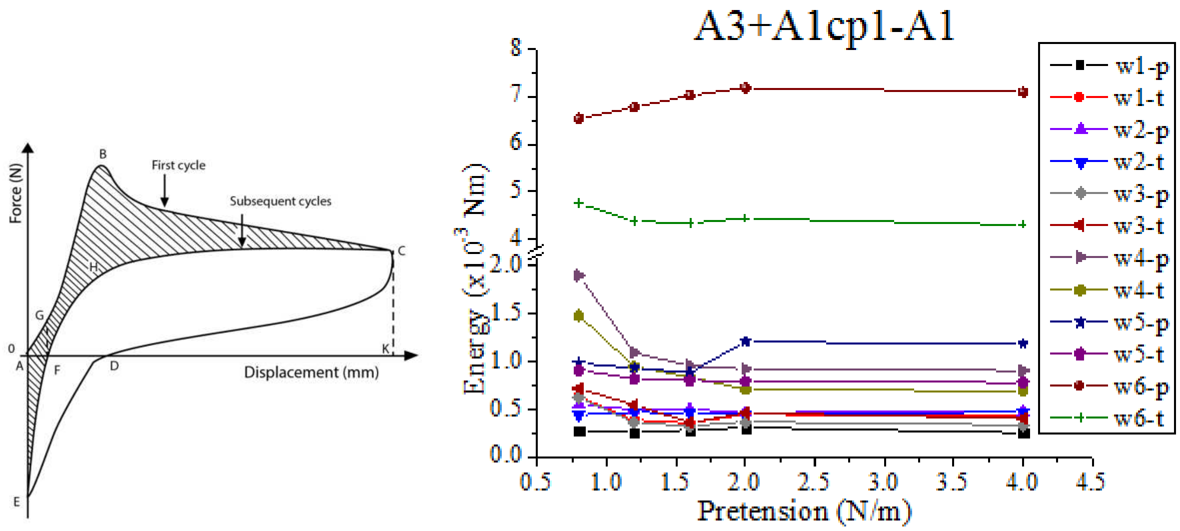


(a) (b)

Fig. 4. Work done by deformed fabric to recover elastic deformations (A2)

3.2.4 The energy consumed to form permanent deformation in the fabric (A3 +A1cp1-A1)

(A3 +A1cp1-A1) is the energy consumed to form permanent deformations in the fabric (see Fig. 5(a)). It is found in Fig. 5(b) that the fabrics having greater mass per unit area (e.g., fabric W6) have greater energy of (A3 +A1cp1-A1). Generally speaking, (A3 +A1cp1-A1) changes with the increase of pre-tension, but does not suggest any common trend for these six woven fabrics. It is found in Fig. 5(b) that this energy hardly changes when the pre-tension is equal or greater than 2.0N/m.

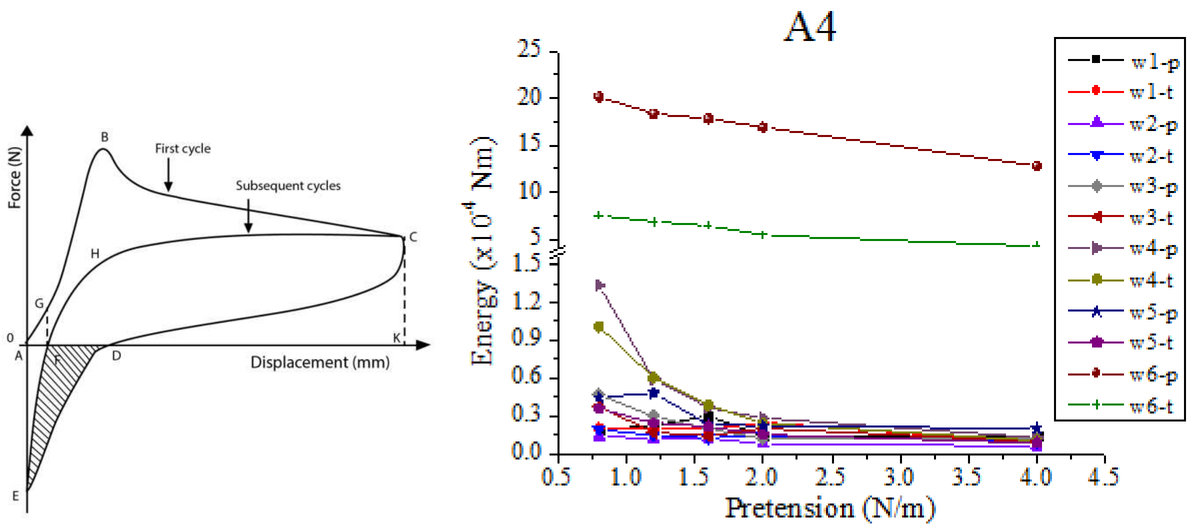


(a) (b)

Fig. 5. Energy consumed to produce permanent deformations (A3+A1cp1-A1)

3.2.5 The energy consumed to recover the recoverable deformation of fabric (A4)

The energy A4 is consumed to recover the recoverable deformations in the deformed fabric during recovery phase by extensional forces (see Fig. 6(a)). In comparison with A1 in Fig. 3(b), A4 in Fig. 6(b) is much smaller than A1 (usually around about one hundredth of A1). It is also found in Fig. 6(b) that A4 decreases with the increase of pre-tensions; this means that much less recoverable deformation is produced with higher pre-tensions during compression buckling phase and that less energy is consumed to recover the deformations with greater pre-tensions. However, this trend seems easily affected by other factors. It is also noticed in Fig. 6(b) that controllable deformation is obtained when pre-tension is equal or greater than 2.0N/m, and that fabrics having greater mass per unit area (e.g., fabric W6) have much greater value of A4 than other fabrics.

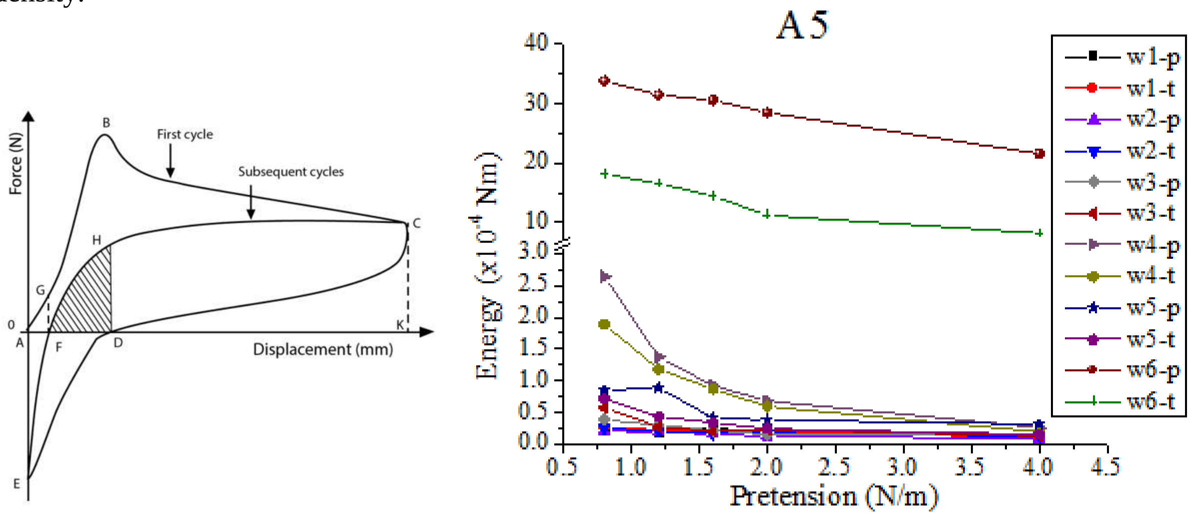


(a) (b)

Fig. 6. Energy consumed to recover recoverable deformations (A4)

3.2.6 The energy consumed to deform recoverable deformation (A5)

The energy A5 is consumed to form the recoverable deformations which is associated with the deformations recovered by external extension force (i.e., A4), and it is a small part of the energy A1 and it is in the same magnitude of A4. It is found in Fig. 7 that, similar to the energy A4, A5 decreases with the increase of pre-tensions, this means that less energy is consumed to form this part of recoverable deformation under greater pre-tensions. It is also noticed that A5 of the fabric having the greatest areal density (i.e., W6) is much greater than that of the other fabrics having smaller areal density.

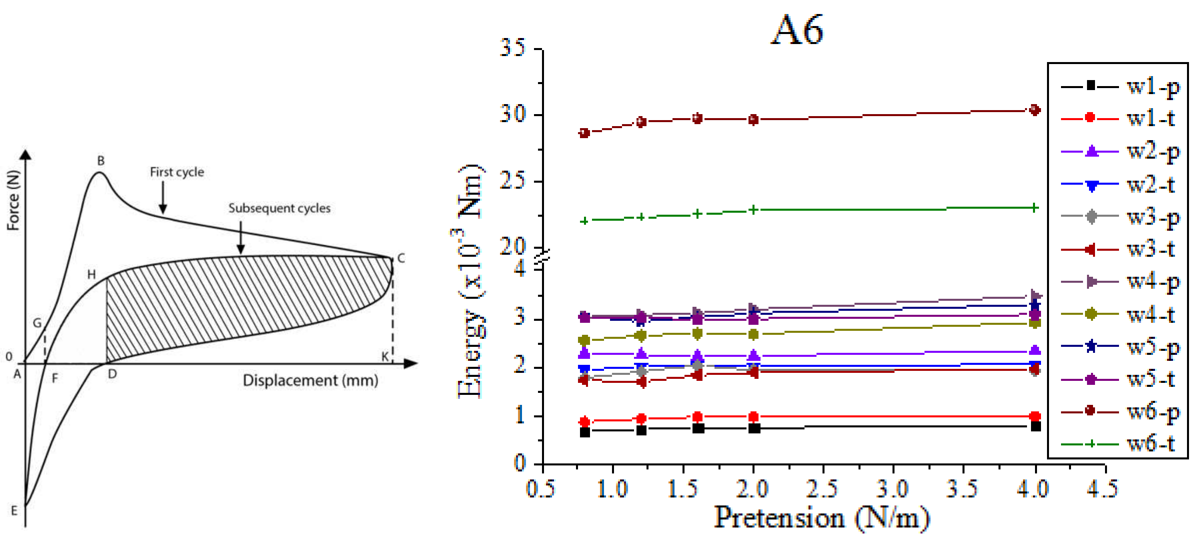


(a) (b)

Fig. 7. Energy consumed to form recoverable deformation A5

3.2.7 The energy consumed to overcome friction to form recoverable deformation (A6)

The energy A6 is consumed to form the recoverable deformations in association with self-recoverable deformations (i.e., A2). It is noticed in Fig. 8 that A6 increases negligibly with the increases of pre-tension, which means that energy A6 consumed to form this recoverable deformations associated with the self-recoverable deformations (A2), is hardly affected by the pre-tensions applied. Similar to other energies (A1~A5), it appears that the heaviest fabric, W6, consumes much greater energy A6 than other fabrics to form this part of recoverable deformations.



(a) (b)

Fig. 8. Energy consumed to overcome friction to form -recoverable deformation A6

3.3 The influence of pre-tension on the energy consumed for different deformations

3.3.1. Influence of pre-tension on the change of fabric structure

When pre-tension is applied on the longitudinal direction of a fabric, yarns aligned in this direction are slightly straightened and their crimps are reduced [28], alignments of fibres in these yarns are reoriented towards the direction of the pre-tensions applied. In contrast, the yarns aligned on the direction perpendicular to the applied pre-tensions are further bended and the wave aplitude of their crimps are increased, and the fibres in those yarns are compacted due to the increases of the yarns' crimps [28].

During compression buckling process of a fabric with pre-tensions applied, there is one specific position that the pre-tension of the fabric cylinder is zero. However, due to the viscoplastic nature of textile fabrics, there are residual structural changes induced by the pre-tensions still remained in the fabric. The residual structural changes maintain the additional compressive forces induced by the pre-tensions at the contact points between yarns and the interaction points between fibres, therefore, pre-tensions lead to the increases of both frictional contact areas and friction forces at these contact points [29] during fabric buckling and recovering processes.

Therefore, pre-tensions applied induced additional yarn-yarn and fibre-fibre friction forces in fabric buckling process, and greater pre-tension could produce greater friction forces at their contact points.

3.3.2 Influence of friction on energy consumption during pre-buckling and post-buckling process

The compression buckling of fabric shell consists of two stages, pre-buckling and post-bucking. Based on the fact that both buckling and bending involve bending moments [30], a simple model on fabric bending behaviour [31] built to explain the fabric buckling properties in pre-buckling stage, Grosberg [32] stated that frictional force in the fabric increases its resistance to fabric bending, which is described by the equations (7) and (8) below,

$$\frac{1}{\rho} = 0 \qquad\qquad M < M_0 \tag{7}$$

$$\frac{B}{\rho} = M - M_0 \qquad M > M_0 \tag{8}$$

Where ρ is the radius of curvature of the bent fabric, B is bending rigidity of the fabric, M is bending moment, M_0 is frictional restraint couple.

When bending moment applied on the fabric is less than the frictional restraint couple, the fabric bending rigidity becomes greater due to the friction restrain and greater bending moment is required to bend a fabric having a great frictional resistant.

The fabric in post-buckling stage with a bending moment, M, produced by the compression force P is shown in Fig. 9. For the fabric regions where the bending moment M is less than the friction restraint couple, M_0 (fabric regions above point A and below point A' in Fig. 9), no bending happens and the fabric is still straight. For the fabric region where M is greater than M_0 (fabric between point A and A' in Fig. 9), the fabric is bended and obeys equation (8). Usually, greater angle α and curvature ρ (see Fig. 9) are achieved with the increases of fabric compression displacement as shown in Fig. 9. As fabrics having greater pre-tension lead to greater frictional resistant moment M_0, both greater compression force P and bending moment B are thus required to deform the fabrics during its compression buckling process.

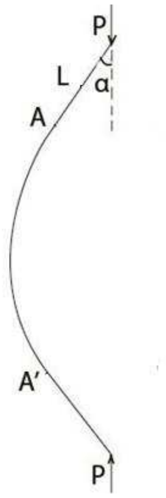


Fig. 9 A type of fabric bending behaviour [32]

In a summery, greater pre-tension lead to greater friction between yarns and fibres in a fabric, which requires greater bending moment (B) to buckle. As a result, greater energies (e.g., A1cp1, A1 and A6) is consumed to deform the fabrics having greater pre-tensions, and increase with the increase of pre-tensions.

3.3.3 Influence of friction between yarns on fabric deformation

During the buckling of a fabric shell, yarns are moved and bended. Yarn's movement during fabric buckling process is described as three possible motions [33]: one motion occurs in the compressive stage when the yarns parallel to the loading direction increase their crimp amplitude and the cross yarns are forced closer to one another. Second motion begins when this compression releases the normal forces at yarn crossover points making it easier for yarns to move. The third motion happens in the post-buckling stage, yarn is deformed by bending.

For fabrics having greater friction force between yarns, it is difficult to have the first motion, because the increase of crimp amplitude also requires relative yarn movement which is restricted by high friction force. As a result, limited normal force is released and less yarn movement happens. Therefore, less recoverable deformation is produced because less yarn movement is induced, also more strain energy is stored in deformed yarns and more elastic deformation is formed.

Because less recoverable deformation is produced, less energy (A4) is consumed to recover recoverable deformation when greater pre-tension is applied, and less energy (A5) is required to form the recoverable deformations. Additionally, more strain energy (A2) is stored in deformed fabric to self-recover its elastic deformations.

3.3.4 Influence of friction between fibres on fabric deformation

The movement of fibres in yarns also relies on the friction between fibres. An example of the movement of fibres during bending of yarns is shown in Fig. 10 when great friction forces exist between fibres:

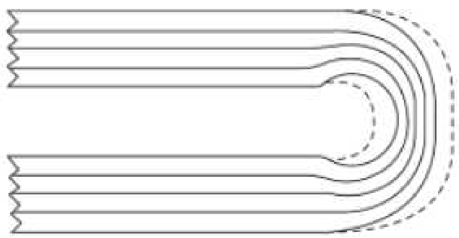


Fig. 10. Bending of yarns with high friction between fibres [34]

During the buckling of fabric, if the freedom of movement of fibres is completely hindered, fibres tend to move towards the neutral plane of the deformation. When greater pre-tensions applied, greater frictions between fibres are produced and the relative movements between fibres are thus reduced which leads to less recoverable deformations produced between fibres. In order to relieve the strain, fibres have to adjust themselves around the bending position, as shown in Fig.10. thus more energy is needed to bend the fibres and more strain energy is stored in deformed fibres and more elastic deformation is formed. Therefore, for fabric having higher pre-tensions, more strain energy (A2) is stored in the deformed fabrics, and less energy A4 is consumed to recover the recoverable deformations and less energy A5 is consumed to form the recoverable deformations.

3.4 The influence of pre-tension on the energy changes in fabrics having different mass per unit area

The effect of pre-tension on the changes of various energies consumed to deform the fabrics might vary with the fabric areal density. In this research, three groups of fabrics, light, medium, and heavy weight fabrics were studied. Group '*light'* includes two fabrics of W1 and W3 which have areal density less than 200g/m^2; Group *'medium'* also includes two fabrics of W2 and W4 which have areal density between 200 and 300g/m^2; Group *'heavy'* comprises the fabrics of W5 and W6 which have areal density greater than 300g/m^2.

The changing rate of energy consumed in the compression-recovery process (as described in section 3.1) per unit pre-tension applied is defined in equation 10 below:

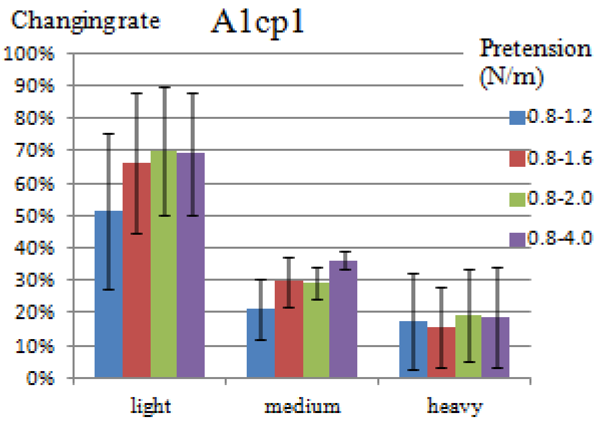
$$Changing\ rate\ (\%) = \frac{A(P_i)-A(0.8)}{A(0.8)\times(P_i-0.8)} \times 100\%\ \ (P_i = 1.2; 1.6;\ 2;\ 4\ N/m) \qquad (10)$$

Where $A(P_i)$ is each of the energy under external pre-tension, P_i, and $A(0.8)$ is each of the energy under pre-tension of 0.8N/m.

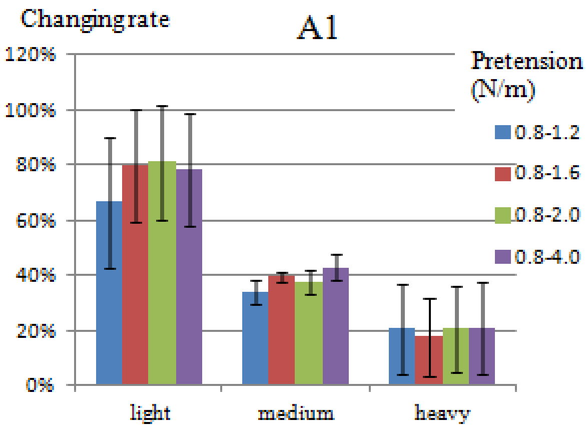
The changing rates of energy when the pre-tension increases from 0.8 to 1.2N/m, 0.8 to 1.6N/m, 0.8 to 2.0N/m, and 0.8 to 4.0N/m are obtained and shown in Figiures 11, 12 and 13 respectively, the standard deviations of the energy changing rate in each group are also shown in the Figures.

3.4.1 The changing rate of A1cp1, A1, A2 and A6

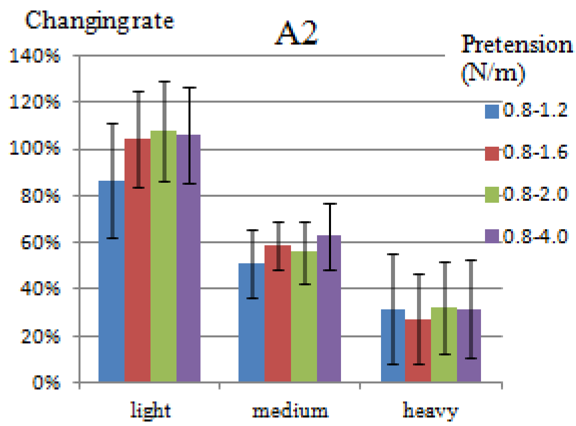
It is shown in Fig. 11 that the changing rates of energy for light and medium weight fabrics are nearly constant when the pre-tension is greater than 1.2N/m, this means that each of these three energies increases stably with the increase of pre-tension after pre-tension is greater than 1.2N/m. In contrast, the changing rates of energy for heavy weight fabrics are nearly constant when the pre-tension is greater than 0.8N/m. In a summary, each of three energies (A1cp1, A1, and A2 **)** for all of the three types of fabric increases stably (in other words, without abrupt changes) with the increases of pre-tension after the pre-tension is greater than 1.2N/m.



(a)



(b)



(c)

Fig. 11 Changing rate of energies A1cp1, A1, and A2 of the fabrics having different areal density

It is shown in Fig. 12 that the changing rates of energies for both medium and heavy weight fabrics are relatively small, less than 5% when pre-tension changes from 0.8N/m to 4.0N/m. For lightweight fabrics, their changing rates of energy decrease with the increase of pre-tension when pre-tension is greater than 1.6N/m. Generally speaking, the changing rates for all fabrics are small (less than 5%) when pre-tension is greater than 2N/m; this means that pre-tension has little effect on energy A6 regardless of fabric areal density when pre-tension applied on the fabric cylinder is greater than 2N/m.

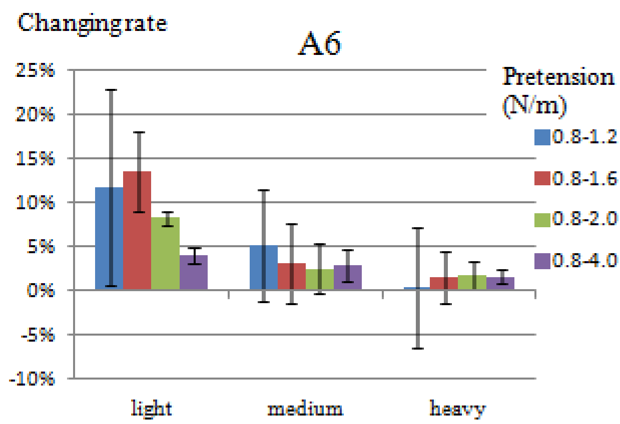
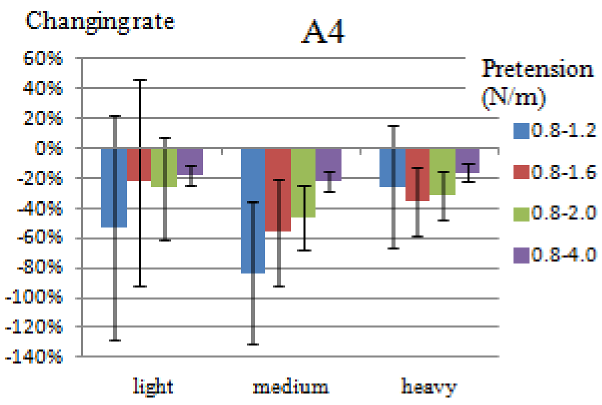


Fig. 12 Changing rate of energy A6 of the fabrics having different areal density

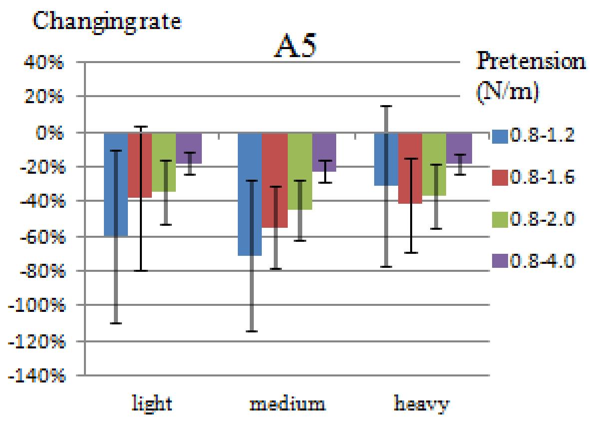
3.4.2 The changing rate of A3+A1cp1-A1, A4 and A5

It is shown in Fig. 5 Fig. 6 and Fig. 7 that energies A3+A1cp1-A1, A4 and A5 decrease with the increase of pre-tension, therefore, their changing rates are negative as shown in Fig. 13. It is noticed that changing rates of energy A4 and A5 for all of the three types of fabric are either less or around 20% when the pre-tension is higher than 2N/m. This means that both energy A4 and A5 are less sensitive to the increase of pre-tension when the pre-tension is greater than 2N/m.

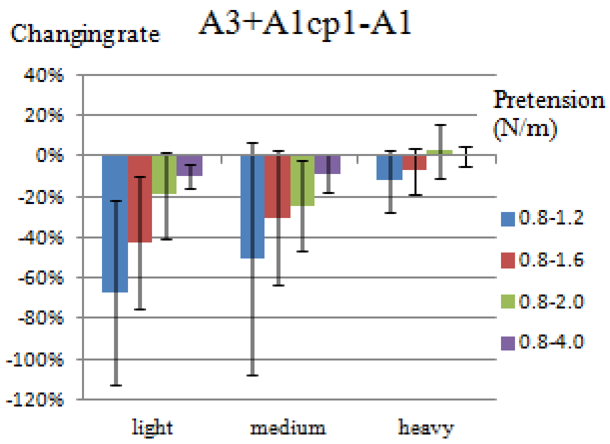
It is also found that changing rate of energy A3+A1cp1-A1 decreases significantly with the increase of pre-tension for these three types of fabrics. The changing rates are around 10% for light and medium weight fabrics, and around 1% for heavy fabric when pre-tension is greater than 2N/m, which means that there is only a small change of the energy A3+A1cp1-A1 obtained in greater pre-tensions (>2N/m) in comparison with 0.8N/m pre-tension.



(a)



(b)



(c)

Fig. 13 Changing rate of the energies A3+A1cp1-A1, A4 and A5 of the fabrics having different areal density

Based on the effect of pre-tension on changing rates of energies, it is concluded that, when pre-tension is greater than 2N/m, energies of A1cp1, A1, and A2 increase stably, and energies of A3+A1cp1-A1, A4, A5 and A6 become less sensitive to the increase of pre-tension. Therefore, it could be concluded that 2N/m would be a suitable pre-tension for light, medium and heavy weight fabrics.

4. Conclusions

The effects of pre-tensions on the deformation behaviour of six woven fabrics during cyclic compression buckling and recovery processes of fabric cylindrical shells were investigated. It is found that the energy consumed to deform the fabrics (A1cp1 and A1) and the strain energy stored in the deformed fabric to self-recover its deformations (A2) increase almost linearly with the increases of the pre-tensions exerted on the fabric shell before buckling. The external energies consumed to recover (A4) and form (A5) the recoverable deformations decrease with the increases of the pre-tensions. Besides, energy consumed to produce recoverable deformation (A6) associated with self-recoverable deformations increases negligibly with the increases of pre-tension, and pre-tension seems has little effect on the energy consumed in forming permanent deformations (A3+A1cp1-A1).

The influences of the pre-tensions on the energy consumed to produce and recover different types of deformation are due to additional friction forces produced between yarns and fibres by the residual structural changes remained in pre-tensioned fabrics. Based on the effect of pre-tension on the energy consumed to produce different types of fabric deformations, it is concluded that 2N/m would be a suitable pre-tension for light, medium and heavy weight fabrics.

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