Effect of meso-scale structures and hyper-viscoelastic mechanics on the nonlinear tensile stability and hysteresis of woven materials

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Abstract

Woven textiles are not only a craft and industrial product but also a thousand-year-old crystallization of human technology. However, the highly sought after mechanical behavior of fabric, generally undergoing large structural distortion along with material deformation even under small stress, is still not clearly understood despite a growing interest in emerging applications, such as flexible electron devices, biomeedicine and other engineering fields. Herein, a numerical methodology was introduced to strengthen the comprehensive understanding of the synergy effect of material mechanics and mesostructures of woven materials. A hyper-viscoelastic constitutive model for yarn materials was proposed, and a meso-scale geometry model captured from a resin-cured woven fabric was used, down to micron-sized weaving structures, to investigate the uniaxial loading and unloading process based on finite element (FE) method. The tensile and hysteresis mechanics was identified based on the validated FE model and parameter study of friction effect and fabric structures. The nonlinear tensile and recovery behaviors were reasonably represented by the developed models and the synergistic effect of inner yarn friction and viscoelasticity on the hysteresis was proved. This study can provide an effective method to analyze and predict the nonlinear tensile and hysteresis behavior of woven fabric, laying down the way to textile-based strain sensing materials by enhancing our design and tuning capabilities of the dimension stability of woven materials under tension.

1. Introduction

Woven fabrics, as a typical kind of multi-scale soft materials [1], are finding greater applications in various innovative areas. For instance, they are widely used as smart textiles in wearable electronics [2], flexible sensors [3], biomedical engineering [4], and protection applications [5]. However, the physical ingredients relating to the deformation and anelasticity behaviors of woven fabrics remain poorly understood.

Woven fabrics are interlaced by quasi-unidimensional yarns in double orientations to form weaving points, from which the effective dimensionality generates topologically. Because of the slippage of yarns among weaving points and the weak interaction of component fibers, the woven fabric can undergo large deformations [6]. Also the fabrics can deform smoothly in double curvature, making it possible to shape the fabric into arbitrary variants with tunable mechanical behaviors [1, 7]. The mesostructure evolution, mesoscopic stress or strain distributions and the interfaces of yarns in the woven fabrics are crucial to the macroscopic mechanical performance of fabrics. Tension effect plays an important role in the deformation of woven fabrics, even having a controlling influence on the bending behavior [8, 9], in which the multiscale structure coupled with the visco-elasto-plasticity of composition materials endows the fabrics with a distinctive load-extension and recovery curve compared to the continuum film and sheet materials. To guide better design and application of intelligence textiles, it is essential to have a deep investigation into the underlying mechanisms of the mechanical and deformation responds of woven fabrics.
Several early studies have focused on the geometry and mechanical modelling of woven fabrics by idealizing the weaving structured unit formed by springless warp and weft yarns to analyze the dimensional properties [10–12], as well as taking the mechanical properties of yarns into consideration by establishing a series of equilibrium equations using beam and truss models [13–15]. These models allow for studying the deformation in terms of various structure parameters and mechanical performance of woven fabrics, but the homogeneous stress and strain distributions are assumed among the weaving unit cells, which results in fundamental difficulties in the exact analysis of the deformation features for the yarn-interlaced heterogeneous fabric materials. Recently, the numerical modeling methods have been used to simulate the multi-scale fabric structure and mechanical properties of woven fabrics, and the computer technology along with finite element and energy methods is developed to investigate the dynamic responds of the fabrics efficiently [16–18]. Various mechanical properties, such as extensibility, stiffness, drape and compression have been simulated and predicted based on the yarn-based models of fabrics [19–22]. However, little work has focused on studying fabrics’ deformation of resilience by coupling the evolution of the microstructure of interlaced yarns with the local strain as well as the stress distribution in the whole fabrics. The underlying mechanisms of the dimension stability and hysteresis behavior of woven fabrics under tension effect are still unclear, despite a long history of domestic use and mass engineering applications.

In this paper, the hyper-viscoelastic constitutive model is presented, and the FE model is developed based on the constitutive model and geometry structure of a typical woven fabric. Moreover, an explanation of the nonlinear tensile property and hysteresis of woven fabrics under a loading-unloading cycle is provided, followed by the validated simulation results with experimental data. Also the effect of friction among yarns and fabric structures on the tensile and hysteresis responds is analyzed.

2. Constitutive law for yarns

Nonlinear tensile behavior of yarns with natural and synthetic fibers have been represented by viscoelastic material model, especially in low strain state [23–26], and the relation between stress \( \sigma \) and preload-dependent strain \( \varepsilon_p \) can be described by a generalized Maxwell model as follows [27],

\[
\sigma(t) = \sum_{m,n} [E_m + E_n^{(t/\tau)}] \varepsilon_p
\]

where \( E_m \) and \( E_n \) denote the respective material constants for \( m \)-th and \( n \)-th spring, and the \( \tau \) is the time constant of the ratio between the viscosity and elasticity. The material performance, by equation (1), is divided into two components, namely elasticity component \( E_m \varepsilon \) and viscoelasticity component \( E_n^{(t/\tau)} \varepsilon \). In order to have a better expression of the elasticity component, a hyperelastic material model is desired to capture the large deformation behavior of woven materials under the assumption of a minimal plastic deformation of yarns. The general hyperelasticity constitutive model in the form of Cauchy stress \( \sigma \) can be given by the strain energy function \( U \) as the following [28],

\[
\sigma = 2 \left( \frac{\partial U}{\partial \varepsilon} + \frac{h}{I_1} \frac{\partial U}{\partial B} \right) B - \frac{\partial U}{\partial B} B^2 - pI
\]

Where \( B \) presents the left Cauchy-Green deformation tensor; \( p \) denotes the hydrostatic pressure, and \( I \) is the principal invariant relating to the stretch ratio of materials. The strain energy function can be fitted in a form of a polynomial model as [29],

\[
U = \sum_{m=0}^{M} \sum_{n=0}^{N} C_{mn}(I_1 - 3)^m(I_2 - 3)^n, \quad C_{00} = 0
\]

Where \( C_{mn} \) is the material constant, and \( I_1 \) and \( I_2 \) is the first and second invariants. Where \( M \) and \( N \) is the number of terms of the polynomial model. It should be noted that the incompressibility is assumed for the hyperelastic materials, and the volumetric part of the hyperelastic equations is neglected.

By setting the number of terms \( M = N = 1 \) and \( m + n = 1 \), or \( M = N = 2 \) and \( 1 \leq (m + n) \leq 2 \) in equation (3), the 1-terms polynomial model, namely Mooney-Rivlin model, and 2-terms polynomial model can be obtained and expressed by equations (4) and (5), respectively.

\[
U_{\text{Mooney-Rivlin}} = C_{10}(I_1 - 3) + C_{01}(I_2 - 3)
\]

\[
U_{\text{Poly}_{12}} = C_{10}(I_1 - 3) + C_{01}(I_2 - 3) + C_{11}(I_1 - 3)(I_2 - 3) + C_{20}(I_1 - 3)^2 + C_{02}(I_2 - 3)^2
\]

Similarly, we can obtain another two reduced polynomial models, namely Neo Hooke model and Yeoh model by respectively setting \( M = 1 \) or 3 and \( N = 0 \), which can be written as,
In order to take the viscoelasticity into consideration, the Prony series is used to describe the stress relaxation effects of yarns, which is given by

\[ U_{\text{Neo Hooke}} = C_1(1 - 3) \]

\[ U_{\text{Yeoh}} = C_1(1 - 3) + C_2(1 - 3)^2 + C_3(1 - 3)^3 \]

In order to take the viscoelasticity into consideration, the Prony series is used to describe the stress relaxation effects of yarns, which is given by [30],

\[ g_R(t) = 1 - \sum_{m=1}^{N} g_m(1 - e^{-1/\tau_m}) \]

Where \( g_R(t) \) denotes the dimensionless shear relaxation modulus; \( g_m \) is a material constant relating to the shear relaxation modulus, and \( \tau_m \) is the relaxation time constant. Applying the relaxation equation (8) to the constants describing the strain energy function of hyperelasticity, we have

\[ C_{mn}^{R}(t) = C_{mn}^{0} \left( 1 - \sum_{m=1}^{N} g_m(1 - e^{-1/\tau_m}) \right) \]

The equation (9) can be applied to the hyper-viscoelasticity model for yarns, which considered the viscoelasticity and non-linear elasticity of yarns materials weaving in the woven fabrics. The corresponding material constants in the models can be obtained from experimental data of uniaxial tension and relaxation test.

3. Materials and experiments

A plain-woven fabric with thickness of 0.4 mm and mass of 203 g/m² was selected in this study to conduct the model experiment (see figure 1). The thread count of the fabric in warp × weft is 135 × 190 per 10 cm. The nylon/spandex fasciated yarns and polyester filament yarns are respectively used as warp and weft. All prepared specimens were balanced at the standard condition (65% ± 3% relative humidity and 20 °C ± 2 °C) for more than 24 h before the tests.

The testing of basic material parameters for FE simulation was carried out on a Shimadzu AGS-X universal testing machine in the unified standard condition, and thus the effect of temperature on the mechanical property of materials is not considered in this study. The tensile tests and relaxation tests were conducted for warp and weft yarns, respectively, where the yarns were clamped at gauge length of 15mm at a testing speed of 100 mm min⁻¹. For the relaxation tests, the applied maximum force is set as 4N and recorded relaxation time is 180s. In the mechanical tests for fabrics, the fabric in size of 20mm width × 30 mm length was stretched along the warp direction while clamped along the weft direction by two jaws of 10mm gauge with the speed of 0.4 mm s⁻¹. The maximum extension before releasing back to the initial state of the fabric is 3mm. The average of three tensile testing curves was reported to compare with simulating results.

4. Identification of materials parameters

4.1. The hyperelastic parameters

The experimental data from the stress–strain curves of uniaxial tensile tests were used to calibrate the four models of equations (4)–(7), viz. Mooney-Rivlin, 2-term polynomial, Hooke and Yeoh. The built-in property evaluation module of the ABAQUS software was used to determine the model parameters based on nonlinear curve fitting algorithm. Figure 2 shows the experimental and fitted stress—strain curves for the warp yarns.
As can be seen, most models fit well with the curve parameters at low strain (less than 15% for warp yarns and 0.6% for weft yarns), while the Neo Hookean model shows relatively big deviations from the experimental data when the strain is large. Therefore, the Neo Hookean model is not recommended to be used in further yarn’s simulation. The 2-term polynomial model can closely fit the experimental data as clearly shown from figure 2(a). In order to verify the imitative effect of the 2-term polynomial model for weft yarns, the overall error between the experimental and fitted stress versus strain was calculated by,

\[
\text{Error}_{\text{overall}} = \sum_i \left( \frac{|\sigma_i^{\text{fit}} - \sigma_i^{\text{exp}}|}{\sigma_i^{\text{exp}}} \right)
\]

Where \(\sigma_i^{\text{fit}}\) and \(\sigma_i^{\text{exp}}\) are the fitted and experimental stress, respectively. The error results further verify that the 2-term polynomial model is suitable to simulate the real stress-strain curve of the yarns with the overall error of 0.49 based on 33 experimental data points, lower than 3.37 for Mooney-Rivlin model and 1.76 for Yeoh model. Therefore, the 2-term polynomial model is finally selected for the FE modelling of the yarns. The values of the model parameters, i.e. \(C_{10}, C_{01}, C_{11}, C_{20}\) and \(C_{02}\) are \(-93.4, 101.0, 3162.4, -1308.1\) and \(-1817.1\) MPa for warp yarns, and \(-3935.9, 4032.4, -1091475.8, 474211.2\) and \(634422.9\) MPa for weft yarns, respectively.

4.2. The viscoelastic parameters
The relaxation experimental data of the yarns were used to calculate the parameters \(g_m\) and \(\tau_m\) as seen in equation (8). The Prony series was selected to describe the viscoelastic behavior of yarns by fitting with experimental data using least square algorithm with the allowable average root-mean-square error of 0.01. A series of consecutive calculation was carried out based on the ABAQUS software, and results of the best fit Prony series along with the experimental data were plotted in figure 3. The 2-term Prony series shows good agreements with the experimental data of both warp yarns and weft yarns. Therefore, the optimised values of parameters \(g_m\) and \(\tau_m\) for warp yarns and weft yarns can be obtained, which are listed in table 1.

5. Simulation of the tensile and hysteretic response of the fabric
5.1. Finite element modeling
The tensile and hysteresis behavior of fabrics can be simulated based on the above constitutive models and material parameters. Considering the significant effect of structure on the deformation characteristics, a meso-scale weaving structure model taking the crimp morphology and cross-section shape into account was developed in this study. An optical microscope was used to capture the geometry structure based on the collodion-solidified slices of the fabric (see figure 4(a)). The cross section of the yarns can be treated as ellipse approximately. Based on previous studies [31, 32], the Bezier spline curve was used to fit the crimp trajectory of yarns in the woven fabric based on series of geometry parameters, namely, distance of adjacent yarns \(L\), height of the flexural wave \(H\), the major axis length \(a\) and minor axis length \(b\) for the ellipse section, as shown in figure 4(b). Then the fabric geometry model with length \(\times\) width of 8mm \(\times\) 5 mm was established (see figures 4(c) and (d)). The average values of the parameters for the geometry modeling are reported in table 2.

The FE model was then established using the hyper-viscoelastic constitutive model based on ABAQUS software. The dynamic implicit procedure was selected to conduct the simulation process. And the displacement

\[
\text{Figure 2. Experimental and fitted stress-strain curves of warp yarns (a) and weft yarns (b) by four strain energy functions for the hyperelastic model.}
\]
load was applied to the transverse plane of the fabric by coupling the cross sections of yarns at the transverse plane with a reference point, as shown in Figure 5, until extension $= 3$ mm with the moving speed of $0.4$ mm s$^{-1}$. The first-order hybrid element (C3D8H) and second-order hybrid element (C3D10H) were selected for meshing the weft yarns and warp yarns, respectively. The friction coefficient of yarns was set as 0.3.
5.2. Tensile and hysteresis mechanism

Figure 6 shows the tensile and hysteresis responds of the fabric from experimental data and FE simulation. It can be seen that simulative result shows good agreement with experimental data by a similar shape and trend between the simulative and experimental curves, and both of which present typical nonlinear tensile behavior. Due to the satisfactory simulation of the FE model for the force—displacement relationship of the fabric, and thus it is reasonable to use this model to summarize a general tensile and hysteresis mechanism of the woven fabric based on several typical deformation stages, which is analyzed in details as follows:

1. The strain distribution by a view of the mesostructure of the fabric at the very initial stretching state is shown in figure 7. It is observed that the tensile deformation leads unexpectedly to a nonuniform strain in the y direction that is perpendicular to the loading direction. This strain is linked to the trimming of yarns in the space position [33], resulting in a deviation from a homogeneous structure of the fabric. The main contribution to the nonuniform strain is probably provided by the friction interaction among yarns, and
the yarn strain is large at the edge of the fabric owing to the relatively week cohesive force. This is in contrast with previous theoretical and simulative studies where the homogeneous deformation of fabrics are assumed by using a weaving unit to describe the geometry and mechanics of a whole fabric \[12, 34, 35\].

(2) After trimming the structure of the fabric, the tensile force exhibits a nonlinear increase, along with a yarn decrimping deformation in warp direction (tensile direction) while an enhancement of the yarn crimp occurs in the weft direction, contributing to distinct out-of-plane buckling of weft yarns (see figure 8(a)). This agrees with the previous studies \[31, 36\] and shows a remarkable difference with the homogeneous plane, where no meso structure adjusts during tension deformation. Thus the tensile process of woven fabrics is not only strongly related to the Young’s modulus of yarns in tensile direction, but also associated with the bending rigidity of yarns in perpendicular direction. In addition, the friction effect from interyarn surface also contributes to the tensile behavior of woven fabrics for the interaction between warp yarns and weft yarns (the interaction effect will be further discussed in the parametric study part), thus indicating a tight coupling effect of the yarn mechanical property and the fabric weaving structure on the tensile stability.

(3) When recovering to the vicinity of the initial position, the model undertakes buckling deformation (see the figure 8(b)) due to the residual elongation, which contributes oppositely to the unloading force in the unloading phase. Therefore, the unloading force decreases to below zero at the end of the recovery deformation stage. The hysteresis of the fabric is obvious as seen from the difference works between loading and unloading phases of the force – displacement curve (see the figure 6). As far as the tensile process goes a cycle route, the structure of the fabric does not retrieve its initial morphology, remaining a plastic elongation (figure 8(b)). Thus, this dissipative performance mainly results from the viscoelasticity of yarn materials as proposed by the previous study [31], but the friction effect between yarns at the interlacing points is regarded as another important factor, which will be further discussed in the following part.

6. Parametric study

6.1. Effect of surface friction of yarns

In order to embody the effect of friction on the mechanical responds, the tensile and recovery curves of the fabric at different friction coefficients, viz. 0.8, 0.3 and 0.001 are calculated. Our study does not access the frictionless case, but a small value of 0.001 was used as friction coefficient to analyze the minimal effect of the friction in order to enhance the convergence character and effectiveness of calculation by FE method. The results are shown in figure 9, indicating that the tensile resistance increases with the increase of the friction coefficient. Thus, the higher friction coefficient of the yarns presents in the fabric, the better stability in dimension and morphology of the fabric with tension possesses.

The hysteresis of the unloading phase has a slight increase but cannot be clearly presented from the curves of figure 9 as the large hysteresis caused by the viscoelastic property of yarn materials covers up the friction effect.
Hence, a model by removing the viscoelastic parameters is used to capture the friction hysteresis effect of the fabric, and an extra FE model with high friction coefficient of 1.5 is created when other parameters are kept unchanged. The calculation results are shown in figure 10, from which an obvious hysteresis between the loading and unloading phases of the force—displacement curve can be found, justifying the friction effect on the mechanical responds of fabrics. Moreover, the model with larger friction between yarns exhibits better stability indicated by the higher force value at the loading phase, while the higher friction enhances the hysteresis, resulting in a low dimension retention property under tensile deformation. The physical basis for this result is that the friction between yarns contributes oppositely in the loading and unloading phases, and thus stiffening the fabric at loading phase while weakening the elasticity of fabrics at unloading phase. In addition, figure 11 shows the position changes of yarns at interlaced points after a loading-unloading cycle, from which it can be seen that the yarns show a striking displacement field towards the direction of the loading, not undergoing irreversible deformation although the viscoelasticity is removed in the mode. This further confirms that the friction between yarns is one of the factors contributing to the hysteretic behavior of fabrics.

6.2. Effect of the weaving structure of fabrics
In order to investigate the effect of meso-scale structure on the tensile behavior of fabrics, two extra models with 1/2 twill and 5/3 satin structures were created (see figure 12). The simulating results based on three primary fabric structures, viz. plain, twill and satin, are shown in figure 13, where it can be seen from the loading phase of the curves that the satin model corresponds to the smallest stretching displacement at the same tensile force, and
Figure 11. The dislocation of the yarns between initial position and end position under a loading-unloading cycle. The blue yarns present the end position after tensile deformation, and the white yarns denote the initial position of yarns before the stretching. The red curves show the changing trajectories at interlaced points.

Figure 12. The FE models with different fabric structures: (a) plain; (b) twill; (c) satin; (d)–(f) the cross-section of plain, twill and satin structures.

Figure 13. The force–displacement curves under loading-unloading action at different fabric structures.
the plain one has the largest stretching displacement among the three models. In other word, the satin fabric has
good dimension stability under tension and is followed by twill fabric, while the tensile stability of plain fabrics is
relatively poor. To analyze the hysteresis, the hysteretic work between the loading and unloading curves, that is,
\[ W = \int F_{\text{loading}} \, ds - \int F_{\text{unloading}} \, ds \] (\( F \) denotes the force; \( s \) and \( s' \) are the displacements for loading phase and
unloading phase), was calculated. They are 1.39 N mm for plain, 1.45 N mm for twill and 1.58 N mm for satin,
respectively, indicating that the plain model has the best recovery ability after tensile deformation, while the
recovery of satin is low. The physical basis for the above results are that the yarns in the plain weaving structure
have more interlacing numbers (see figures 12(d)–(f)), contributing to the zigzag path of internal yarns, and thus
showing a structure-induced elastic behavior. Therefore, the plain model exhibits the best elasticity and
resilience among the three primary structures. However, the satin model has least interlacing points, and thus
undergoes the highest force at the same displacement when it is loading, and shows poor resilience under
unloading phase.

7. Conclusion

A hyper-viscoelastic constitutive model for yarn materials was proposed, and the FE analysis on the tensile and
hysteresis responds of the woven fabric was conducted based on the meso-scale structure model and material’s
nonlinearity. The simulation results provided a satisfactory prediction for the relationship between loading-
unloading force and the displacement by comparing with the experimental data. The tensile and hysteresis
mechanics of the woven fabric was analyzed with the simulation of the FE models. It was found that the friction
effect in the meso-scale weaving structure of a woven fabric contributes to a nonuniform strain field between the
margin and central areas of the fabric at the initial stretching state. The peculiar out-of-plane buckling of the
yarns perpendicular to the tensile direction was observed, indicating the integrated influences of orthogonal
warp and weft yarns on the tensile property of woven fabrics. The FE model also detects the hysteresis effect and
the plastic deformation after a loading-unloading cycle. By referring to the parameter study, it was confirmed
that the dissipative performances of woven fabric under tension resulted from the synergistic effect of the
material’s viscoelasticity and surface friction among yarns of fabrics, and also the higher friction coefficient of
the yarns contributes to a better stability in dimension and morphology of the fabric. The FE model was
extended to twill and satin structures, and it was found that the plain model possessed the best elastic and
recovery property, while satin model had good tensile stability under tension compared with twill and plain
models.

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