International Journal of Mechanical, Industrial and Aerospace Sciences
ISSN: 2517-9950
Vol:6, No:8, 2012

A visco-elastic model for high-density cellulose insulation materials

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Abstract—A macroscopic constitutive equation is developed for a high-density cellulose insulation material with emphasis on the out-of-plane stress relaxation behavior. A hypothesis is proposed where the total stress is additively composed by an out-of-plane visco-elastic isotropic contribution and an in-plane elastic orthotropic response. The theory is validated against out-of-plane stress relaxation, compressive experiments and in-plane tensile hysteresis, respectively. For large scale finite element simulations, the presented model provides a balance between simplicity and capturing the materials constitutive behaviour.

Keywords—Cellulose insulation materials, Constitutive modelling, Material characterisation, Pressboard.

I. Introduction

HIGH density cellulose insulation materials have attracted commercial interest due to their wide range of applicability as mechanically load carrying construction materials in the power industry.

Due to the intrinsic properties of cellulose and the common fabrication process: where cellulose fibres are sprayed on to a moving cloth, exposed to a sheet forming operation and dried under high pressure, these materials often have a dense microstructure of collapsed cellulose fibres, cf. Fig. 1. As a result, these materials often shows, for reasonably small strains, a clear in-plane visco-elastic ortothropic mechanical response and an out-of-plane non-linear visco-elastic behavior.

Surprisingly, almost no results are published on the mechanical properties of high-density cellulose materials and especially for the out-of-plane constitutive behavior computational models are rare. This is remarkable since the out-of-plane direction often is the primary loading direction for many applications in the power industry, cf., e.g., when the material is used as spacers in the clamping system of electrical conductors etc. Here, especially the out-of-plane constitutive stress relaxation behavior must be precisely described for being able to design for long time mechanical withstand-ability and short circuit safety. To be mentioned as previous work are [1]–[4] and references therein. The experimental and modelling work by [1] investigates the influence of temperature on the compression behaviour of paper in the thickness direction, [2] presents a small strain model for the through-thickness elastic-plastic behaviour of paper and [3] introduces a non-linear visco-plastic visco-elastic material model for fibre composites in compression. Notable is that, to the best of the authors knowledge, there exist no published material on modeling of high-density ($1200kg/m^3$) cellulose fibre compounds. A related publication is [4] who used Ansys built-in functionality to predict the characteristics of pressboard under press forming.

The objective of the present study is to develop a small strain elastic, visco-elastic constitutive equation for high-density ($1200kg/m^3$) cellulose insulation materials applicable for constant temperature and humidity. Emphasis is primarily on predicting the non-linear out-of-plane stress relaxation behaviour for simple as well as cyclic deformation - hold-time histories. Here, we propose the evolution of the visco-elastic strain to be sufficiently described by a combination of two non-linear Perzyna type equations, cf. [5] and a von Mises effective stress measure. Also, a linear elastic orthotropic formulation is included for predicting the materials in-plane response.

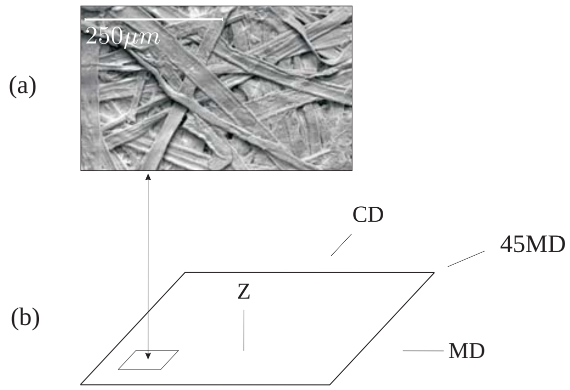

Fig. 1. (a) Typical in-plane microstructure of a high-density cellulose insulation material (the out-of-plane direction is orthognal to the image). (b) Material directions: MD (machine direction, in-plane), CD (cross machine direction, in-plane), 45MD is $45°$ w.r.t. MD and CD, in-plane, respectively, and Z (out-of-plane).

II. Experimental

Cellulose based materials are often sensitive to temperature and humidity. Therefore monitoring and control of the environmental condition is of high importance for producing reliable experimental results.

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Manuscript received March 30, 2012; revised ....

For the material characterisation, presented herein, the temperature and humidity were in the intervals 23 ± 2°C and $65 \pm 10\%$, respectively.

All specimens were dried and wrapped in plastic before testing. Also, all specimens were in temperature equilibrium with the surrounding environment before examined. For the out-of-plane stress relaxation experiments the plastic wrapping was kept during the whole test due to the extended testing periods. For the out-of-plane compressive and in-plane tensile experiments the plastic wrapping was removed during the tests. Here, the specimens were subjected to the surrounding environment for a shorter period of time.

A. *Out-of-plane stress relaxation*

The stress relaxation experiments were performed on stacks of 23 rectangular specimens with dimensions $base \times width \times height : 30 \times 60 \times 1.75mm$ each. Here, all specimens were dried at 110°C for $48h$ under vacuum to a moisture weight percentage of 0.5. After drying, the stacks were wrapped in plastic. Every type of test, cf. Figs. 2–4 were performed with a new stack of specimens. Three different types of relaxation tests are given. In all experiments each stack of specimens is subjected to a repeated compression and relaxation history. In Fig. 2, the stack is subjected to a constant deformation for $1h$ and then put at rest (meaning not subjected to any load) for $1h$ in between each relaxation. In Fig. 3 the stack is subjected to a constant deformation for $1h$ and then put at rest (meaning not subjected to any load) for $5min$ in between each relaxation of the different compressions $1 - 3$. The rest between compression 3 and 4 is $264h$. In Fig. 4 four different specimens are subjected to different hold-times of $0 - 5h$ before measuring the stress relaxation. The scatter in experimental data is according to Figs. 2–4. The results for the out-of-plane stress relaxation experiments are shown in Figs. 2–4.

B. *Out-of-plane uni-axial compression*

The specimens for the out-of-plane uni-axial compressions were dried in a ventilated oven following the norm IEC 60641-2. For the examination a 8500 tensile test machine with a MTS $250kN$ load cell was used together with a stress controlled triangular loading path. For examining the rate sensitivity, three different loading rates: 0.5, 20, $40kN/s$ were considered on three individual specimens. A $1s$ hold-time at peak stress was applied. Every test was made using a single square specimen with dimensions $base$ (MD)$\times width$ (CD)$\times height$ (Z): $25 \times 25 \times 8mm$. Teflon film was used between the specimen and the compression platens on the machine to lower the friction. To reduce scatter in experimental data an initial compressive pre-stress of $5kN$ is applied before the actual loading. The results from the out-of-plane uni-axial compressions are given in Fig. 5. Note, the viscous effect (in terms of creep strain) due to the hold-time at peak load for the elevated loading-rates: 20 and $40kN/s$, respectively.

C. *In-plane uni-axial tension*

The specimens for the in-plane uni-axial tension were dried in a ventilated oven following the norm IEC 60641-2. For the examination a 8500 tensile test machine with a MTS $250kN$ load cell was used together with a strain controlled sinusoidal loading at $0.1Hz$. An Instron 2620 extensometer was bonded to the specimens using rubber O-rings. Every test was performed using a single square specimen with dimensions $base \times width \times height : 3 \times 15 \times 133mm$. For the three individual directions: MD, 45MD and CD, nine specimens are used, respectively. The scatter in experimental data is $\pm 5MPa$. The results from the in-plane uni-axial tension experiments are given in Fig. 6.

III. Model

Since there exists very limited, published, literature on the herein investigated material, no effort is put on developing an *advanced* constitutive model at this stage. Instead standard formulations are used as a baseline. The simple material model development within this contribution serves well to provide guiding w.r.t. improvements.

Based on the above, the underlying model development idea is to find a suitable formulation with emphasis on the stress relaxation behaviour. Still, the out-of-plane compressive and in-plane orthotropic responses are somewhat considered by utilizing a balance between predictability and computational efficiency. Also, emphasis is put on keeping material parameters to a minimum for facilitating material parameter calibration. Therefore, by reflecting on the provided material characterisation, the assumption is that a combination of two isotropic non-linear visco-elastic Perzyna type equations, cf. [5] together with a von Mises effective stress measure are adequate for the out-of-plane behaviour and a classical linear elastic orthotropic model is sufficient for the in-plane mechanical response.

Thus, the total stress is expressed additively as

$$\sigma_{ij}^{\mathrm{tot}} = \sigma_{ij}^{\infty} + \sum_{q=1}^{2} \sigma_{ij}^{\mathrm{v}_q}, \tag{1}$$

where

$$\sigma_{ij}^{\infty} = D_{ijkl}^{\mathrm{a}} \varepsilon_{kl}^{\mathrm{e}}, \tag{2}$$

$$\sigma_{ij}^{\mathrm{v}} = D_{ijkl}^{\mathrm{i}} \left(\varepsilon_{kl} - \varepsilon_{kl}^{\mathrm{v}} \right). \tag{3}$$

In (2) and (3) the stiffness tensors D_{ijkl}^{a} and D_{ijkl}^{i} are the standard small strain elasticity tensors for ortotropy and isotropy, respectively.

Further, the evolution equation for the viscous strain is assumed to be coupled to the deviatoric stress s_{ij} and the effective von Mises stress, i.e.,

$$\dot{\varepsilon}_{ij}^{\mathrm{v}} = \frac{3}{2} \left(\frac{\sigma_{\mathrm{vM}}}{\sigma_0} \right)^m \frac{s_{ij}}{\sigma_{\mathrm{vM}}}, \tag{4}$$

with

$$\sigma_{\mathrm{vM}} = \sqrt{\frac{3}{2} s_{ij} s_{ij}} \tag{5}$$

International Journal of Mechanical, Industrial and Aerospace Sciences
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and

$$s_{ij} = \sigma_{ij} - \frac{1}{3}\sigma_{kk}\delta_{ij}. \quad (6)$$

Finally, in the power law (4), m is the parameter for strain-rate sensitivity.

Combining (1) and (4) gives the resulting constitutive equation on rate format as

$$\begin{aligned}\dot{\sigma}_{ij}^{\mathrm{tot}} &= D_{ijkl}^{\mathrm{a}}\dot{\varepsilon}_{kl}^{\mathrm{e}} + \\ &\left[D_{ijkl}^{\mathrm{i}}\left(\dot{\varepsilon}_{kl} - \frac{3}{2}\left(\frac{\sigma_{\mathrm{vM}}}{\sigma_0}\right)^m \frac{s_{kl}}{\sigma_{\mathrm{vM}}}\right)\right]_1 + \\ &\left[D_{ijkl}^{\mathrm{i}}\left(\dot{\varepsilon}_{kl} - \frac{3}{2}\left(\frac{\sigma_{\mathrm{vM}}}{\sigma_0}\right)^m \frac{s_{kl}}{\sigma_{\mathrm{vM}}}\right)\right]_2. \end{aligned} \quad (7)$$

IV. Results

The ability of the model to predict the high-density cellulose material in out-of-plane stress relaxation, out-of-plane uni-axial compression and in-plane uni-axial tension is shown in Figs. 2–6. The used parameter set is obtained from calibration w.r.t. Figs. 2, 3, 5 (for loading rate $5kN/s$) and 6. A prediction, obtained by using the result from the parameter calibration, is given in Fig. 4.

A. Out-of-plane stress relaxation

Model prediction and experimental response in out-of-plane stress relaxation is shown in Figs. 2–4.

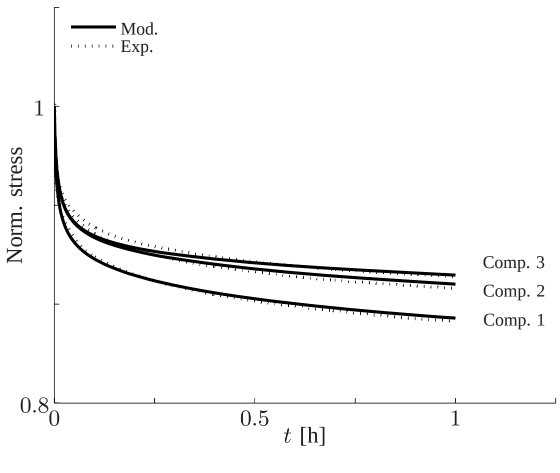

Fig. 2. Prediction and experimental response in out-of-plane relaxation for repeated compression and relaxation behaviour of one stack of samples. The stack is put at rest (meaning not subjected to any load) for 1 hour in between each relaxation.

B. Out-of-plane uni-axial compression

Model prediction and experimental response in out-of-plane uni-axial compression is shown in Figs. 5.

C. In-plane uni-axial tension

Model prediction and experimental response in in-plane uni-axial tension is shown in Figs. 6.

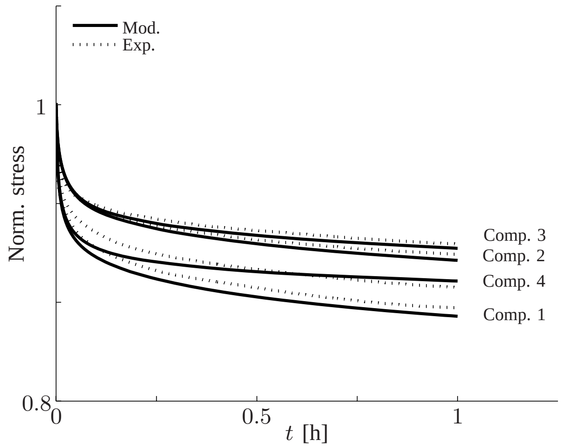

Fig. 3. Prediction and experimental response in out-of-plane relaxation for repeated compression and relaxation behaviour of one stack of samples. The stack is put at rest (meaning not subjected to any load) for 5 min in between each comression/relaxation w.r.t. Comp. 1-3. The rest between comression/relaxation Comp. 3 and 4 is $264h$.

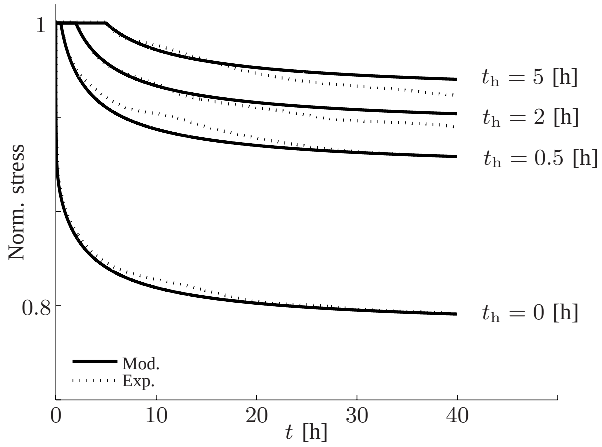

Fig. 4. Prediction and experimental response in out-of-plane relaxation with initial hold times (t_{h}) of $0 - 5$ hours.

V. Conclusion

The experimental investigation of the of the high-density cellulose insulation material reveals, at prescribed boundary conditions (deformation, temperature, humidity and time), that

1) the out-of-plane stress relaxation behaviour is well developed,
2) the out-of-plane compressive response is essentially time dependent linear in on-loading but reveals residual deformations at off-loading,
3) the in-plane hysteresis behaviour is essentially time dependent linear.

By comparing the model with the experiments, cf. Figs. 2–6 it is noted that the formulation is well suited for predicting the out-of-plane stress relaxation response. Further, the out-of-plane compressive and in-plane tensile responses are not

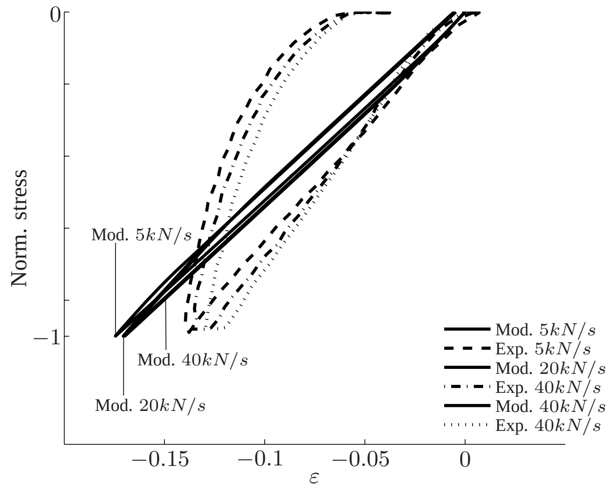

Fig. 5. Prediction and experimental response in out-of-plane compression.

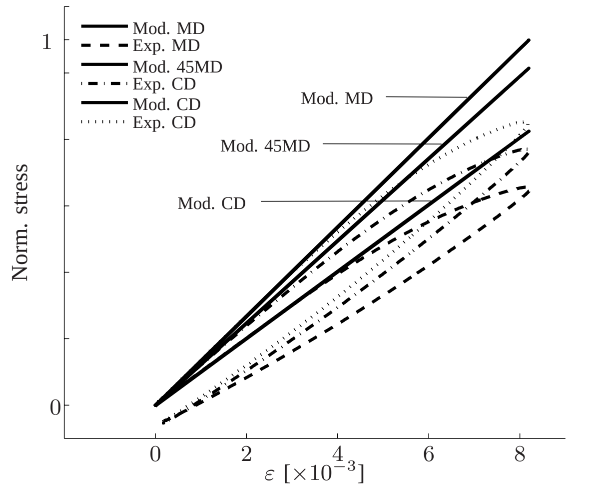

Fig. 6. Prediction and experimental response in in-plane tension. The given experimental data are each averaged from nine specimens, respectively. The scatter is $\pm 5MPa$.

adequately captured. This is primarily due to that the formulation for the out-of-plane behaviour: (3) does not include visco-inelasticity. The models in-plane tensile response could be improved by introducing visco-elasticity to (2).

ACKNOWLEDGMENT

The authors especially would like to thank Torbjörn Brattberg at ABB Figeholm for supplying specimens for the material characterisation.

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