*Proceedings of the IASS 2024 Symposium*
*Redefining the Art of Structural Design*
August 26-30, 2024, Zurich Switzerland
Philippe Block, Giulia Boller, Catherine DeWolf,
Jacqueline Pauli, Walter Kaufmann (eds.)

# Investigations into load history dependencies in the stress-strain behaviour of PVC-coated polyester fabric

Jörg UHLEMANN*, Natalie STRANGHÖNER*

*University of Duisburg-Essen, Institute for Metal and Lightweight Structures, Universitätsstr. 15, 45141 Essen, Germany
joerg.uhlemann@uni-due.de

## Abstract

Structural textile fabrics in architectural applications are exposed to varying loads. In combination with the curvature of the membrane structure this leads to changing biaxial stress states in a local point of the structure. Furthermore, it is well known that the stress-strain response of a structural textile fabric depends on the applied stress ratio warp:fill. The present contribution presents investigations regarding to what extent the stress-strain response depends on past stress ratios, i.e. on the applied previous load history. Particularly different orders of load were experimentally investigated. The experiments were performed with a PVC-coated polyester fabric.

In the design practice, stiffness parameters for modelling are evaluated from the measured fabric's stress-strain response. In the consequence, if this response depends on the order of loads, stiffness parameters would not be valid in a general sense but would have to be given dependent on the order of loads. This contribution shows in how far these considerations are necessary for the investigated PVC-coated polyester fabric.

**Keywords**: Textile membranes, stress-strain behaviour, stiffness, load history, biaxial test, cyclic test

## 1. Introduction

PVC-coated woven polyester fabrics (short: PES-PVC fabric) are frequently used in different structural applications like membrane roof or façade structures, biogas storages or air ship envelopes.

The load bearing elements are polyester yarns, woven in “warp” and “fill” direction orthogonal to each other. Thus, a thin planar structural element is produced with no significant compression and flexure stiffness. For outdoor applications and for the ability to connect fabric parts to each other via weld seams, the fabric is coated on both sides with flexible PVC. The yarns lie crimped in the matrix, crossing over and under each other. When an in-plane tensile load applies to the yarns, they straighten. Thus, crimp is reduced in the loaded yarns. Observed fabric strains partly come from the geometrical straightening of the yarns and partly from yarn elongation under tensile load. It is remarkable that under a monoaxial load, the yarns in the orthogonal direction are forced to crimp stronger. This effect leads to transverse contraction. It is called crimp interchange [1].

As the yarn crimp in warp and fill directions reacts to loads, it is apparent that the yarn crimp at a given time depends on previous load incidents. Here the question arises whether the yarn configuration just depends on the current loads in warp and fill direction or whether the fabric response depends on the yarn configuration just before this load.

As the fabric has the two predefined principal directions warp and fill, stiffness properties are usually determined using biaxial tensile tests. As a rule, various stress ratios warp:fill have to be tested in a given order specified by standards, see e.g. [2], [3]. Two elastic moduli $E_x$ and $E_y$ as well as two Poisson's ratios $\nu_{xy}$ and $\nu_{yx}$ are fitted to the recorded stress-strain data. Herein, x-direction is congruent with warp direction and y-direction with fill. However, in none of these procedures, the possible impact of the order of loading is considered in depth. Only indirect, by the fact, that for each tested stress ratio three load cycles are performed, it can be assumed that the authors of [2] and [3] have implied a certain dependency on where the load cycle is located in the loading history.

Indeed, it is well known from many biaxial tests that the first load cycle after a change of the stress ratio provides a very different stress-strain path than for all following ones. In other words: the stress-strain path of the first load cycle after a change of the stress ratio strongly depends on the previous stress ratio. This probably has to do with the current weave geometry, i.e. with the actual yarn crimp right before the change of the stress ratio. It is also well known that in case more load cycles in the new stress ratio follow, the weave geometry adapts somehow to the new stress state. In this way, the mechanical behaviour saturates. The question is whether the yarn geometry can adapt so far to the new stress state that after a certain number of load cycles the impact of the previous stress state is "overwritten".

Different researchers have stated or considered a certain load history dependency of architectural woven fabrics, see e.g. [4], [5], [6], [7], but it has only been analyzed in detail in a few studies. For PES-PVC fabrics, *van Craenenbroeck et al.* [8] have investigated variations of the order of stress ratios in an extended load protocol according to MSAJ/M-02-1995. The extension was mainly that three load cycles have been performed in every stress ratio. They found significant impact of the different orders in the recorded stress-strain paths. But they assessed the impact as not relevant for the computational model. The newer biaxial test standard EN 17117-1 suggests a similar load protocol as [3] but considers the findings in [8]. For the stress ratios other than 1:1, also three load cycles are foreseen. Usually, the last load cycle of every stress ratio is evaluated.

Again for a PES-PVC fabric, *Galliot & Luchsinger* [9] applied blockwise five load cycles of stress ratio 1:1 alternating with load blocks consisting of five load cycles of other stress ratios than 1:1. A comparison of all the resulting fifth stress-strain paths of the different 1:1 load blocks revealed that they were very similar – independent of the previous load history.

*Van Craenenbroeck et al.* [10], see also [11], compared different load protocols to each other. They observed for the investigated PES-PVC fabric that 1:1 stress-strain paths were very similar, independent of the load history. They also pointed out that a stress settlement period at a prestress level previous to the main load profile significantly reduced viscous effects in the loading and unloading paths.

However, single biaxial tests on a PTFE-coated glass fibre fabric carried out in the frame of a currently conducted DFG research project indicated that a previous load history can influence the stress-strain paths [12]. This material seems to have a memory for previous loads. The dependencies appear to be particularly pronounced in stress ratio 1:1. This means that this particular stress ratio, as considered in EN 17117-1 and MSAJ/M-02-1995, is unsuitable as an intermediate stress ratio for the investigated fabric type.

In the present paper, a systematic investigation into possible load history dependencies of a PES-PVC fabric as typically used in architectural applications is reported. To achieve a full assesment in how far the different stress ratios respond with or without load history dependencies, saturation characterisics as defined in [13] are used here. Together with multiple load cycle biaxial tests, this allows to check possible load history dependencies for different mechanical properties of the stress-strain paths.

## 2. Materials and methods

Biaxial tests were performed on a PVC-coated polyester fabric with properties given in Table 1. For the biaxial tests, cruciform tests specimens with long and slitted arms conforming to EN 17117-1 [2] were used.

Three load protocols with different load histories were developed, see Figure 1 and Figure 2. Their main characteristic is that different stress ratios warp:fill are performed in different load blocks, with each load block containing 20 load cycles. The number of 20 load cycles in each block was chosen to achieve information on the mechanical saturation behaviour. More than 20 load cycles were assumed to be unnecessary, see [14]. Block 1 naturally has no pre-history. In contrast, block 2 has the load cycles of block 1 as pre-history. With load protocol 1.1, data on stress ratio 1:0.5 without previous load history is available from block 1 and data on the reciprocal stress ratio 0.5:1 from block 2 with 20 load cycles of 1:0.5 as previous load history. However, stress-strain data for stress ratio 0.5:1 without previous load history is available from load protocol 1.2 and subsequently also for stress ratio 1:0.5 with previous load history. The same applies for load protocol 2.1 and 2.2, performing stress ratio 1:0.25 and the reciprocal stress ratio 0.25:1. The reason why the reciprocal stress ratio is chosen as the counterpart is the assumption that this has the highest impact on the yarn crimp and thus would lead to a clear appearance of load history dependency if it exists at all. Subsequently to block 2, a hold time on full stress is scheduled followed by another load cycle in block 2v. Block 2v provides stress-strain data after viscous effects have faded. This can give a hint in how far the saturation behaviour depends on the load rate. Block 3 delivers stress-strain data in stress ratio 1:1, with different pre-histories. Load protocol 3, see Figure 2, is established to get information on stress ratio 1:1 without previous load history. It is combined with stress ratio 1:0.5 from which it was known from previous biaxial tests that it is oftentimes difficult to interpret due to fill stress-strain data fluctuating around zero strain.

Stress ratios 1:0.25 and the reciprocal value 0.25:1 are used instead of the typically used pure monoaxial stress ratios 1:0 and 0:1 because they are assumed to reflect more realistic the stress ratios in real structures.

The load rate is chosen high with 1.0 kN/m/s to enable short tests.

Table 1: Basic characteristics of the investigated fabric

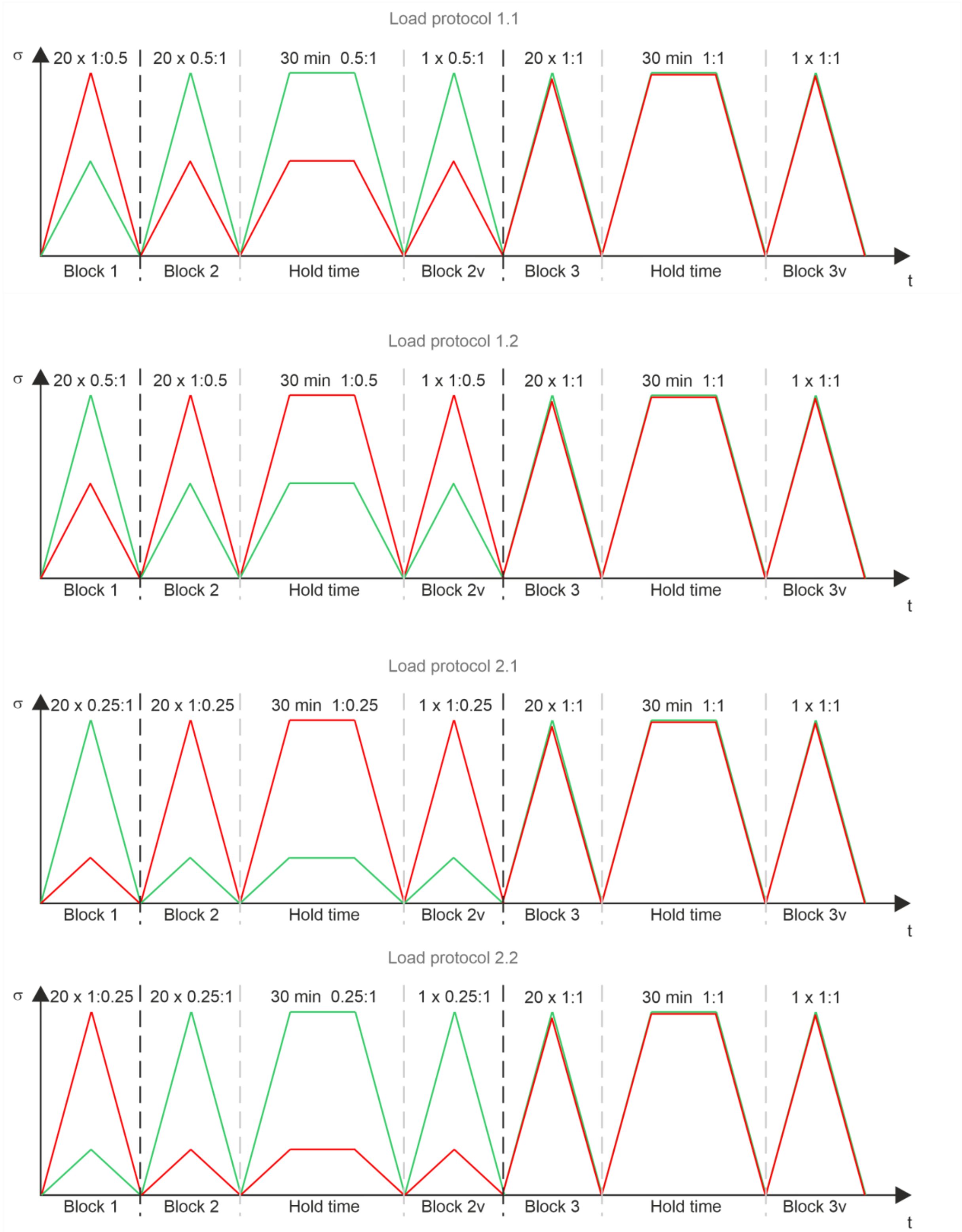
| Property | Standard/Reference | Specified Values | Unit |
|---|---|---|---|
| Tensile strength (warp/fill) | EN ISO 1421 | 116 / 108* | kN/m |
| Type | PD CEN/TS 19102 | III | - |
| Weave | - | Panama 2/2 | - |
| Total weight | EN ISO 2286-2 | 1200* | g/m$^2$ |

* according to product data sheet

Three single tests were performed for each load protocol, i. e. 15 biaxial tests in total. The analysis of the recorded stress-strain data in each load cycle was carried out using the method stated in [13]. Herewith, three main characteristics of a stress-strain curve are determined. These are: total strain increment $\Delta\varepsilon_{tot}$ after loading, the irreversible strain increment $\Delta\varepsilon_{irr}$ after unloading and the curve's measure of nonlinearity $\eta$. These three inspection characteristics are illustrated in Figure 3.

Each inspection characteristic is evaluated for every load cycle. With this, the development of the inspection characteristic can be plotted against the load cycle number. The developments of a characteristic for the cases "without load history" and "with load history" are compared to each other. With three tests each, the deviations can be recognized and assessed. If the scattering bands are clearly differentiated from each other and do not overlap, it can be stated that the behaviour is different in the state "without load history" from the state "with load history". However, if the scattering bands clearly overlap, it can be stated that there is no load history dependency.

The experimental data are fitted by polynomial asymptotic functions of the 4$^{th}$ degree, see also [13]. This allows extrapolation of the data.




Block 1: Starting test ratio, naturally without preliminary load history
Block 2: Reciprocal stress ratio, with block 1 as preliminary load history
Block 2v: as block 2, after elimination of viscosity
Block 3: stress ratio 1:1, with preliminary load history
Block 3v: as Block 3, after elimination of viscosity

Figure 1: Load protocols with uneven stress ratios in load block 1

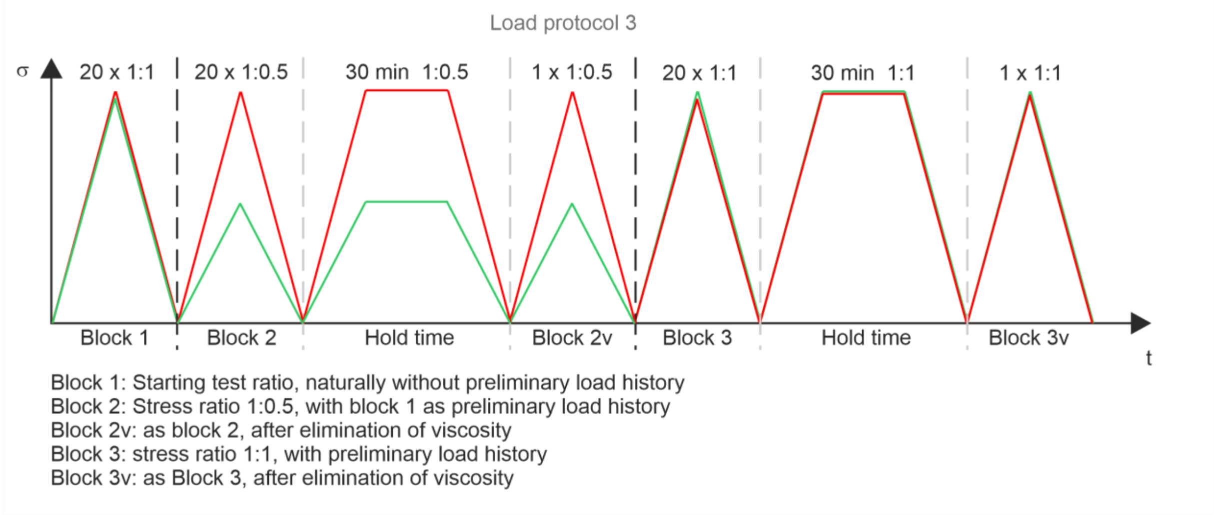



Figure 2: Load protocol with stress ratio 1:1 in load block 1

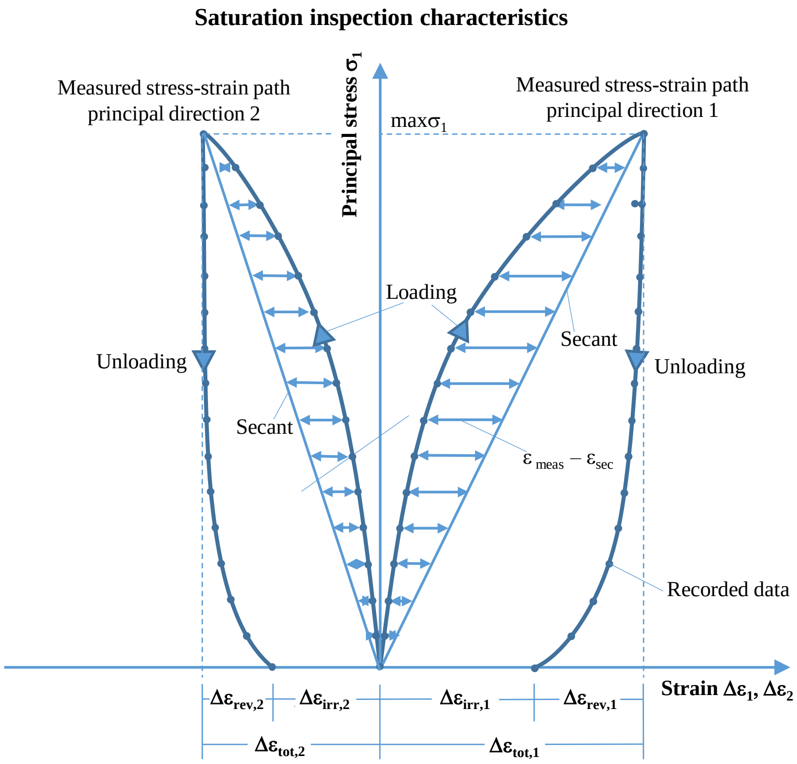



Figure 3: Saturation inspection characteristics ($\Delta\varepsilon_{irr}$: irreversible strain increment, $\Delta\varepsilon_{rev}$: reversible strain increment, $\Delta\varepsilon_{tot}$: total strain increment, $\varepsilon_{meas}$: measured strain, $\varepsilon_{sec}$: claculated strain along the sceant)

## 3. Experimental results and discussion

Assessing characteristic-load cycles diagrams, firstly, it becomes obvious that they start with particularly high values in load cycle 1 which subsequently drop down to smaller values and saturate at a low level. This can also occur in reverse: They start with particularly low values in load cycle 1 which subsequently rise to higher values, saturating there. A very typical development is shown in Figure 4 for the inspection characteristic $\Delta\varepsilon_{irr}$. This behaviour can be described by asymptotic functions. All following diagrams show the measured experimental data “without history” as the reference and comparatively “with history”. Moreover, the best fitting asymptotic path is shown, respectively. The asymptotic function allows an extrapolation beyond load cycle 20.

For all investigated stress ratios, the inspection characteristic irreversible strain $\Delta\varepsilon_{irr}$ changes fast after load cycle 1 and after a few load cycles it approaches zero. Figure 4 shows the behaviour for stress ratio 0.25:1 as an example. This means, that in all cases there is quickly no further increase in irreversible strain. The comparison of the paths without load history and with load history shows no noteworthy differences. This clearly indicates that there is no load history dependency regarding the inspection characteristic irreversible strain $\Delta\varepsilon_{irr}$ as the first investigated mechanical property.

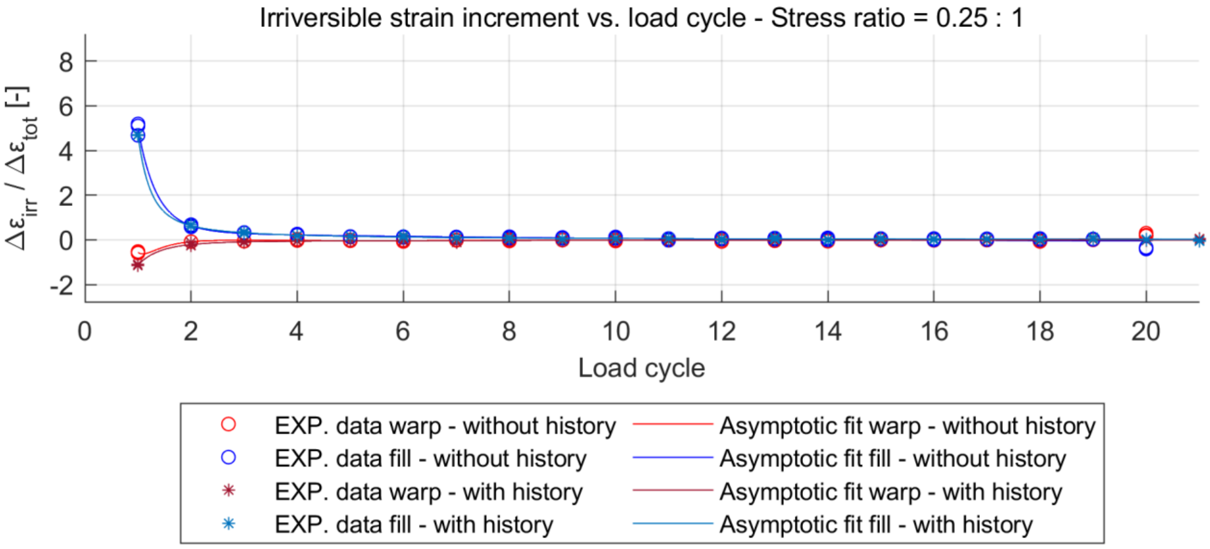



Figure 4: Inspection characteristic irreversible strain $\Delta\varepsilon_{irr}$ under stress ratio 0.25:1

For the characteristics total strain $\Delta\varepsilon_{tot}$ and intensity of nonlinearity $\eta$, the interpretation is not always so clear. Figure 5 shows the developments for the inspection characteristic total strain $\Delta\varepsilon_{tot}$ for fill direction under stress ratio 1:1. They look similar for warp direction as well as for the inspection characteristic intensity of nonlinearity $\eta$ in both directions warp and fill. Independent of the differences in load cycle 1 the values approach the reference without load history. The process is fast, it needs only a few load cycles. It is the same for all investigated preliminary load histories. Herewith, one can draw the following interim conclusion: The response of the investigated polyester fabric in the different investigated mechanical characteristics under stress ratio 1:1 is fully independently of the pre-history. This confirms the findings of *Galliot & Luchsinger* [9]. Moreover, it justifies – at least for the investigated polyester-PVC fabric – the use of stress ratio 1:1 as an intermediate rearranging stress ratio in a biaxial load protocol. Apperently, the weave geometry can be rearranged by three to four load cycles under stress ratio 1:1.

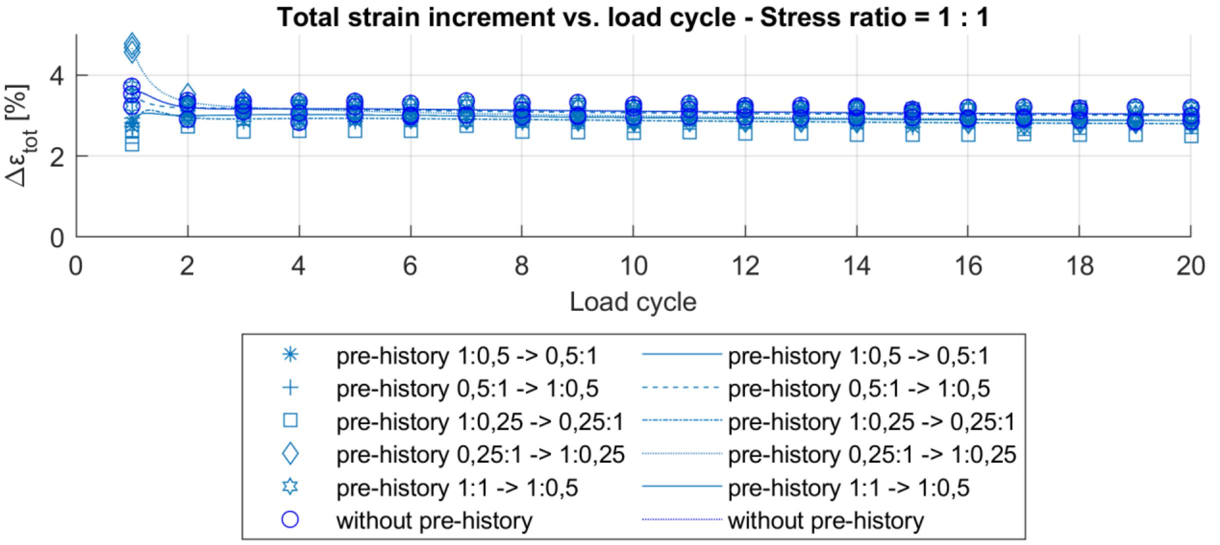



Figure 5: Inspection characteristic total strain $\Delta\varepsilon_{tot}$ for fill direction under stress ratio 1:1

The total strain behaviour under stress ratio 0.25:1 is an example of partial load history dependency, see Figure 6. In warp direction no overlapping of the scattering ranges occur. The experimental data with load history can be clearly separated from the data without load history. Using the found asymptotic fits, the behaviour can be extrapolated until load cycle n = ∞ where a relative difference in total strain of roughly 40% is observed. The difference occurs at small strains ($\varepsilon_{tot,\infty}$ = -0,59 % at reference $\varepsilon_{tot,\infty}$ = -0,92 %), so that the absolute difference is small. This could mean that the impact on structural analysis results is rather moderate. However, this must be checked in future in parametric studies. In fill direction, the experimental data overlaps beginning at load cycle 2. This means that from this early stage on, the load history dependency is eliminated. As the reason for this behaviour, it is assumed that compared to the warp yarns the fill yarns are strongly pulled under stress ratio 0.25:1. Unhindered by the warp yarns, the fill yarn crimp is largely reduced to a minimum, independent of previous load incidents.

It is interesting to see that the same thing happens in reverse for the reciprocal stress ratio 1:0.25. Here load history dependency with a relative difference of 23% at n = ∞ is observed in fill direction while none is recognized in warp direction.

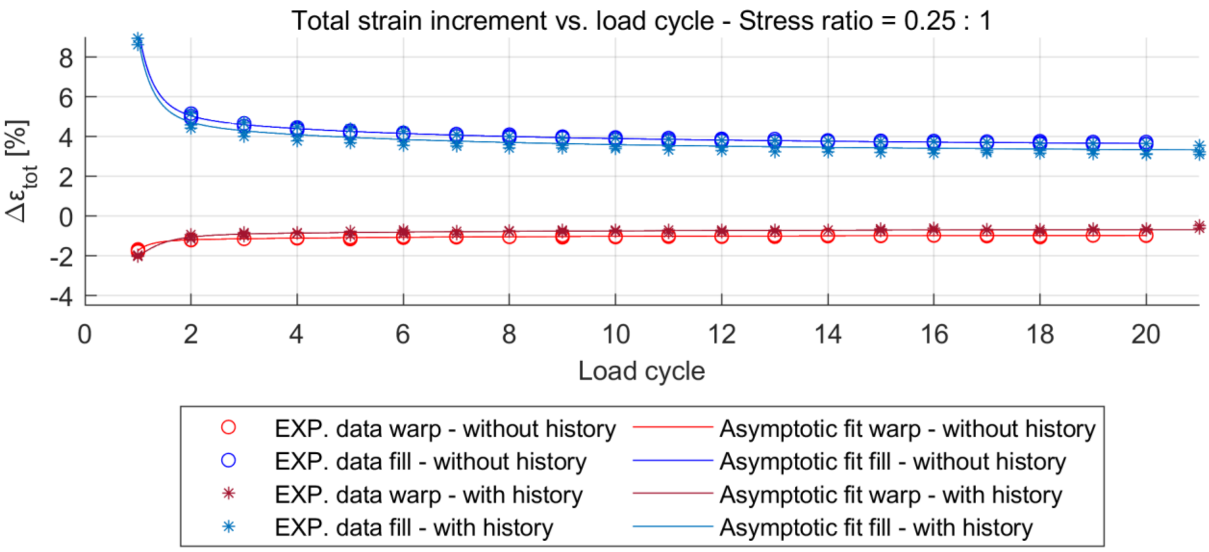



Figure 6: Inspection characteristic total strain $\Delta\varepsilon_{tot}$ under stress ratio 0.25:1

For stress ratio 0.5:1, weak load history dependencies are observed, see Figure 7. In the saturated state in warp direction a minimal fluctuation of the total strain around zero is recognized. In fill direction the asymptotic fit is clearly lower in all load cycles. But looking at the experimental data shows an overlapping of scattering ranges in some load cycles beginning at load cycle 6. Thus, no clear load history dependency can be stated.

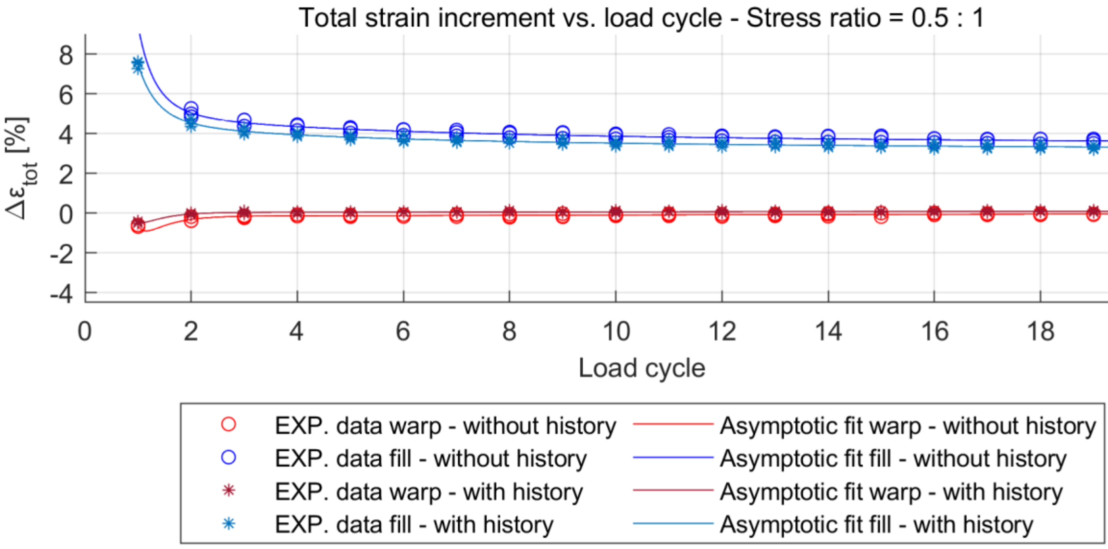



Figure 7: Inspection characteristic total strain $\varepsilon_{tot}$ under stress ratio 0.5:1

For stress ratio 1:0.5, see Figure 8, overlapping of the scattering ranges is observed in warp after two load cycles and in fill after 10 load cycles.

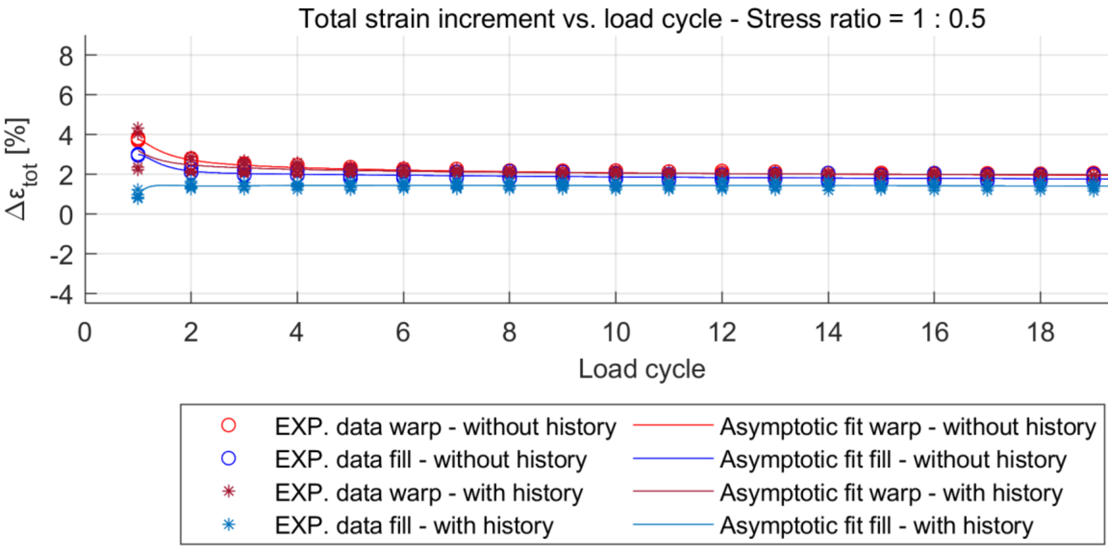



Figure 8: Inspection characteristic total strain $\varepsilon_{tot}$ under stress ratio 1:0.5

Regarding the intensity of nonlinearity of the stress-strain paths, load history dependency can mostly be clearly denied. At early load cycles, latest at load cycle 4, an overlapping of the experimental data can be observed. Sometimes the asymptotic fit curves are not close together in every load cycle, see Figure 9 depicting stress ratio 1:0.5 as an example. However, the scattering ranges overlap in this example beginning at load cycle 2 so that load history dependency cannot be recognized at any time.

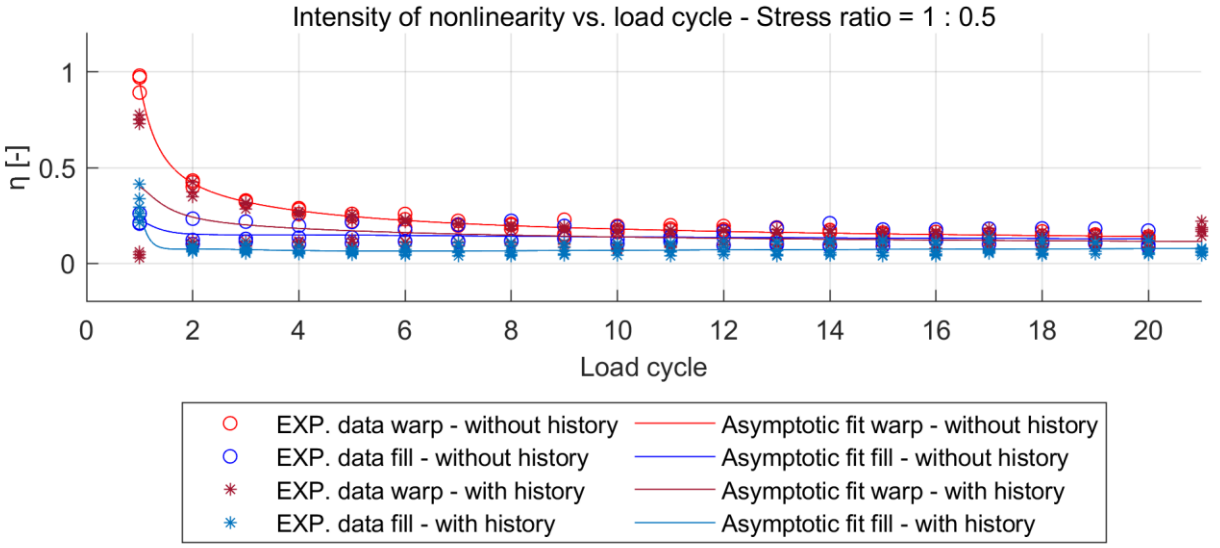



Figure 9: Inspection characteristic intensity of nonlinearity η under stress ratio 1:0.5

Overall, in cases where a load history dependency could be eliminated by load cycling, this occurs not later than load cycle 10, mostly much earlier between load cycle 2 and 4.

Over all, it can be deduced that as soon as a significant force occurs in a yarn, it is forced into the crimp geometry associated with the stress ratio, no matter if the yarn experienced a previous load history or not. This happens independent of the orthogonal yarn. This can be seen particularly at stress ratio 1:1 where the high force in orthogonal yarns do not hinder yarns to get to their geometry belonging to the stress ratio. This may be the case due to small crimp interchange of PES-PVC fabrics compared to e. g. glass-PTFE fabrics. The reason for the lower crimp interchange is possibly that glass fibre fabrics are usually woven as plain weave whereas many PES-PVC fabrics such as the one investigated here is woven as Panama weave 2:2. The latter is characterized by less yarn crimp. Significant load history dependency was only found in the lower stress direction in the pronouncedly uneven stress ratios 1:0.25 and 0.25:1.

The high load rate has no significant influence on the results. This can be seen from the data shown in load cycle 21 in the diagrams. This is the load cycle after the hold time in which creep could occur. The data are in the same range as the data before.

## 4. Conclusions and outlook

The present paper gives some insights in investigations in how far measured stress-strain data in biaxial tests depend on the order of loads in the test protocol. The investigation was conducted for a PVC-coated polyester fabric, woven with Panama 2/2. The test protocols were designed to deliver stress-strain data for the typical stress ratios (only uniaxial stress ratios were replaced by the more realistic stress ratios 1:0.25 and 0:25:1) without previous load history (reference state) and with previous load history. Twenty load cycles each were performed and the development of the mechanical characteristics total strain, irreversible strain and nonlinearity of the stress-strain paths were evaluated.

No load history dependency was observed in the developments regarding the irreversible strain after unloading as well as the intensity of nonlinearity of the stress-strain paths.

Beyond the results of [8], [9], [10], it was found for the total strain in the weaker pulled directions in stress ratios 1:0.25 and 0.25:1 as well 0.5:1 that a small to moderate load history dependency exists which could not be eliminated by multiple load cycling. Future parametric structural analyses must show how big the impact of this phenomenon is on the analysis results. In case it is relevant, biaxial load protocols have to be developed that consider the load history dependency.

## Acknowledgements

The authors wish to express thanks for the funding of this research by the Deutsche Forschungsgemeinschaft (DFG – German Science Foundation) in the framework of the research project „Characterization and modelling of the nonlinear material behaviour of coated fabrics for textile architecture“ (project No. 278626677, GZ STR 482/5-2).

## References

[1] B. Bridgens, P. Gosling, M. Birchall. Membrane material behaviour: concepts, practice and developments, *Structural Engineer*, vol. 82, pp. 28-33, 2004.

[2] EN 17117-1:2018. Rubber or plastics-coated fabrics – Mechanical test methods under biaxial stress states – Part 1: Tensile stiffness properties.

[3] MSAJ/M-02-1995. Membrane Structures Association of Japan, Testing Method for Elastic Constants of Membrane Materials, 1995.

[4] T. D. Dinh, A. Rezaei, L. de Laet, M. Mollaert, D. van Hemelrijck, W. van Paepegem. A new elasto-plastic material model for coated fabric, *Engineering Structures,* vol. 71, pp. 222-233, 2014.

[5] J. Xu, Y. Zhang, Q. Yu, L. Zhang. Analysis and design of fabric membrane structures: A systematic review on material and structural performance, *Thin-Walled Structures*, vol. 170, 108619, 2022.

[6] S. Xue, F. Yan, G. Sun. Mechanical properties of coated fabric membranes at high temperature, Journal of Engineered Fibers and Fabrics, vol. 17, 155892502211013, 2022.

[7] B. Forster, M. Mollaert (Eds.). *European design guide for tensile surface structures*, TensiNet Association, Brussels, 2004.

[8] M. van Craenenbroeck, S. Puystiens, L. de Laet, D. van Hemelrijck, M. Mollaert. Biaxial testing of fabric materials and deriving their material properties – A quantitative study, in: International Association for Shell and Spatial Structures, Proceedings of the IASS Symposium, 2015.

[9] C. Galliot, R. H. Luchsinger. Determination of the response of coated fabrics under biaxial stress: comparison between different test procedures, in: E. Oñate, B. Kröplin, K.U. Bletzinger (Eds.). International Conference on Textile Composites and Inflatable Structures V: STRUCTURAL MEMBRANES 2011, pp. 636–647.

[10] M. van Craenenbroeck, M. Mollaert, L. de Laet. The influence of test conditions and mathematical assumptions on biaxial material parameters of fabrics, Engineering Structures, vol. 200, 109691, 2019.

[11] M. van Craenenbroeck. *Biaxial testing of fabrics: Test methodologies and their impact on material parameters and the structural design process*. PhD Thesis, Vrije Universiteit Brussels, Belgium, 2016.

[12] J. Uhlemann, N. Stranghöner. Does the stress-strain behaviour of PTFE-coated glass fibre fabrics depend on the load history?, in: C. Lazaro, R. Rossi, R. Wüchner (Eds.). XI International Conference on Textile Composites and Inflatable Structures, STRUCTURAL MEMBRANES 2023.

[13] J. Uhlemann, F. Surholt, A. Westerhoff, N. Stranghöner, M. Motevalli, D. Balzani. Saturation of the stress-strain behaviour of architectural fabrics, *Materials & Design*, vol. 191, 108584, 2020.

[14] M. Motevalli, J. Uhlemann, N. Stranghöner, D. Balzani. The Elastic Share of Inelastic Stress–Strain Paths of Woven Fabrics, *Materials* 2020;13:4243.