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MECHANICAL SATURATION OF COMMON ARCHITECTURAL COATED FABRICS

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Summary. *Architectural coated fabrics, which are mainly woven textiles made from polyester or glass fibre yarns, are known to exhibit a nonlinear and viscoplastic stress-strain behaviour. The behaviour changes with the number of load cycles applied. Changes concern global slope and degree of nonlinearity of stress-strain paths and the magnitude of remaining irreversible strain after unloading. These changes are significant in the first load cycles and decline rapidly in the following ones. This shows an increasing mechanical saturation to a mainly elastic behaviour. However, some of the changes of the mechanical properties do not come to a halt. Only close to infinity they approach an invariable, mechanically saturated state. Nonetheless, in a state acceptably close to the ideal saturated state, the stress–strain paths reveal well the elastic share of the initially inelastic stress–strain paths of woven fabrics.*

This contribution investigates the number of load cycles required to achieve a mechanically saturated state by means of monotonous cyclic biaxial tensile tests on PVC-coated polyester fabrics and PTFE-coated glass fibre fabrics. It is found that irreversible strain increments decrease fast to low constant levels with low scatter after approximately a dozen load cycles. In contrast to that, other properties like the global slope or nonlinearity of the stress-strain paths saturate only after a number of load cycles of several orders of magnitude more than those for the irreversible strain. Changes of the stiffness parameters in late cycles are slow but can be considerably compared to early ones. For instance, the elastic moduli in load cycle 1000 can be roughly twice as high as the ones of load cycle 5.

1 INTRODUCTION

Coated architectural fabrics show a distinct nonlinear and viscoelasto-plastic material response under tension forces. However, it is well known that under cyclic loading irreversible strain after unloading decreases, changes of the nonlinear form of both loading and unloading stress-strain paths appear, stiffness increases etc.[1,2]. These processes slow down cycle by cycle. The material tends to mechanically saturate.

Different approaches were made to model material nonlinearity and viscoelasto-plastic effects in both principal directions of the fabric, i.e., warp and fill, and additionally to integrate shear stiffness[3-8]. However, they are usually costly to handle and focus on specific aspects and time scales of the material response of coated fabrics. None are well-established in design practice by now and available in commercial software and thus it is common to perform simplified linear elastic structural analyses of fabric structures. For viscoelasto-plastic materials like coated fabrics it means that the elastic share of the material response has to be separated from the viscoelastic and plastic share. This is the basis for accurate modelling with elastic models on the one hand and viscoelasto-plastic models on the other hand.

Up to now, criteria are missing to assess whether a fabric after cyclic loading becomes sufficiently saturated or not. Early publications suggested that a couple of load cycles are appropriate[1,2,9]. Usually, three to five load cycles are generally used in commercial biaxial testing of architectural fabrics[10-14]. But cyclic tests by Yingying et al.[15] and own cyclic tests with 50 load cycles[16] indicate that up to this number, stiffness parameters have indeed slowed down considerably but are not fully settled.

This paper summarizes latest findings on the saturation behaviour of coated architectural fabrics first presented in Uhlemann et al.[17] and Motevalli et al.[18]. A procedure for saturation tests and their interpretation is developed enabling an assessment of the mechanical saturation behaviour based on objective criteria. The detailed saturation analysis presented in this contribution reveals that many thousands of load cycles are required to saturate coated architectural fabrics so that the deviation from full saturation reached in infinity becomes acceptably small. This is impractical for daily material testing. Nevertheless, to be able to estimate the saturated state, an extrapolation function developed by Motevalli et al.[18] can be used. With this, the saturated state can be achieved by extrapolation of test data from early load cycles.

The findings are assumed to facilitate the further development of elastic and viscoelasto-plastic material models. The presented saturation analysis together with the mentioned extrapolation function will serve these demanded advancements.

2 MATERIAL PROPERTIES AND EXPERIMENTAL METHODS

Saturation tests have been conducted for two different types of architectural fabrics: PVC-coated polyester fabric (PES-PVC) and PTFE-coated glass fibre fabric (glass-PTFE). The basic properties of the fabrics investigated here are shown in Table 1.

Saturation tests have been performed with 1000 load cycles each. The usual five different stress ratios warp:fill defined in MSAJ/M-02-1995[10] have been investigated, namely 1:1, 2:1, 1:2, 1:0 and 0:1, each one with a new test specimen. The maximum stress has been ¼ of the tensile strength representing the typically usable service stress range. The minimum stress was close to zero. All tests have been performed on the two biaxial test rigs available in the Essen Laboratory for Lightweight Structures (ELLF), part of the Institute for Metal and Lightweight Structures at the University of Duisburg-Essen. Both rigs comply with EN 17117-1[11], Annex A.4.

Table 1: Basic properties of the investigated fabrics

Material	Property	Standard/Reference	Specified Value	Unit
PES-PVC	Tensile Strength f_t (warp/fill)	DIN EN ISO 1421	130/114	kN/m
	Type	(1)	III	-
	Weave	-	P1/1	-
	Total weight	Din EN ISO 2286-1	1200	g/m^2
Glas-PTFE	Tensile Strength f_t (warp/fill)	DIN EN ISO 1421	140/120	kN/m
	Type	(1)	III	-
	Weave	-	L1/1	-
	Total weight	Din EN ISO 2286-1	1150	g/m^2
(1) According to the proposed harmonization in [prCEN/TS 19102]				

The plane cross-shaped test specimens are characterized by long arms. Close to the 200 mm^2 central measurement field, they are slit parallel to the arm length. The slits provide a homogeneous strain field in the center region. Orthogonal forces are applied to the arms in warp and fill direction via hydraulic actors. In-plane deformation and strain are measured contactless with a high precision one-camera optical system tracing four markers placed at the corners of a 100 mm^2 square within the measurement area[19]. The measurement uncertainty is in the magnitude of 10 µm. For the present investigation, this is a minimum factor of 20 lower than the measured variables and is thus neglected in the interpretation of the results. The loading rate is 15 kN/m min. Thus, the duration of each test was several days.

3 SATURATED ELASTIC STATE

The saturation analysis of both fabrics is performed using the method proposed in Uhlemann et al.[17]. It is based on the evaluation of three different properties, called inspection characteristics in the following:

1. Irreversible strain increment $\Delta\varepsilon_{irr}$,
2. Total strain increment $\Delta\varepsilon_{tot}$,
3. Intensity of nonlinearity η.

The interpretation of all three together enables the evaluation of how close a material comes to the fully saturated state and thus to elasticity and when this happens. Figure 1 illustrates how the inspection characteristics are evaluated from the recorded stress-strain data of each load cycle. The inspection characteristics are determined for both principal directions 1 and 2, with principal direction 1 being the direction subjected to the major stress of a given stress ratio, except in the even biaxial stress ratio 1:1 where principal direction 1 equals warp direction by definition. The intensity of nonlinearity is computed as a usual least squares approach summing up differences between measured strain and secant. The total strain is an indicator of the overall slope of the ascending part of a stress-strain path. The lower the total strain, the higher is the stiffness. Ideal elasticity is present when

(a) the irreversible strain increment converged to zero and

(b) the total strain increment and
(c) the intensity of nonlinearity converged against constant values.

It has been shown by Uhlemann et al.[17] that the curve progressions can be fitted well with an asymptotic polynomial function of the form

$$y(i) = a + \frac{b}{i} + \frac{c}{i^2} + \frac{d}{i^3} + \frac{f}{i^4} + \frac{g}{i^{1/2}} \tag{1}$$

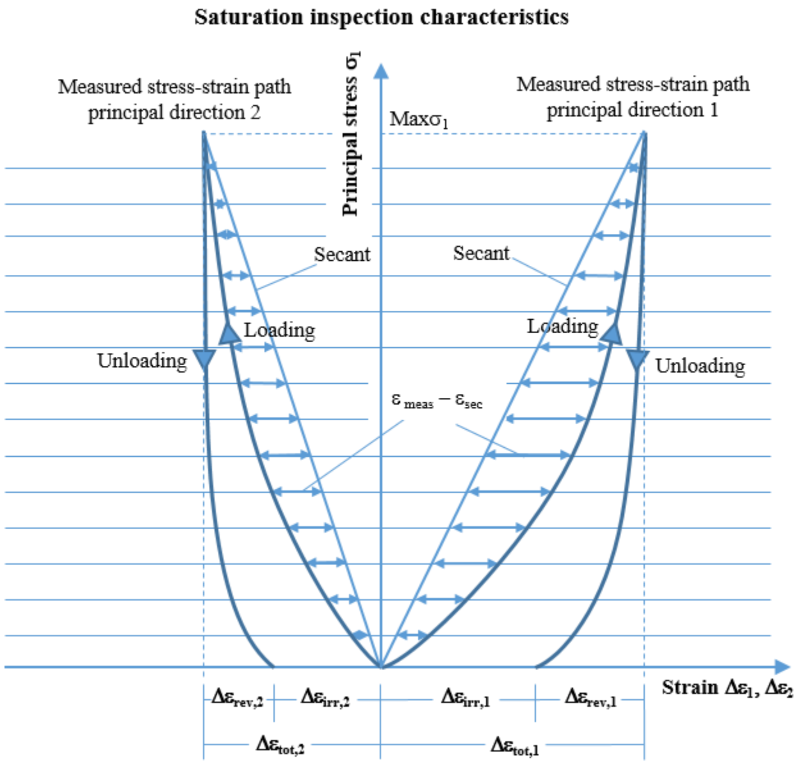

Figure 1: Saturation inspection characteristics, illustrated at normalized stress–strain paths in principal directions 1 and 2.

The curve progressions slowly approach the calculated asymptotes. The saturated state has been defined to be achieved when the irreversible strain increment becomes smaller than 1% of the total strain increment in the same load cycle and when additionally, the total strain increment and the intensity of nonlinearity approximate “their” asymptotes of the fitted progression functions with an acceptable error of less than 3%. The defined requirement of the irreversible strain increments being smaller than 1% of the total strain increment fits to observations of the material behaviour – it usually comes down to 1% – and also matches structural requirements. Regarding the limit definition of the other two inspection characteristics, a maximum deviation of up to 3% is acceptable from the authors’ point of view and could reasonably be covered by safety factors in the structural design. A stricter definition could be applied by the user. It would result in much higher load cycle numbers required to obtain the saturated state.

4 RESULTS AND DISCUSSION

Figure 2 shows as an example of recorded stress-strain paths of the investigated PES-PVC material for load cycles 1, 3 and 1000.

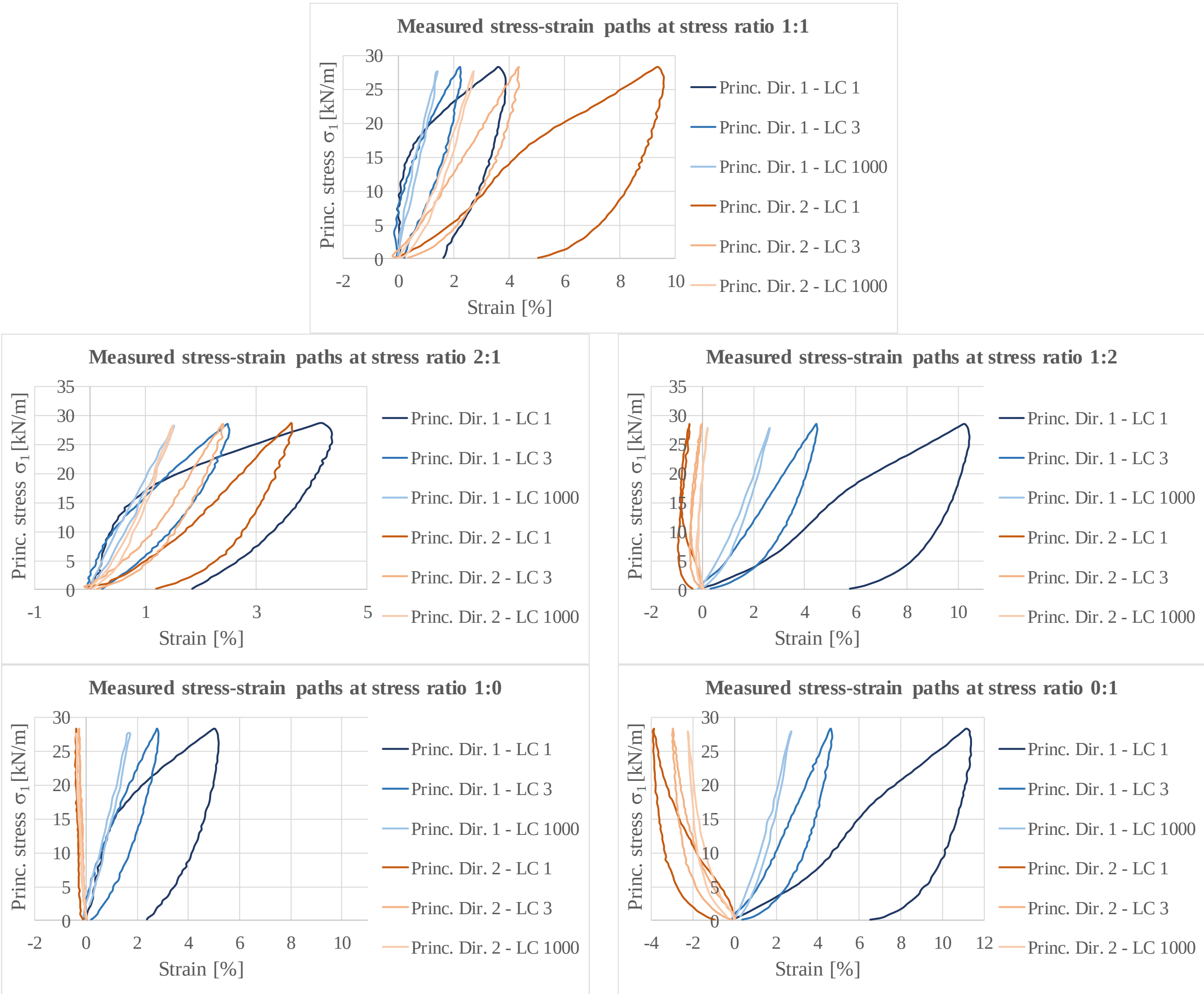

Figure 2: Measured stress-strain paths for load cycles 1, 3 and 1000 for the investigated PES-PVC fabric for all five tested stress ratios

Note that all curves are plotted against the principal stress σ_1 to avoid that the "zero-stress paths" in the monoaxial stress ratios would appear just as horizontal lines on the x-axis. It can be seen that the intensity of nonlinearity, the amount of irreversible strain as well as the overall slope of the ascending part of the paths is considerably different between the three load cycles. Only the progress of irreversible strain occurs to be small from load cycle 3 to 1000. In load cycle 1000, the stress-strain paths appear to be steep, almost elastic – and also almost linear.

However, both investigated fabrics did not reach the defined saturated state within the tested 1000 load cycles. The required number of load cycles to reach the defined saturated state has been computed with eq. (1). The results are plotted in Table 2. Many of the numbers are far beyond a few dozens, which happens to be impractically high for daily commercial biaxial testing. Apparently, it is not reasonable from a technical and financial point of view to perform saturation tests with such high numbers of load cycles in the frame of a design project. These extremely high numbers also mean for a real fabric structure that the fabric material would never completely saturate under natural loading.

Table 2: Saturated state load cycles for the investigated fabrics

Material	Stress Ratio Warp:Fill	Principal Direction	Hypothetical Computed Saturated State Load Cycle* for		
			Irr. Strain Increment	Total Strain Increment	Intensity of Nonlinearity
PES-PVC Type III	1:1	1 (warp)	6	2805	65,602
		2 (fill)	13	10,247	100
	2:1	1 (warp)	18	7,525	34,861
		2 (fill)	-	15,857	5,023
	1:2	1 (fill)	15	11,426	15,782
		2 (warp)	-	24,235	136,836
	1:0	1 (warp)	8	6,179	6,639
		2 (fill)	-	100	205,938
	0:1	1 (fill)	15	19,144	60,257
		2 (warp)	6	10,754	11,131
Glas-PTFE Type III	1:1	1 (warp)	4	17,999	8,378,928
		2 (fill)	9	16,161	968,343
	2:1	1 (warp)	11	50	432,654
		2 (fill)	10	27,318	6,230
	1:2	1 (fill)	14	18,193	51,811
		2 (warp)	12	104,124	5,183
	1:0	1 (warp)	9	10,920	20,472
		2 (fill)	10	340	6,879
	0:1	1 (fill)	9	30,893	75,419
		2 (warp)	12	5,093	50
* Given saturated state load cycles are computed based on eq. (1) and are not experimentally verified					

In three cases for the PES-PVC, the saturated state definition is not reached in principal direction 2, see Table 2. This happens when the irreversible strain stabilizes above the defined limit value. In the mentioned exceptions it actually occurs for the stress ratios 1:0 and 1:2 that the absolute values of the total strain increment are small and thus also the absolute values of the irreversible strain increments are very small. Due to this small magnitude of irreversible strain it is justified to handle such material behaviour as elastic.

Curve progressions of the inspection characteristics plotted against load cycle numbers are shown in Figure 3 to Figure 5. As examples, they are illustrated for the tested biaxial stress states and principal direction 1.

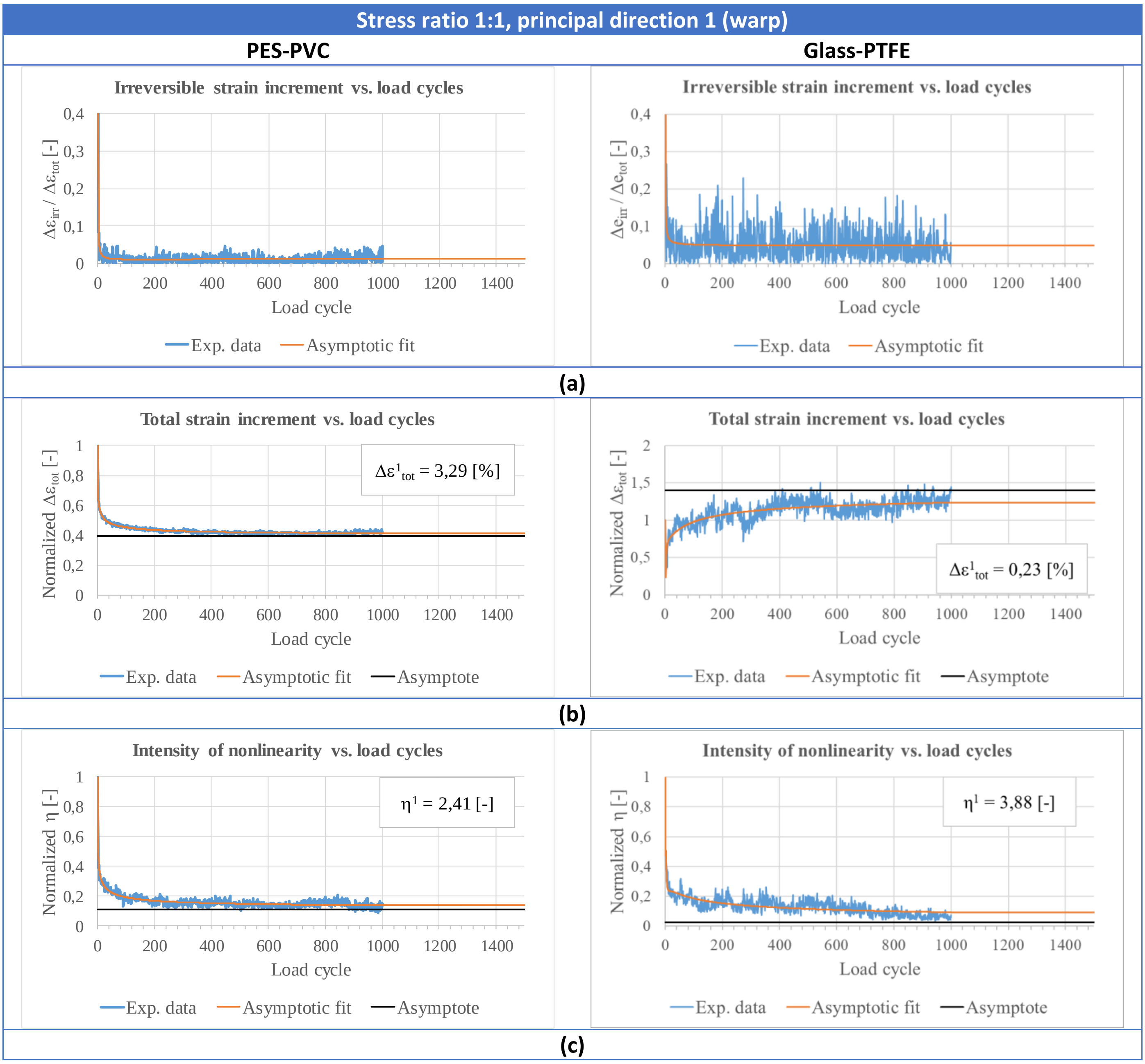

Figure 3: Curves of the inspection characteristics in principal direction 1 for uniform biaxial stress (1:1): (a) irreversible strain increment vs. load cycles, (b) total strain increment vs. load cycles, (c) intensity of nonlinearity vs. load cycles.

The irreversible strain increment is given in relation to the total strain in each load cycle. For the inspection characteristics total strain increment and intensity of nonlinearity normalized values are plotted on the ordinates to focus on the progress. Nevertheless, in order to be able to estimate the order of magnitude, the initial values of load cycle 1 are plotted in the diagrams. Besides the inspection characteristics data, an asymptotic fit is illustrated with fits derived from eq. (1). They are required for the inspection characteristics total strain increment and intensity of nonlinearity because they converge slowly and not within the tested load cycles and thus have to be extrapolated.

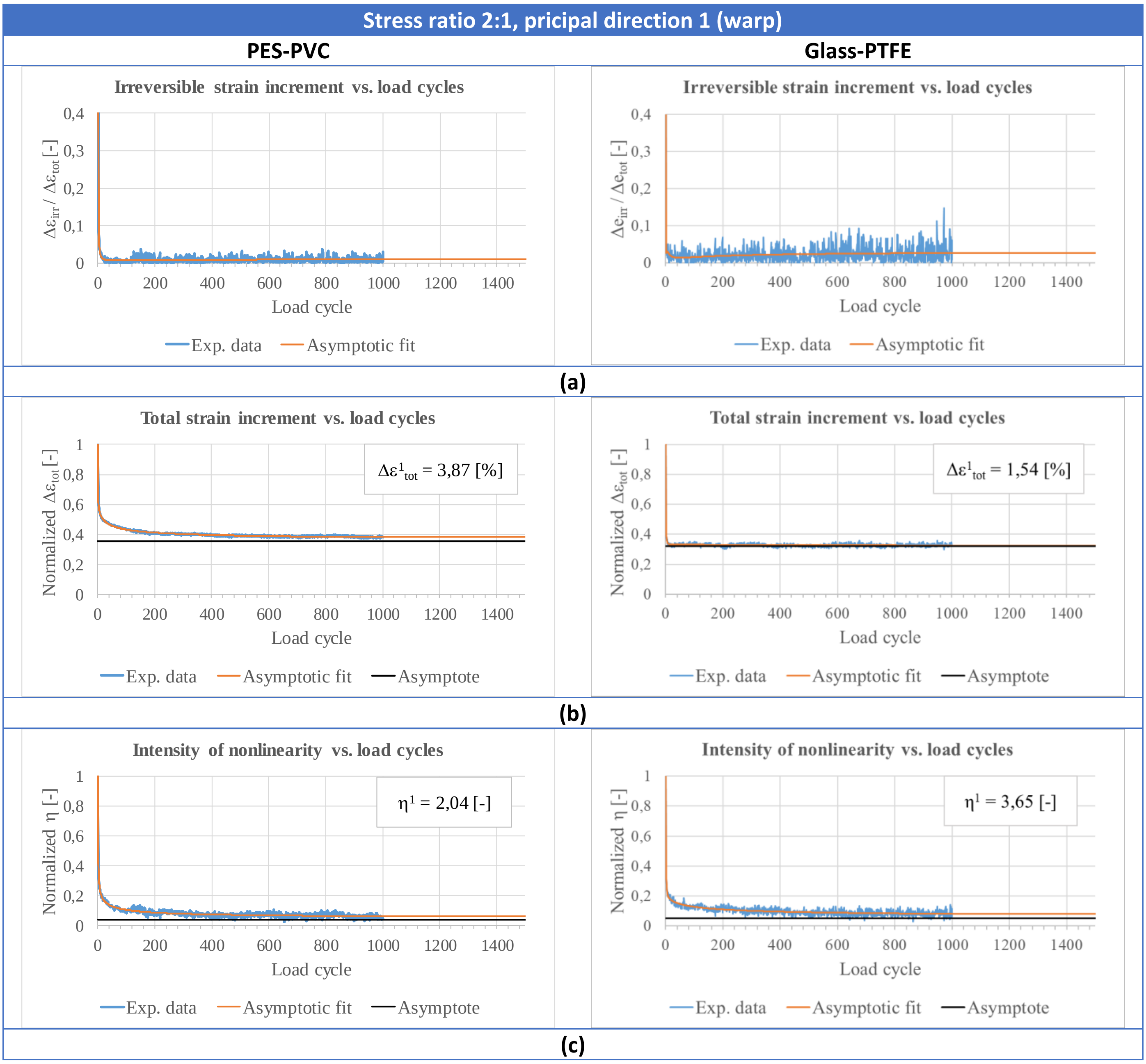

Figure 4: Curves of the inspection characteristics in principal direction 1 for stress ratio 2:1: (a) irreversible strain increment vs. load cycles, (b) total strain increment vs. load cycles, (c) intensity of nonlinearity vs. load cycles.

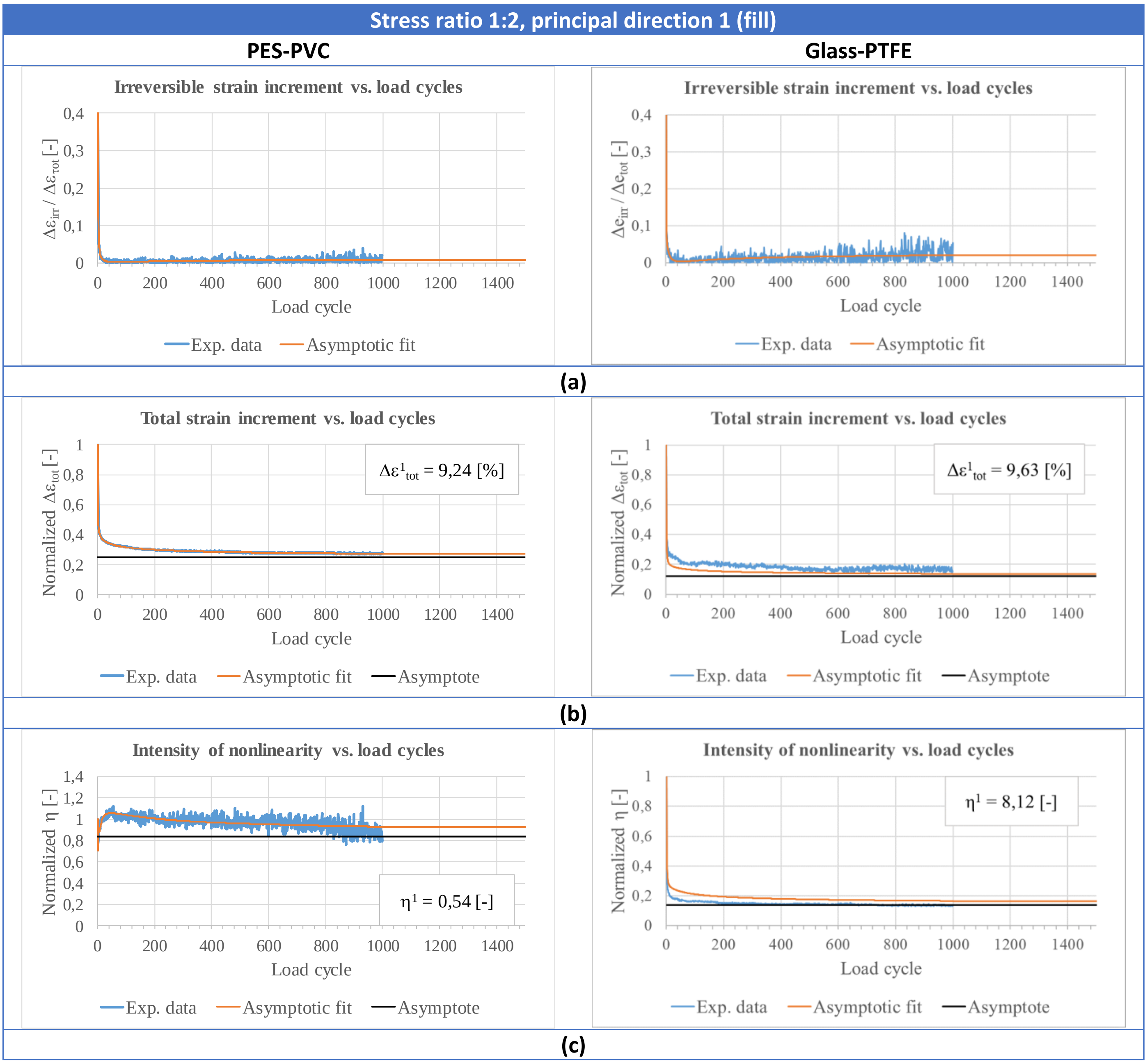

Figure 5: Curves of the inspection characteristics in principal direction 1 for stress ratio 1 :2: (a) irreversible strain increment vs. load cycles, (b) total strain increment vs. load cycles, (c) intensity of nonlinearity vs. load cycles.

Although some curves are not monotonously decreasing, the diagrams show that all inspection characteristics converge. To achieve convergence, simply enough load cycles must be carried out.

Most important for the consistency of the structural analysis with the assumption of nominal prestress in the form-found structure is that the progress of the irreversible strain increment comes to a halt. Actually, the irreversible strain increments decrease fast to low, constant levels. After approximately a dozen load cycles, there is only a low scatter left. Taking into account all investigated stress ratios, the defined drop-down limit to 1% occurred after 12±5 load cycles for the investigated PES-PVC fabric, and after 10±4 load cycles for the investigated glass-PTFE fabric.

However, to get a good impression of the elastic share of the viscoelasto-plastic material response, the stress-strain paths in the fully saturated state should be considered. Knowledge about the elastic share enables to clearly separate elastic and non-elastic shares from each other and to generate accurate input for elastic and non-elastic material models.

In contrast to that, the other two inspection characteristics saturate only after a much higher number of load cycles, being several orders of magnitude more than those for the irreversible strain, only seldomly below 1,000, oftentimes above 10,000, in single cases above 100,000.

A not monotonously decreasing progression or a comparably big scatter typically happens when the starting value of an inspection characteristic is already small. This can occur for both, the total strain increment and the intensity of nonlinearity. Then, it naturally does not come to a significant decrease, but more or less to a sideways movement in the curve progression, see e. g. the intensity of nonlinearity for the PES-PVC fabric in stress ratio 1:2 in Figure 5. Nonetheless, all curves strive against a fixed value and the saturated state can be reached in both principal directions in all loading situations. The proposed procedure proves to be able to detect the saturated response via the asymptotic curve fit.

In Motevalli et al.[18], additionally stiffness parameters have been computed for all load cycles. Although changes of stiffness parameters in late cycles progress slowly, saturated state parameters can be considerably different compared to early ones due to the huge number of load cycles required to reach the defined saturated state. To give an impression: For the investigated glass-PTFE fabric for instance, the elastic moduli in load cycle 1000 can be roughly twice as high as the ones of load cycle 5.

In Motevalli et al.[18], a function is developed to extrapolate stiffness parameters from load cycle 20 to a higher load cycle, i. e. to the saturated state load cycle. So far, the proposed method has been verified up to load cycle 1000 and showed to work well within good tolerance for the investigated fabrics. Herewith, test data only up to load cycle 20 is required, which is not expensive for experimental purposes.

6 CONCLUSIONS

Various mechanical properties of coated architectural fabrics saturate under cyclic loading, e. g. stiffness parameters, irreversible strain increments and also the nonlinear form of the stress-strain paths. The mechanical saturation behaviour of two coated architectural fabrics was experimentally investigated, a PVC-coated polyester fabric and a PTFE-coated glass fibre fabric. To assess the saturation behaviour on an objective basis, a novel saturation analysis procedure was developed and used. Three inspection characteristics and respective limit values were defined to determine a state acceptably close to the fully saturated state which turned out to be reached only in infinity. An asymptotic polynomial function was presented to fit the saturation behaviour in the various testing conditions and extrapolate it. Overall, both investigated fabrics show a saturating mechanical behaviour approaching the elastic share of the initially inelastic stress–strain paths while converting them into an elastic state. But for both fabrics many thousand load cycles are required to achieve the defined saturated state. Changes of stiffness parameters in late cycles are slow but can be considerably different compared to early ones. For instance, elastic moduli in load cycle 1000 can be roughly twice as high as the ones of load cycle 5.

The huge number of load cycles required to saturate a fabric is of course impractical for commercial biaxial testing of architectural fabrics. But with the help of the extrapolation function presented by Motevalli et al.[18], stiffness parameters of the saturated state can be estimated from test data up to load cycle 20.

The given procedure is able to recognize the elastic share from the viscoelasto-plastic stress-strain paths of coated architectural fabrics. The results presented here can serve as a fundament for future developments of elastic and inelastic material models which require knowledge about the different parts of the material response.

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