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Architectural woven fabrics: Is it possible to classify stiffness values in correlation with strength values?

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Abstract

Down to the present day, the determination of stiffness parameters for architectural fabrics, mainly used as coated woven fabrics, is a field of intense discussion. Designers and material producers are affected by an existing uncertainty. The present contribution investigates the possibility to provide tables of stiffness parameters for specific materials in which stiffness values are given dependent on the material's tensile strength. The focus is on PVC-coated polyester fabrics as the most commonly used material for textile architecture. Materials of four different material producers and of different strength classes have been tested experimentally. Stiffness parameters have been determined based on a standardized test and evaluation method and have been statistically evaluated and compared. In order to achieve a required basis, standardized and project specific biaxial test procedures are presented and analysed in combination with established evaluation procedures.

A tabulation of stiffness parameters would be of great help for design engineers and material producers. The presented results indicate the possibility of a classified tabulation for the investigated materials.

Keywords: architectural coated woven fabrics, PES/PVC fabrics, mechanical properties, stiffness parameters, biaxial test

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1. Introduction

The material behaviour of coated architectural fabrics is well known to be nonlinear, viscoelastic and usually orthogonal anisotropic (orthotropic). Due to the lack of technically mature alternative models, the actual nonlinear viscoelastic material behaviour is modelled in the design practise with a linear elastic approach. The inhomogeneous composite is idealized as a homogenous continuum, assuming a plane stress state. Besides the low shear stiffness of fabrics – which is neglected in the frame of this contribution – tensile stiffnesses E (Young's moduli) and Poisson's ratios ν in both principal directions warp and weft are used:

$$\begin{bmatrix}\varepsilon_x \\ \varepsilon_y\end{bmatrix} = \begin{bmatrix} \frac{1}{E_x} & -\frac{\nu_{xy}}{E_y} \\ -\frac{\nu_{yx}}{E_x} & \frac{1}{E_y} \end{bmatrix} \begin{bmatrix}\sigma_x \\ \sigma_y\end{bmatrix} \tag{1}$$

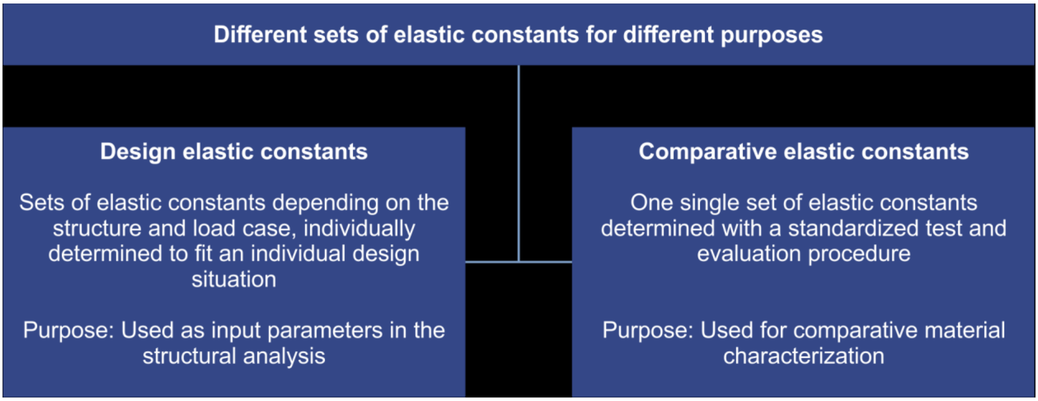
where ε is the strain and σ is the membrane stress (for fabrics given in the unit force per length [kN/m]). The compliance matrix is composed of four elastic constants. For the indices of the Poisson's ratios the following is defined: the first index indicates the direction of contraction, the second index indicates the direction of stress that causes the contraction. The x-direction refers to warp and the y-direction to weft.

The requirement for a symmetrical compliance matrix leads directly to the fact, that the terms with Poisson's ratios are identical. Herewith, only three of the four elastic constants are independent of each other. Usually, a set of elastic constants is given by the two tensile stiffnesses E_x and E_y and is completed by one Poisson's ratio. In case of anisotropy and assuming $E_x > E_y$, one will get $\nu_{yx} > \nu_{xy}$.

Different from isotropic materials, the Poisson's ratios have not to fulfil the requirement of $\nu < 0.5$. According to the theory of anisotropic elasticity, the requirement $\nu_{xy} \cdot \nu_{yx} < 1$ must be fulfilled (Lempriere, 1968). As some fabrics show huge transverse contractions, this is of great advantage.

Biaxial tensile tests are conducted on plane test specimens under in-plane stress in order to determine the stiffness parameters. The magnitude of stiffness parameters depends very much on the applied stress ratios warp:weft as well as on the stress magnitude and the load protocol, i. e. number of load cycles and whether hold times are scheduled or not etc.

Because stress ratios and stress levels for prestress and maximum stress under service loads are different for every membrane structure, stiffness parameters obtained from standardized methods cannot be used – or only as a rough approximation. Modifications or adjustments of the load protocol and/or the evaluation methods are essential and must be specified individually for each project. This leads to "design elastic constants". However, to provide the design engineer a tool with which stiffness properties of different materials can be compared, a standardized test and evaluation procedure is desired (Schmidt, 2012). This leads to "comparative elastic constants", see Figure 1.



Different sets of elastic constants for different purposes

Design elastic constants

Sets of elastic constants depending on the structure and load case, individually determined to fit an individual design situation

Purpose: Used as input parameters in the structural analysis

Comparative elastic constants

One single set of elastic constants determined with a standardized test and evaluation procedure

Purpose: Used for comparative material characterization

Figure 1: Different sets of elastic constants for different purposes

In a first step, the present contribution discusses possibilities for (a) a standardized determination of elastic constants (comparative elastic constants) and (b) individual determination methods, tailored for individual structures and load cases (design elastic constants). In a second step, it is investigated whether stiffness properties of PVC-coated polyester(PES)-fabrics can be classified. This investigation is conducted experimentally by means of random samples of strength types II, III and IV. A classification would enable a tabulation of stiffness parameters. Such a tabulation would be of great help for design engineers for appropriate assumptions of stiffness parameters as well as for material producers to support the material characterization. The present contribution is an updated version of Uhlemann & Stranghöner (2017).

2. Standardized comparative vs. design oriented stiffness parameters

In the past, several attempts tried to standardize biaxial test and evaluation methods for the determination of elastic constants of architectural fabrics (ASCE/SEI 55-10; Blum, Bögner, & Némoz, 2004; MSAJ/M-02-1995; Société d'Edition du Bâtiment et des Travaux Publics, 2009). Nevertheless, the Japanese guideline MSAJ/M-02-1995 was the only one providing a sufficient precise procedure for reproducible biaxial testing and for the evaluation of the recorded test data (Uhlemann, 2016). However, the results are rather "fictitious" elastic constants: they are a linear approach to nonlinear material behaviour and they are not able to model all measured stress-strain paths in acceptable approximations simultaneously. For a more detailed background on MSAJ/M-02-1995, see Uhlemann & Stranghöner (2017).

Recently, the novel European biaxial test standard EN 17117-1 for the determination of elastic constants for coated fabrics has been published. This standard emphasizes the importance of design elastic constants and offers principles to set up individual design oriented load protocols and evaluation procedures. Examples known from literature are listed as a first orientation. On the other hand, EN 17117-1 provides also a precisely defined load protocol and evaluation procedure to achieve reproducible comparative elastic constants. The basic features are oriented towards the Japanese guideline MSAJ/M-02-1995, e. g. the load profile consists of the three biaxial stress ratios warp:weft 1:1, 2:1 and 1:2 as well as of the two monoaxial stress ratios 1:0 and 0:1. But single weaknesses of the Japanese guideline (van Craenenbroeck et al., 2016; Uhlemann, 2016) are improved, e. g. a prestress level is considered in the load protocol and further load cycles are added so that for all stress ratios three load cycles are scheduled. For the determination of comparative elastic constants, a precise evaluation procedure is stated based on the least squares method minimizing the strain error. As comparative elastic constants are not used as input parameters in a structural analysis, they do not have to fulfil the mechanical restrictions described above, i. e. the Poisson's ratios are not limited. Thus, the measured stress-strain behaviour can be characterized more accurately and different materials that behave differently can be better distinguished.

As the linear elastic orthotropic constitutive model is not able to completely cover the fabric behaviour, i. e. acceptable modelling of all stress ratios simultaneously is impossible, it is required to determine structure and load case dependent sets of elastic constants individually. This is possible for instance by focusing on the evaluation of specific stress ratios of MSAJ- or EN 17117-1-tests. Stress ratios that are not expected to occur in a specific membrane structure or in a specific load case are disregarded in the evaluation. For instance, monoaxial stress ratios do not usually appear in synclastic structures, thus they can be disregarded in the evaluation. This method has already been intensely discussed in Uhlemann, Stranghöner, Schmidt & Saxe (2011).

Apparently, it is more appropriate to tailor the load protocol as well. This is actually demanded and performed in practise, see e. g. Stimpfle & Günther (2016). Refined methods for individual load protocol set ups and evaluation procedures are stated in Uhlemann (2016). However, all tailored methods require sufficient assumptions of the stress ratios over a membrane surface under a specific load. These assumptions can be made in the frame of a preliminary structural analysis. A sufficient preliminary structural analysis, in turn, requires appropriate start values for the stiffness parameters. The presentation of appropriate stiffness parameters fitting the basic shapes of membrane structures and the most relevant fabrics in a tabulated form would be of great help for design engineers for this task.

3. Investigations into tabulating stiffness parameters for architectural fabrics

This contribution presents comparisons of standardized stiffness parameters of PVC-coated PES fabrics types II, III and IV. Products with similar tensile strength properties of four different material producers are compared. The material producers are numbered arbitrarily in order to maintain anonymity. Only "traditionally coated" fabrics are considered here, i. e. fabrics which are prestressed in weft direction during the coating process are not included. All experimental tests have been performed in the Essen Laboratory for Lightweight Structures (ELLF), belonging to the Institute for Metal and Lightweight Structures of the University of Duisburg-Essen.

The tensile strength properties of all investigated materials have been measured at T = 23 °C according to DIN EN ISO 1421 and are given in Table 1 as mean values. The fabrics are classified according to the type classification presented in Stranghöner et al. (2016). Table 1 illustrates that the investigated materials have similar strength magnitudes when compared typewise.

Table 1: Tensile strength (mean values) and statistical data at T = 23 °C of the investigated coated fabrics of different material producers

Producer	Warp			Weft		
	Tensile strength $f_{m,23}$ [kN/m]	Standard deviation [kN/m]	Coeff. of variation [%]	Tensile strength $f_{m,23}$ [kN/m]	Standard deviation [kN/m]	Coeff. of variation [%]
PES-PVC Type II						
1	95.5	2.7	2.9	93.3	1.4	1.5
2	87.5	3.1	3.6	92.6	4.6	4.9
3	91.4	0.7	0.7	84.1	1.8	2.1
PES-PVC Type III						
1	127.3	1.2	0.9	113.6	1.3	1.2
2	129.4	1.4	1.1	120.2	2.8	2.3
3	118.9	2.1	1.8	104.1	1.6	1.5
4	123.7	5.6	4.5	107.8	4.4	4.1
PES-PVC Type IV						
1	167.4	1.3	0.8	162.0	0.8	0.5
2	167.9	2.9	1.7	160.6	3.4	2.1

Stiffness parameters have been achieved form biaxial tests and have been computed as fictitious elastic constants according to MSAJ/M-02-1995 using the least squares method minimizing the strain error. They are fitted to all five tested stress ratios simultaneously. Note, that in the original MSAJ-evaluation – as used here – the stress-strain paths of the unloaded directions in the monoaxial stress ratios are disregarded. The resulting sets of fictitious elastic constants are given in Table 2 for PES-PVC type II, in Table 3 for PES-PVC type III and Table 4 for PES-

PVC type IV. As an example, Figure 2 illustrates for all type III biaxial tests the small deviation of the evaluated stress-strain paths in the five stress ratios.

The deviation of tensile stiffness values (Young's moduli) is found to be very low. The impact of this deviation range on structural analysis results can be assumed to be negligible, see Bridgens & Birchall (2012), Uhlemann & Stranghöner (2013), Uhlemann, Stranghöner & Saxe (2015), van Craenenbroeck (2016). On the contrary, the deviations of the Poisson's ratios are higher. Nevertheless, the absolute values of the Poisson's ratios are still small, so that only a small impact is expected on structural analysis results (Uhlemann et al., 2015; Uhlemann & Stranghöner, 2013). From a practitioner's point of view, the stiffness properties appear to be independent of the material producer in this random sample. Comparing Tables 2, 3 and 4 with Table 1, a positive correlation of tensile stiffness and strength can be observed. Additionally, distinct differences of stiffness properties of types II, III and IV become obvious. The small deviations of stiffness properties – from batch to batch (Schmidt, 2012) as well as from producer to producer – indicate, that standardized stiffness properties of PES-PVC fabrics of types II, III and IV can be tabulated.

On the basis of the presented experimental investigations and statistical evaluations, a first proposal of sets of fictitious elastic constants according to MSAJ/M-02-1995 for PES-PVC fabrics types II, III and IV is presented in Table 5 based on mean values.

Basically, a classification is only possible for standardized and reproducible tests. It seems likely to carry out such a classification on the basis of the new European biaxial test standard EN 17117-1 instead of MSAJ/M-02-1995. Tabulated stiffness values according to the procedure of EN 17117-1 could serve as a first rough approximation of stiffness properties for preliminary design calculations in a European design context. However, it must be ensured that for an individual fabric structure all relevant stress-strain paths can be modelled in acceptable approximation by the tabulated sets of elastic constants and that the mechanical constraints are considered. In order to ensure safe and economic stiffness parameters, it is recommended to evaluate stiffness parameters from design oriented biaxial tests. Nonetheless, for fabrics that can be tabulated in general it is imaginable to tabulate design oriented stiffness parameters for different structural configurations. They could be tabulated depending on specific stress ratios and stress magnitudes. Herewith, the designer could directly specify appropriate stiffness parameters for the use as input parameters in the design of different shapes of membrane structures and different load situations.

Biaxial "compensation tests" – performed to measure pattern compensation values which in turn ensure a target prestress in the membrane structure – are not affected by the proposed classifications. The determination of compensation values is based on the irreversible constructional stretch of a fabric after unloading. It is well known that this measure strongly deviates from producer to producer and from batch to batch. That means, project oriented biaxial compensation tests remain inevitable.

Table 2: Sets of experimentally determined fictitious elastic constants according to MSAJ/M-02-1995 for PES-PVC fabrics type II of three different material producers

PES-PVC Type II			
Producer	Tensile stiffness		Poisson's ratio ν_{yx} [-]
	E_x [kN/m]	E_y [kN/m]	
1*	738	456	0.21
	758	534	0.17
	744	462	0.21
Mean value producer 1	747	484	0.20
2**	664	530	0.05
	720	542	0.04
Mean value producer 2	692	536	0.05
3	699	508	0.13
Statistical evaluation including all producers			
Mean value***	713	514	0.12
Standard deviation***	30	27	0.08
Coefficient of variation [%]***	4.2	5.3	62.9

* Three coating batches were available from producer 1.

** Only one coating batch was available from producer 2.

*** The statistical evaluation is based on mean values per producer, if available.

Table 3. Sets of experimentally determined fictitious elastic constants according to MSAJ/M-02-1995 for PES-PVC fabrics type III of four different material producers

PES-PVC Type III			
Producer	Tensile stiffness		Poisson’s ratio ν_{yx} [-]
	E_x [kN/m]	E_y [kN/m]	
1*	978	650	0.10
	990	662	0.10
	974	648	0.10
	972	646	0.10
Mean value producer 1	979	652	0.10
2**	972	646	0.00
	972	646	0.00
	984	658	0.00
Mean value producer 2	976	650	0.00
3	963	644	0.09
4	1060	708	0.03
Statistical evaluation including all producers			
Mean value***	994	663	0.06
Standard deviation***	44	30	0.05
Coefficient of variation [%]***	4.5	4.5	87.2

* Three coating batches were available from producer 1. One batch has been tested two times.

** Two coating batches were available from producer 2. One batch has been tested two times.

*** The statistical evaluation is based on mean values per producer, if available.

Table 4. Sets of experimentally determined fictitious elastic constants according to MSAJ/M-02-1995 for PES-PVC fabrics type IV of two different material producers

PES-PVC Type IV			
Producer	Tensile stiffness		Poisson’s ratio ν_{yx} [-]
	E_x [kN/m]	E_y [kN/m]	
1	1274	786	0.13
2	1222	812	0.03

Table 5. Proposal of sets of fictitious elastic constants according to MSAJ/M-02-1995 for PES-PVC fabrics types II, III and IV (mean values)

PES-PVC			
Type	Tensile stiffness		Poisson’s ratio ν_{yx} [-]
	E_x [kN/m]	E_y [kN/m]	
II	710	510	0.12
III	990	660	0.06
IV	1250	800	0.08

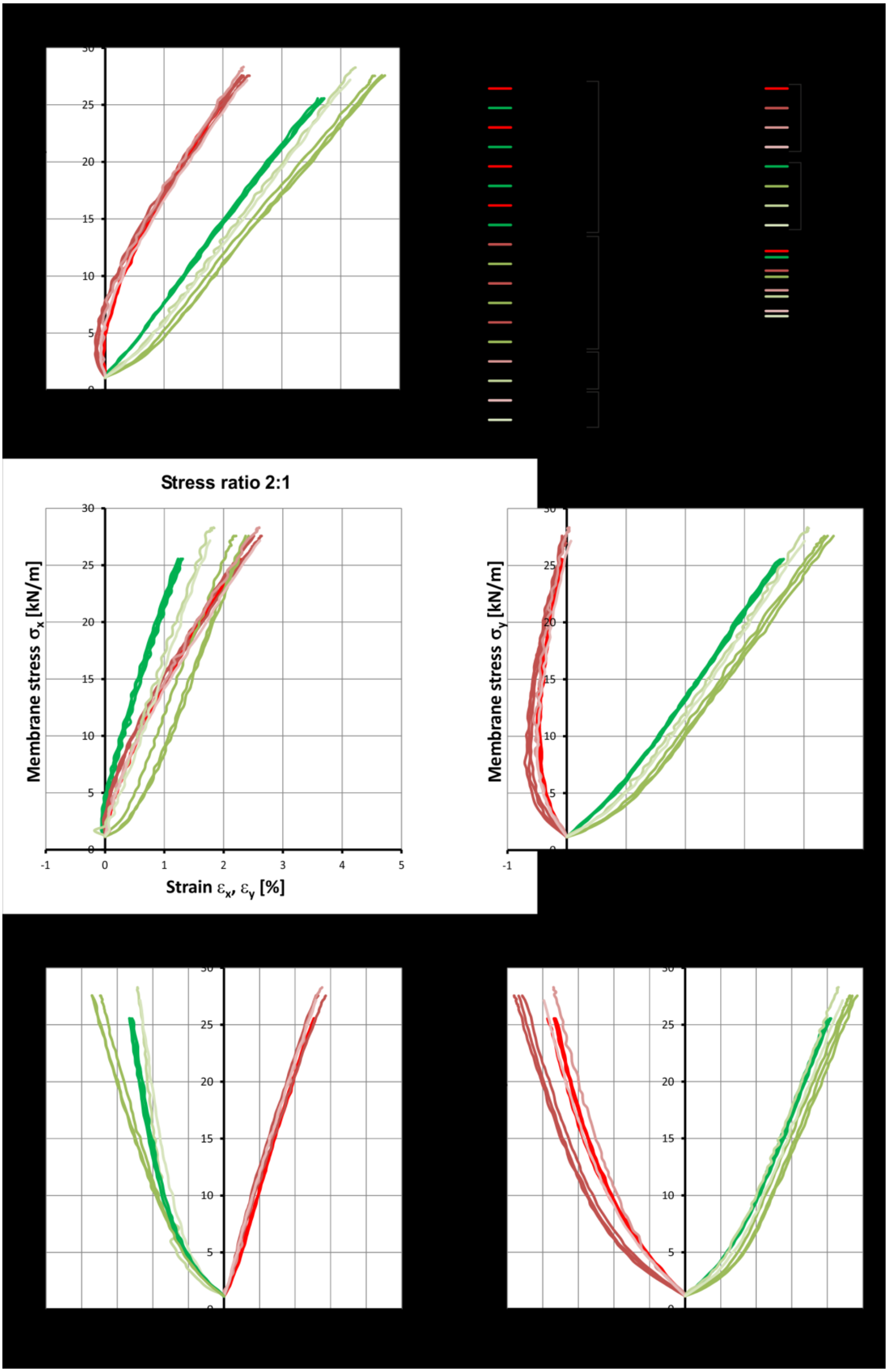


Figure 2: Evaluated stress-strain paths for all PES-PVC type III tests

4. Conclusions

In a first step, methods for a standardized as well as for a design oriented determination of stiffness parameters have been presented and discussed. In a second step, it could be shown that stiffness parameters of PVC-coated PES-fabrics can be classified correlated only to the tensile strength or strength classification, respectively. To come to this conclusion, a random sample of fabrics types II, III and IV has been tested.

A tabulation of either standardized or structure and load case dependent stiffness parameters appears to be possible for the investigated PES-PVC fabrics. This can be of great help for design engineers handling the difficult task of choosing appropriate stiffness parameters for architectural fabrics. As a first proposal, on the basis of the presented experimental investigations and statistical evaluations, sets of fictitious elastic constants according to MSAJ/M-02-1995 for PES-PVC fabrics types II, III and IV are presented as mean values. Thereby, the stress-strain paths of the five tested stress ratios of the MSAJ test procedure are implicitly fitted simultaneously by the fictitious elastic constants – as good as achievable by the MSAJ evaluation procedure.

In the framework of the research project „Charakterisierung und Modellierung des nichtlinearen Materialverhaltens von beschichteten Gewebemembranen für Membranstrukturen im Bauwesen“ (Characterization and modelling of the nonlinear material behaviour of coated fabrics for membrane structures), funded by Deutsche Forschungsgemeinschaft DFG (German Research Foundation), the determination of appropriate stiffness parameters is going to be further developed at the Institute for Metal and Lightweight Structures of the University of Duisburg-Essen. Simultaneously, the suitability of simplified assumptions for stiffness parameters as it is used since decades in the membrane structure design will be reviewed systematically with the help of membrane component tests on a novel membrane component test stand.

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