Elastic Constants of Architectural Fabrics for Design Purposes

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Abstract

Architectural tensile surface structures – often made from coated woven fabrics – carry external loads only by activating tensile stress in the membrane plane, typically in the form of biaxial stress states. One important and challenging aspect of structural fabric analysis is the determination of stiffness parameters that sufficiently model the stress-strain behaviour for these stress states. The particular difficulty is that coated woven fabrics exhibit very complex stiffness behaviour. In general, it is nonlinear, nonelastic and considerably anisotropic. Nevertheless, current membrane structure design practice is based on a simplified orthotropic linear-elastic plane stress relationship, where the elastic constants are “tensile modulus” and “Poisson’s ratio”. The elastic constants must be determined for each material using biaxial tensile tests.

The intention of the present work is to develop principles for determining elastic constants that closely approximate the actual fabric stress-strain response for any fabric structure and all common types of coated woven fabrics. The focus lies on the most commonly utilised materials: PVC coated polyester fabrics and PTFE coated glass fibre fabrics.

The foundation of the present work is a comprehensive survey of the structural behaviour of all types of membrane structures – anticlastic, synclastic and plane – as well as of the stiffness properties of coated woven fabrics for architectural applications. Discussion of the mechanical background to the constitutive law for orthotropic linear-elastic plane stress provides the frame of application for elastic constants, particularly in relation to the boundaries of the Poisson’s ratios. An analysis of internationally established biaxial test and evaluation procedures identifies the strengths and weaknesses of current practice. Gaps in knowledge are closed with experimental investigation into the full range of commonly used architectural fabrics.

Combining all insights, principles for refined biaxial test and evaluation procedures are stated with the objective of determining elastic constants for design purposes. As a basic principle, procedures for anticlastic structures and for synclastic or plane structures are developed separately. Their commonality lies in the fact that they are based on what is defined as the stable state of the fabric. Using stable state elastic constants makes it possible to calculate with the nominal prestress in the fabric structure analysis.

Example application of the refined procedures illustrates that deviations between the measured and calculated strain on a specific evaluation stress level are low throughout. This is striking evidence that linear elastic constitutive law can actually be very useful in approximating the stress-strain behaviour of all common PVC coated polyester fabrics and PTFE coated glass fibre fabrics.

Kurzfassung

Membrantragwerke – häufig hergestellt aus beschichteten Geweben – tragen externe Lasten nur durch Zugspannungen in der Membranebene ab, typischerweise in Form von biaxialen Spannungszuständen. Ein wichtiger und herausfordernder Aspekt der Tragwerksberechnung ist die Bestimmung von Steifigkeitsparametern, die das Spannungs-Dehnungs-Verhalten der Gewebe in diesen Spannungszuständen in geeigneter Weise modellieren. Dies gestaltet sich für beschichtete Gewebe wegen ihres sehr komplexen Steifigkeitsverhaltens äußerst schwierig. Im Allgemeinen verhalten sich Gewebe nichtlinear, nichtelastisch und deutlich anisotrop. Gleichwohl basiert die aktuelle Membranbaupraxis auf einem vereinfachten orthotropen, linear-elastischen, ebenen Materialgesetz, das auf den elastischen Konstanten "Verformungsmodul" und Querkontraktionszahl beruht. Die elastischen Konstanten müssen für jedes Material in biaxialen Zugversuchen bestimmt werden.

Das Ziel der vorliegenden Arbeit ist die Entwicklung von Prinzipien zur bemessungsorientierten Bestimmung elastischer Konstanten derart, dass sie das tatsächliche Spannungs-Dehnungs-Verhalten von allen üblichen Architekturgeweben für alle Tragwerksformen gut approximieren. Der Fokus liegt dabei auf den gebräuchlichsten Produkten: PVC-beschichtete Polyestergewebe und PTFE-beschichtete Glasfasergewebe.

Das Fundament der vorliegenden Arbeit ist sowohl eine umfassende Studie des Tragverhaltens aller typischen Membranbauformen – antiklastisch, synklastisch und eben – als auch der Steifigkeitseigenschaften der Architekturgewebe. Eine Erörterung des mechanischen Hintergrunds zum orthotropen, linear-elastischen Materialgesetz bei Anwendung auf den ebenen Spannungszustand liefert die Randbedingungen für die Anwendung der elastischen Konstanten, besonders im Bezug auf Grenzwerte für die Querkontraktionszahlen. Eine Analyse internationaler Biax-Versuchs- und Auswerteprozeduren identifiziert die Stärken und Schwächen der aktuellen Praxis. Vorhandene Wissenslücken werden durch experimentelle Untersuchungen an der ganzen Bandbreite der gebräuchlichen Gewebetypen für die textile Architektur geschlossen.

Aus der Kombination aller Erkenntnisse werden Prinzipien für fundierte Biax-Versuchs- und Auswerteprozeduren abgeleitet. Das Ziel ist die Bestimmung von elastischen Konstanten, die als Eingangsparameter in der Bemessung dienen. Grundsätzlich wird zwischen Prozeduren für antiklastische und synklastische bzw. ebene Strukturen unterschieden. Beiden ist allerdings gemein, dass sie den "eingespielten Zustand eines Gewebes" nutzen. Erst die Nutzung von elastischen Konstanten im eingespielten Zustand ermöglicht es, die Strukturberechnungen auf den nominellen Vorspannungszustand zu gründen.

Beispielhafte Anwendungen der weiterentwickelten Prozeduren verdeutlichen, dass die Abweichungen zwischen gemessenen und berechneten Dehnungen auf einem

zuvor für die Auswertung definierten Spannungshorizont durchweg klein sind. Dies zeigt eindrucksvoll, dass das linear-elastische Materialgesetz durchaus sehr geeignet ist, auch das Spannungs-Dehnungs-Verhalten aller typischen PVC-beschichteten Polyester- und PTFE-beschichteten Glasfasergewebe zu beschreiben.

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Oberhausen, in March 2016 Jörg Uhlemann

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Symbols

Latin

E Young's modulus for material in [N/mm^2] or
tensile modulus for a structural component such as the composite coated fabric, here in [kN/m], or
error in conjunction with the correlation analysis routine [%]

f tensile strength [kN/m] or
deflection

G shear modulus [kN/m]

n load cycle number [-]

p prestress [kN/m]

Greek

$\Delta\varepsilon$ strain difference between final strain and starting strain during a loading sequence or within a chosen stress interval [%]

$\Delta\sigma$ stress increment or stress interval [kN/m]

ε strain [%]

σ membrane stress, given in force per unit width [kN/m] as no defined section height exists

ν_{xy} warp Poisson's ratio describing strain in warp direction due to stress in fill direction [-], assuming that warp is aligned with x and fill is aligned with y

ν_{yx} fill Poisson's ratio describing strain in fill direction due to stress in warp direction [-], assuming that warp is aligned with x and fill is aligned with y

Indexes

Latin

c	carrying direction in anticlastic structures
d	design value
e	evaluation level
f	fill direction
i	initial
irr	irreversible
k	characteristic value
m	mean value
r,del	delayed reversible (viscoelastic)
r,spon	spontaneous reversible (elastic)
s	supporting direction in anticlastic structures
t	tensile
w	warp direction
x,y,z	coordinate directions
	x-direction in the mechanical model is aligned with the warp direction in the fabric, y-direction in the mechanical model is aligned with the fill direction in the fabric

Greek

ε	strain
ξ,η,ζ	coordinate directions

Numerical

23	room temperature 23°C

Abbreviations

LSM	Least Squares Method
PA	polyamide
PE	polyethylene
PES	polyester
PET	polyethylene terephthalate
PTFE	polytetrafluoroethylene
PVC	polyvinylchloride
SIR	stress increment ratio
THV	tetrafluoroethylene-hexafluoropropylene-vinylidene-fluoroide
UV	ultraviolet