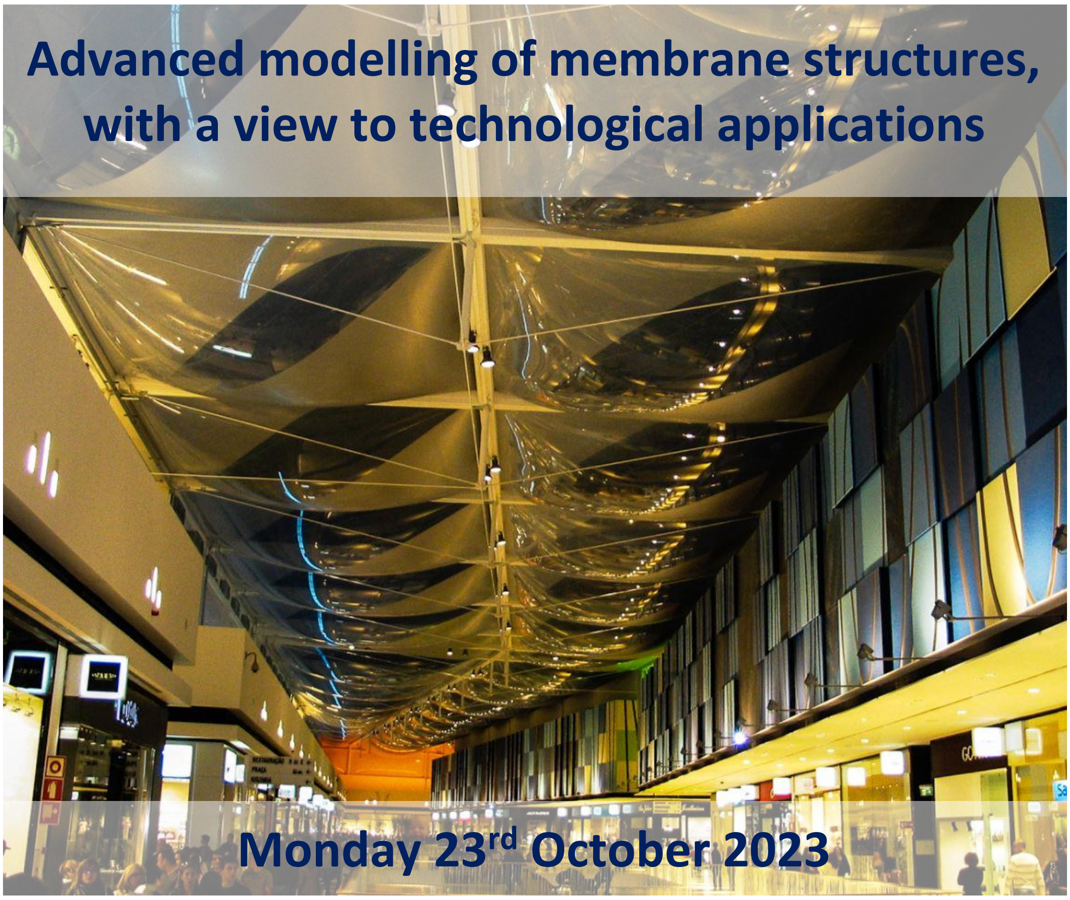
WORKSHOP PROGRAM
&
BOOK OF ABSTRACTS



[Zoom link to the event]

Meeting ID: 919 7228 3096

Workshop Objectives:

The workshop will bring together scientists and engineers with expertise and research experience in the characterisation, modelling and design of ultralightweight materials and structures to discuss the state of the art and the current challenges in the field.

Workshop Chairs:

Adam Bown, *Tensys*

Prof. Federico Bosi, *University College London and SUPSI*

Adrian Cabello, *Tensys*

Prof. Francesco Dal Corso, *University of Trento*

Workshop scientific committee:

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Prof. Miguel Bessa
Brown University

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Dr. Massimo Penasa
CAEmate srl

Organised by:

UCL · TENSYS Engineering • Analysis · University of Trento · CAEmate Engineering, Made Easy · TU Delft · SUPSI

Supported by:

LIGHTEN

Ultralight membrane structures towards a sustainable environment

H2020-MSCA-ITN ~ ITN - Innovative Training Network ~ EID - European Industrial Doctorates

Funded by the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement Number 956547 – LIGHTEN

Monday 23rd October 2023
(Schedule is in UK time - GMT)

08:45 - 09:00 Welcome and Introduction

09:00 - 10:30 SESSION 1 – Chaired by: Prof. Francesco Dal Corso

09:00 - 9:30 Ann-Kathrin Goldbach
The integration of CAD and FEA for lightweight design and analysis

9:30 - 10:00 András A. Sipos
The influence of the Mullins effect on the wrinkling of highly stretched thin film

10:00 - 10:20 Andrea Nobili
Compression induced localized instability in supported pre-stressed incompressible plates

10:20 - 10:45 Coffee Break

10:45 - 12:15 SESSION 2 – Chaired by: Adrián Cabello

10:45- 11:15 Paolo Beccarelli
The Evolution in the Design Tools for Membrane Structures

11:15 - 11:45 Antionio E Forte
Inverse design of inflatable structures through modelling, optimization and machine learning

11:45 - 12:15 Remi Journo
Parametric workflow approach in membrane design, from details to construction

12:15 - 13:30 Lunch Break

13:30 - 15:00 SESSION 3 – Chaired by: Adam Bown

13:30 - 14:00 Katja Bernert
Lightweight ideas for a built environment beyond concrete

14:00 - 14:30 Kawai Kwok
Determination of 'permanent strain' based design criteria

14:30 - 15:00 Mohammad Hosein Nejabatmeimandi
Dynamic Instabilities in Tensile Membrane Structures: A Study on Vortex-Induced Vibrations

Monday 23rd October 2023
(Schedule is in UK time - GMT)

15:00 - 15:15 Coffee Break

15:15 - 16:45 SESSION 4 – Chaired by: Prof. Federico Bosi

15:15 - 15:45 Alessandro Comitti
Thermomechanical characterization and modelling of EFTE membranes

15:45 - 16:15 Luis Miguel Seixas
Viscoplastic modelling and yield criterion for ETFE membranes

16:15 - 16:45 Harikrishnan Vijayakumaran
Hybrid Machine Learning for Constitutive Modelling: A case study on hyperelastic composite material

16:45 - 17:00 Closure

The integration of CAD and FEA for lightweight design and analysis

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The design cycle of membrane and lightweight structures, consisting of the highly non-linear analysis steps of formfinding, structural analysis, cutting pattern generation and construction staging, is well established. Computer Aided Design (CAD)-integrated analysis not only keeps the smoothness of the typically double-curved surfaces of structural membranes intact and available for analysis, but also maps the connections and dependencies of the mentioned analysis steps. Therefore, it captures the interaction of form and force as well as the iterative nature of the design process, see e.g. Goldbach (2021). Design decisions can therefore be made under consideration of the whole design cycle, which is analyzed within one software environment. This leads to unifying the design and analysis model and thus the computational tools of architects and engineers. Furthermore, a parametric environment allows for very flexible modeling with respect to geometrical as well as mechanical properties of the structure. Optimization loops can easily be added to any parameter to ensure the ideal utilization of the design space, also with respect to the verification of the ultimate and serviceability limit states. The basis for CAD-integrated design and analysis, namely Isogeometric B-Rep Analysis (IBRA) is a Finite Element Method based on the mathematical description of the CAD model (as introduced in Breitenberger et al. 2015). In line with the creation of a (structural) digital twin, the CAD model is enhanced by additional information, in this case the mechanical properties to build a FE model.

This contribution will show the advantages of the integration of CAD and Finite Element Analysis (FEA) and introduce the idea of a structural digital twin, that is capable of depicting the design and construction process of lightweight structures. In addition, advances will be presented and illustrated with an exemplary model of a lightweight structure. For this, the freeware Kiwi!3D of str.ucture and TUM will be used as a plugin to a parametric CAD software.

Acknowledgements: The collaboration with Prof. Dr.-Ing. Lars Schiemann in teaching the “Membrane Workshop” at TUM is gratefully acknowledged, as well as the design project contribution by the architecture and engineering students.

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The influence of the Mullins effect on the wrinkling of highly stretched thin films

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A finite-deformation pseudo-elastic model accounting for the Mullins effect is introduced to qualitatively and quantitatively explain experimental data measured on highly stretched, thin elastomer sheets [1]. Recognizing the anisotropic nature of damage, a simple model characterized by a single state variable is tuned to capture the measured residual strain and stress softening behavior, as well as the measured re-emergent wrinkling behavior observed upon unloading. Our motivating experimental observation, namely, that the first appearance of wrinkles for specific aspect ratios occurs during the first unloading of the specimen is then accurately predicted by the new pseudo-elastic model (Figure 1). By considering the dominance of the stress in the main stretch direction, the classical pseudo-elastic model with two dissipation fields [2] can be significantly simplified such that the model accurately predicts the residual strain/stress softening and wrinkling behavior recorded in the measurements.

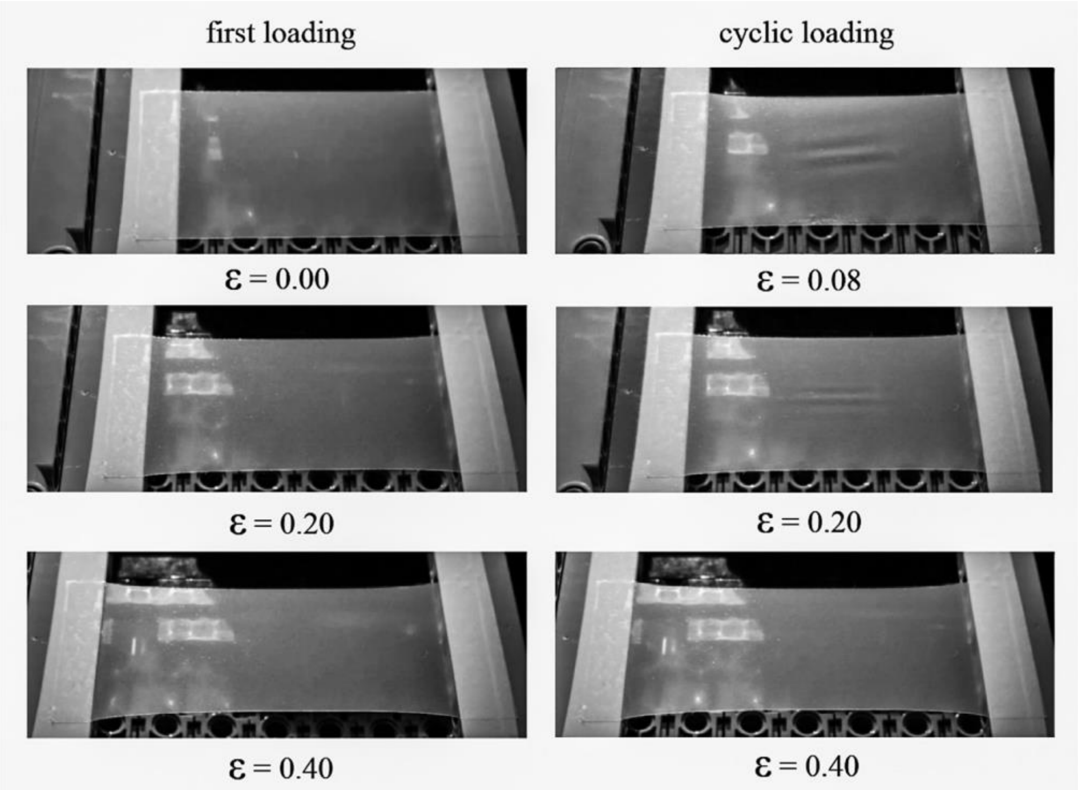

Figure 1. Under uniaxial stretch characterized by the macroscopic strain ε, the film is flat during the first loading, but it wrinkles under subsequent cyclic loading

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Compression induced localized instability in supported pre-stressed incompressible plates

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We develop an incremental analysis of the localized instability in thin elastic plates subjected to biaxial pre-stress and bilaterally supported by an elastic local (Winkler) foundation. The procedure follows the Kirchhoff approach, by which a restricted kinematics is introduced and then variational reduction is employed to determine the corresponding static quantities. The kinematics in question is a power series expansion in the thickness variable and, to leading order, it is a generalization of the Euler-Bernoulli kinematics. In contrast, the plane behavior of the associated fields remains determined by the governing equations. We find that the support properties play a fundamental role in shifting the instability mode from global to local. Also, we see how pre-stress combines with the support stiffness in a nontrivial manner. This work is in collaboration with Michel Destrade and Yibin Fu [3].

Acknowledgements: This research was supported by the Italian National Group of Mathematical Physics (GNFM), within the Institute of Higher Mathematics (INDAM).
AN acknowledges support from the project "Mathematics for Industry 4.0 (Math4I4)", PRIN 2020F3NCPX. He is also grateful for support by the European Union's Horizon 2020 MSCA-RISE-2020, Research and Innovation Staff Exchange programme, grant agreement No 101008140, EffectFact, within the H2020-EU.1.3. - EXCELLENT SCIENCE - Marie Skłodowska-Curie Actions Main Programme.

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The Evolution in the Design Tools for Membrane Structures

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The design of tensioned membrane structures went through a rapid evolution in the last century: physical models, hand drawings and analytical structural calculations have been gradually replaced by digital 3D modelling tools, CAD software and FEM engineering software.

This presentation provides a summary of the key developments in the architectural and engineering design of tensioned membrane structures with an overview of the analytical structural methods and hand calculations of the early pioneering project [1]. The presentation also includes a description of the physical models and experimental methods to determine the form of structures [2] and the gradual development of reliable computational methods to improve the accuracy and effectiveness of the design process.

The potential of the new design tools is illustrated with pratical examples and built projects developed with the support of the new engineering and modelling computer software.

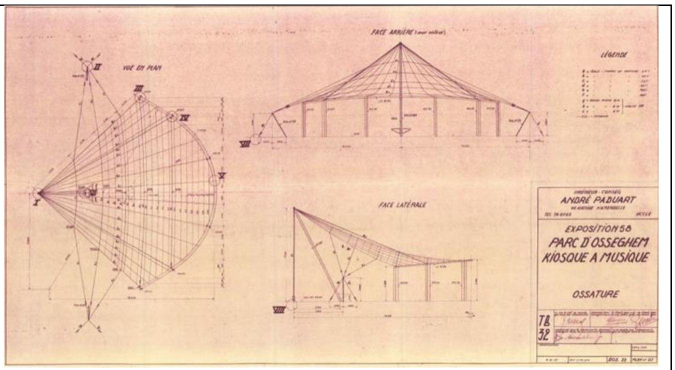

Figure 1. Left, The bandstand at Expo 58 [3] . Right, plan of the steel members for the bandstand by Paduart, Dec 1958 [4, file 2326]

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Inverse design of inflatable structures through modelling, optimization and machine learning

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When a rubber balloon is inflated its shape changes. This property has been exploited in the design of inflatable structures and soft robots. Harnessing the dramatic deformation resulting from the inflation of a soft membrane, scientists have been able to transform flat objects into shelters [1], storm surge barriers [2] and space modules [3].

For most application, controlling the final inflated/actuated shape of the device is of paramount importance. Therefore, across fields of science, researchers have increasingly focused on designing soft devices that can morph into target shapes to achieve functionality.

Here, I present different approaches for the inverse design of inflatable structures. Kirigami [4], soft pixelated membranes [5] and multistable origami [6] are powerful design platforms to create functionality through shape-changing capabilities. Classical optimization approaches and machine learning methods can be used to solve ill-posed inverse problems where a target shape in input is given and the optimal design to achieve that target shape upon inflation (or deflation) is obtained as result.

Acknowledgements: This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 798244

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Parametric workflow approach in membrane design, from details to construction

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Complex geometries using membrane envelopes are often used as illustration for parametric architectural design. The generation of freeform has never been as easy as nowadays, through the democratisation of tools like Grasshopper for Rhinoceros3D for example. Doing so, details are often overlooked, while the focus is kept on the optimisation of the membrane parameters.

The membrane, although resulting in a complex form, actually depends on simple geometric parameters (points, border conditions, cables, bars…). It is the form-finding solver that deals with the complex task of generating the final 3D shape.

But the details are depending on the form-finding geometry itself. They must adapt to it, intersect with it, keep distance to it, or provide water tightness. In designing those envelopes, we need a workflow that adapts to this type of geometry for different situations, for each update of the rerun of the form-finding routine.

How does a good parametric workflow allow to extend the parametric design approach of the form-finding of membranes structures further into the project development?

How can it be applied to the detailed design, the workshop planning, the creation of a BIM model, and the construction?

This paper will present examples of detailed design parametric workflows both for membrane and ETFE envelopes. Using grasshopper for Rhinoceros3D as a core, we are able to both link existing software, and develop custom tools, either project specific, or reusable on other structures. It will explain how using a smart constellation of parametric tools allows for a better planning, communication, and organisation of the production.

Acknowledgements:
Architect: Jacek Bułat, Poznan, Poland
Concept design: Andrzej Kowal, Wrocław, Poland
Execution foil cushions: Temme // Obermeier, Rosenheim, Germany
Structural engineering and workshop design for the cable-surrounded cushions as well as interface details: formTL Ingenieure für Tragwerk und Leichtbau GmbH, Radolfzell Germany

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Lightweight ideas for a built environment beyond concrete

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A space suit is a home – as is the liveable textile bubble. Following this path the article will literally dwell in options for using textiles in between the dimensions of a shirt and a pneumatic house – exploring the options of energy savings when limiting our heated comfort zone to a minimum. The 1960s are a valuable starting point for this evaluation. The escapist notion of what Haus Rucker Co did when covering a whole villa with a huge pneumatic structure is an example for textile options if all other means stopping the climatic collapse fail. Taking the same artists' proposal for the documenta art exhibition in Kassel serves as a more optimistic example of what a tensioned structure can do for limiting energy consumption to the direct personal realm. Peter Cook and Archigram set examples when proposing the inhabited capsules as house models for the future – their future which is our present. The presentation will explore if these 60 year old ideas are ready to be transformed into a possible answer to nowadays energy saving needs. It delivers the proof that within the last 60 years innovative lightweight structures transformed fabrics and foils into a grown-up seventh building material.

Acknowledgements: When preparing this article I led a workshop at the Arts School in Bremen, HfK. Within the workshop the students of various design units explored soap film models. It was their first venture into the world of tensile structures. For me it was a most valuable eye opener. Dwelling in the world of Textile Architecture limits our thinking to well established forms and hence tends to make us blind for new input. I am very grateful for the innovative interchange – be it in Bremen or coming from 60 year old ideas of architects and artists.

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Permanent Stain Accumulation and Strain-Based Design Criteria of Polyethylene

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Stratospheric balloons employ low density polyethylene thin film as the envelope material. When stretched beyond its yield point, polyethylene starts accumulating irrecoverable deformation, but is capable of recovering part of the imposed deformation. Understanding the accumulation of permanent strain is useful for evaluating the risk of operating stratospheric balloons, especially when polyethylene yields at relatively low strains. However, the characterization of permanent strain in viscoelastic materials poses significant challenges due to the long recovery times involved in measuring the true irrecoverable deformation. Here we make use of a recently developed stress-gradient test method to significantly increase the data resolution and volume. Both uniaxial and biaxial creep-recovery experiments have been conducted on polyethylene using the stress-gradient method, resulting in a continuous series of creep-recovery curves from a single experiment. We find that the majority of the imposed strain after yielding is recoverable, and the rate of accumulation is insensitive to temperature. A strain-based design criterion is proposed for polyethylene based on tolerable accumulated irrecoverable strains.

Acknowledgements: We are grateful for the financial support from the NASA Goddard Space Flight Center under grant 80NSSC21K0913. We thank the NASA Balloon Program Office and Tensys Dynamics Limited for helpful comments and discussion.

Dynamic Instabilities in Tensile Membrane Structures: A Study on Vortex-Induced Vibrations

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Vortex shedding is a phenomenon in which vortices or swirling air currents are generated as wind flows past bluff bodies such as bridges, antennas, and lightweight membrane structures. This vortex formation can induce structural vibrations, particularly when the shedding frequency aligns with the structure's natural frequency, causing resonant oscillations [1].

Observations of vortex shedding can be traced back centuries, evident in the aeolian tones produced by wind harps. Today, we acknowledge the potential risks for modern materials like tensile membrane structures, which are susceptible to dynamic instabilities from phenomena such as flutter and vortex-induced vibrations. If left uncontrolled, these vibrations can result in fatigue and a reduced structural lifespan.

The discussion in LIGTHEN's Second workshop will employ computational fluid dynamics simulations of a cantilever panel in a wind flow to provide a comprehensive explanation of vortex shedding mechanics. We will visualize and analyze the vortices as they form and detach from the panel's trailing edges, demonstrating how this cyclic pattern can trigger structural vibrations. Additionally, we will explore how factors like wind speed influence vortex-shedding behaviour and the resulting dynamics.

In summary, this methodology harnesses modern computational power and multiphysics simulations to comprehend the Vortex-Induced Vibration (VIV) phenomenon and pave the way for a new approach to analyzing tensile membrane structures.

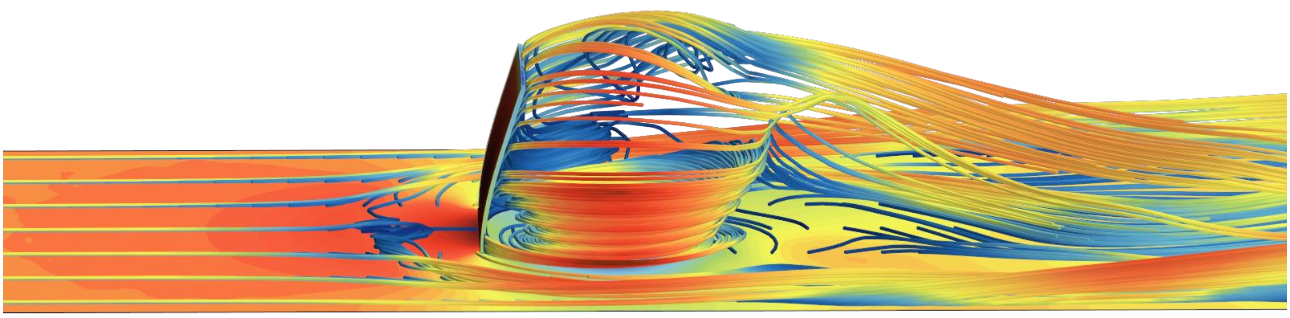

Figure 1. Wind current around a flat panel in the wind

Acknowledgements: MHN gratefully acknowledges the support of the H2020- MSCA-ITN-2020-LIGHTEN-56547 grant.

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Thermomechanical characterisation and modelling of ETFE membranes

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ETFE (ethylene-tetra-fluoroethylene) is a polymer employed in membrane structures as a tensioned foil or shaped into inflated cushions. Its relevance arises from its exceptional features, which include high stiffness, ductility, recyclability, durability, light transmission and self-extinguishing properties [1]. Although the material's mechanical properties strongly depend on both time and temperature effects [2-4], the lack of a comprehensive understanding of the mutual influence of these variables prevents an optimal design and a wider exploitation of ETFE in sustainable lightweight construction [5].

In the first phase of the study, an experimental characterisation was performed using a quasi-static universal electromechanical machine coupled with digital image correlation, and a Dynamic Mechanical Analyser (DMA). Uniaxial properties were investigated across a range of temperatures spanning from -20 to 60° C, at different displacement rates. Additionally, cyclic and creep tests were performed on the DMA. ETFE revealed a peculiar response that strongly depends on temperature, while the strain rate dependence is less pronounced. Two inflection points have been identified from the stress-strain response, the first of which was found to be associated with the onset of yielding. The polymer is proven to be in a glassy phase in the range of temperature of interest.

The study's second phase was devoted to linear viscoelastic modelling, in which a compliance master curve was built from the creep data through the time-temperature superposition principle. Rheological modelling of the master curve was performed through a single integral representation, expressing the time dependence with a Prony series. A recursive integration algorithm was used to implement the constitutive relation in a MATLAB script [6]. The model obtained is proven to accurately predict the effects of time and temperature on ETFE, as it was validated against independently acquired data.

The implemented model has a high potential in obtaining an accurate prediction of the ETFE behaviour, resulting in better and safer structural designs. Further improvements in capturing the nonlinear viscoelastic and biaxial responses are planned as future research efforts.

Acknowledgements: Funding of the European Union. Project: H2020-MSCA-ITN- 2020-LIGHTEN-956547.

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Viscoplastic Modelling and Yield Criterion for ETFE Membranes

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The energy transition requires the reduction of emissions in the building industry, for which new and sustainable technologies are required to overcome the massive environmental footprint of construction. One of the most promising materials for roofing and facades is the semi-crystalline polymer ethylene tetrafluoroethylene (ETFE), typically produced as lightweight structural membranes. Despite its potential, there is still a lack of robust material models for ETFE, which hinders its use among designers. In particular, a reliable time and temperature-dependent viscoplastic constitutive model and yield criterion are still missing.

An ongoing experimental campaign performed within the EU H2020 MSCA LIGHTEN program has enabled the mechanical characterization of ETFE's response. It has been found that both the onset of plasticity and the strain-stress relations strongly depend on temperature and strain rate effects. Furthermore, ETFE's strain-stress diagrams exhibit a double yield point phenomenon related to its semi-crystalline structure [1].

A molecular model was developed to predict ETFE´s onset of plasticity based on the strain-rate temperature superposition principle [2]. The yield law was then integrated into the von Mises criterion, allowing the prediction of different yield loci under varying thermo-mechanical loading conditions. A plane stress viscoplastic model incorporating the yield criterion was formulated and implemented as a user material subroutine. In this model, the yield surface changes not only due to strain hardening, but also with strain-rate/temperature hardening/softening effects. Furthermore, the formulation offers the ability to integrate various yield laws, allowing for the exploration of a wide range of strain-rate and temperature yield dependencies.

The validation of the ETFE viscoplastic model and yield criterion demonstrated good agreement with experimental data, providing a solid foundation for the development of safer and more efficient ETFE building designs.

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Hybrid Machine Learning for Constitutive Modeling: A case study on hyperelastic composite material

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Modeling and computational simulation of physical systems governed by partial differential equations are central to solving challenging problems in engineering mechanics. The state-of-the-art numerical techniques for solving PDEs such as the finite element method have the potential to model arbitrarily complex problems in terms of geometry, loads, boundary conditions, and governing equations. However, a significant challenge in numerically solving these axiomatic equations is that the solution is dependent on a reliable description of the constitutive relationships which connect the kinetic and kinematic quantities of the physical systems. While theory-based models of phenomenological or mechanistic origins have been historically employed in modeling non-trivial constitutive relationships, they are prone to epistemic uncertainties due to incomplete understanding and lack of sufficient information when the domain under consideration becomes complex. Machine learning models, such as artificial neural networks powered by state-of-the-art optimization techniques, offer promising data-driven alternatives in such scenarios due to their potential as universal function approximators.

Despite their approximation capabilities and flexibility in capturing arbitrarily complex functions, these machine learning models however are data intensive and also have low interpretability and explainability. The modeling challenge becomes detrimental when the data availability is scarce and its generation is expensive. In this work we propose a novel hybrid paradigm in constitutive modeling wherein partial prior knowledge, in the form of interpretable theory-based models, is fused with machine learning models in a principled and systematic approach. For evaluating the predictive performance of the different models, the load-response dataset for uncharacterized multiphase hyperelastic representative volume elements (RVE) is numerically generated by controllably varying microstructure configurations and phase constitutive laws. We observe that the hybrid strategy in constitutive modeling results in models that outperform the purely theory-based as well as purely machine learning-based constitutive models indicating that hybridization results in complementary predictive abilities.

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