*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.)

# Evaluation of the wind load history of environmentally exposed ETFE foils

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## Abstract

When it comes to Ultralightweight building skin, ETFE (ethylene-tetrafluoro-ethylene) foil cladding systems are acknowledged as the optimum solution not only in terms of transparency and mechanical performance but also in terms of longevity. To simulate the response of the material against wind loads, Vector Foiltec GmbH has developed the biaxial tensile hysteresis tests. This method is now part of the PD CEN/TS 19102. The wind is simulated according to the Deaves and Harris model by the cycling of biaxial loads between 2/3 and full load in a 5-second duration, representing the interaction of the ETFE with average wind background and wind gusts. The results show a combination of elastic, viscoelastic and plastic deformation of the material. The present manuscript adapts the same method with the uniaxial hysteresis tests. After the end of exposure, the foil relaxes to a residual strain, which is a result of the plastic deformation according to the specific load interaction. In 2023 the Westminster and Chelsea Hospital building roof in London was refurbished. The ETFE foil roof was built by Vector Foiltec in 1990. Nowofol Kunststoffprodukte GmbH & Co. KG provided a virgin retainment sample of 150µm bottom foil from 1988 out of their archive. Environmentally exposed ETFE foil sample and the Archive sample are analysed with uniaxial stress-strain hysteresis test. Based upon these results the load history of the exposed ETFE film is elucidated.

**Keywords**: ETFE foil, Cladding system, Wind load, Refurbishment, Mechanical behaviour

## 1. Introduction

ETFE (ethylene-tetra-fluoro-ethylene) foil is an ultralightweight building skin, having high UV resistance, ductility and greater light transmission than glass (Comitti et al. [1]). The transparent nature of ETFE makes it a desirable material for Architectural applications (Cremers [2]). Tensile building skins such as architectural membranes provide inherent properties of lightness and flexibility (Monticelli [3]). In case of ETFE foils, the material-system also showcased excellent life span exceeding 30 years, for example the Chelsea and Westminster Hospital project, installed in 1988.

The mechanical behaviour of ETFE foil has been largely studied by multiple scholars, such as Yoshino and Kato [4] who observed the viscoelastic characteristics of ETFE foil under biaxial tensile tests. Galliot and Luchsinger [5] observed the mechanical behaviour of ETFE foil under uniaxial and biaxial tensile tests. Wu and Li [6] presented a revised creep model to elucidate the short-term creep and recovery behaviour of ETFE foil. Chen and Wu [7] determined the uniaxial tensile properties of prestressed ETFE foil. Saxe [8] have assessed the mechanical performance of ETFE foils under various temperatures by means of uniaxial and bi-axial tensile tests. Maywald and Missfeld [9] have analysed the ageing of ETFE foils based on the biaxial hysteresis test and by means of Raman Spectroscopy (Popa et al. [10]).

The presented manuscript wants to assess the experienced wind loads on ETFE foil and elucidate the wind load history of environmentally exposed ETFE foils. This is carried out by analysing the uniaxial hysteresis test performed on a reclaimed 150µm thick bottom foil of the Chelsea and Westminster Hospital building (London) (*Project foil*). The project was built in 1990 by Vector Foiltec GmbH (Germany) and refurbished in 2023, establishing a lifespan of 33 years. The test results are compared with the results of uniaxial hysteresis test of archive sample of 150µm thick foil provided by Nowofol Kunststoffprodukte GmbH & Co. KG (Germany) (*Archive foil*).

The uniaxial hysteresis test results presented in this manuscript elucidate the experienced wind loads on the environmentally exposed foil and show the ageing effect resulting in enhanced stiffness in the project foil. Moreover, the results develop a methodology to evaluate the wind load history by means of uniaxial tensile tests.

## 2. Research Method: Uniaxial Hysteresis test

The research method is based on the bi-axial hysteresis tests developed by Vector Foiltec (Maywald and Missfeld [9]) and is now also part of PD CEN/TS 19102:2023 (CEN [11]). The test method was established on the wind model developed by Deaves and Harris [12], representing the cycling of biaxial loads between 2/3 and full load in a 5-second duration, to elucidate the interaction of the ETFE with average wind background and wind gusts.

The present manuscript uses the same test method to perform uniaxial hysteresis tests on 150µm thick ETFE foil reclaimed from the ETFE roof of the Chelsea and Westminster Hospital (London) and 150µm thick archive foil provided by Nowofol Kunststoffprodukte GmbH & Co. KG (Germany). The initial tensile tests were conducted with the standard specimen size of 20 mm x 150 mm showing inconclusive results due to the nature of the loads that are in the (low) range of 4.2 MPa to 20 MPa, therefore the hysteresis test was adapted with the specimen size of 60 mm x 150 mm as shown in Figure 1.


Figure 1. 60mm x 150 mm foil specimen mounted on the Uniaxial Tensile testing machine [source: author]

| Loop [Nos] | Upper load limit (MPa) | Lower load limit (MPa) |
|---|---|---|
| 1 | 8.0 | 4.8 |
| 2 | 10.0 | 6.0 |
| 3 | 12.0 | 7.2 |
| 4 | 15.0 | 9.0 |
| 5 | 18.0 | 10.8 |
| 6 | 20.0 | 12.0 |

Table 1. Testing method implemented for the Uniaxial Hysteresis test [source: Vector Foiltec]

The basic load of 4.2 MPa is considered to reflect the standard inner pressure of the ETFE foil cushion of 250 Pa. Six load cases have been considered representing the different wind gust scenarios of 8 MPa, 10 MPa, 12 MPa, 15 MPa, 18 MPa, and 20 MPa (Table 1). The basic load due to constant wind speed was estimated to be 60% of the maximum wind load based on the wind model by Deaves and Harris [12]. The time between different wind gusts comprising 50 cycles each was set to be 10 minutes allowing for elastic relaxation at the basic load level of 4.2 MPa. The time per loading-unloading cycle is 1 MPa/s and the test temperature was 23±2°C with uncontrolled humidity values in the range of ~45-60%.

## 3. Uniaxial Hysteresis test: Chelsea and Westminster Project foil – Archive foil

A comparison of the stress-strain uniaxial tensile test is shown in Figure 2. At the basic load of 4.2 MPa, the elongation for the project foil is 0.15%, whereas for archive foil it is 0.20%. The tensile test was stopped at 20 MPa due to saturation of the hysteresis loops. The project foil achieved the stress of 20.2 MPa with 2.31% elongation, similarly, archive foil achieved same stress level with 2.39% elongation. Within the first three hysteresis loops of 8.0-4.8 MPa, 10.0-6.0 MPa, and 12.0-7.2 MPa plastic deformation is visible, the load cycles are not overlapping within this range for both project and archive foil, presenting the loads experienced by the foil during its lifespan. Furthermore, a shift of 0.05% strain is visible within first three hysteresis loops.

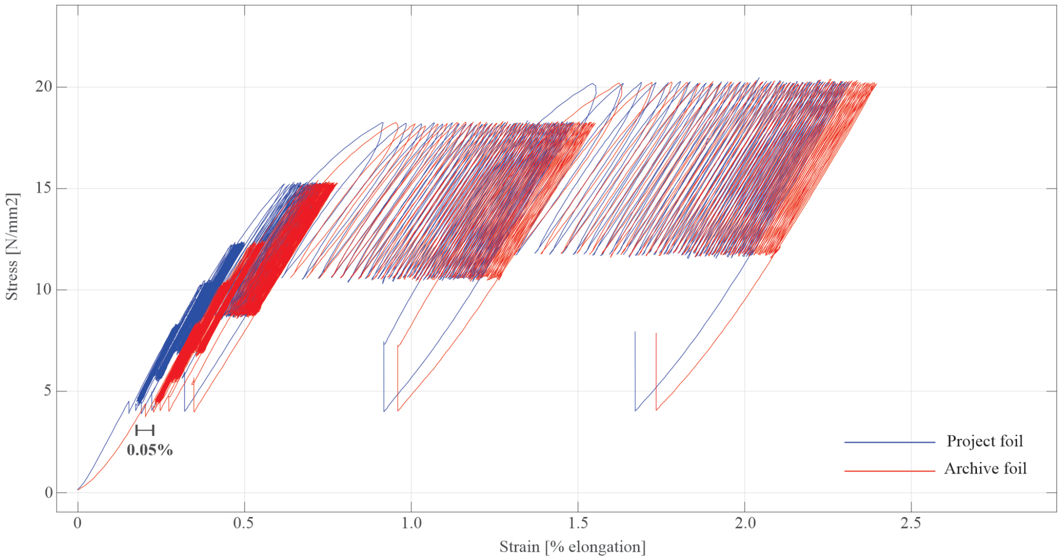


Figure 2. Stress-Strain diagram of uniaxial tensile test of Chelsea Hospital project bottom foil vs. archive foil of 150µm [source: author]

Figure 3 represents the stress-strain uniaxial hysteresis of Project foil. Similarly Figure 4 represents the stress-strain uniaxial hysteresis of archive foil. The hysteresis loops are compared to understand the ageing effect resulting in enhanced stiffness and reduced strain rate. The load cycles within the first three loops show the same strain rate of the hysteresis loops with the shift of 0.05%. the fourth, fifth and sixth hysteresis loops show similar strain rate have been experienced by both project and archive foil. There is no significant change in the modulus of elasticity is visible in both project and archive foil, at the beginning or at the end of load cycles.

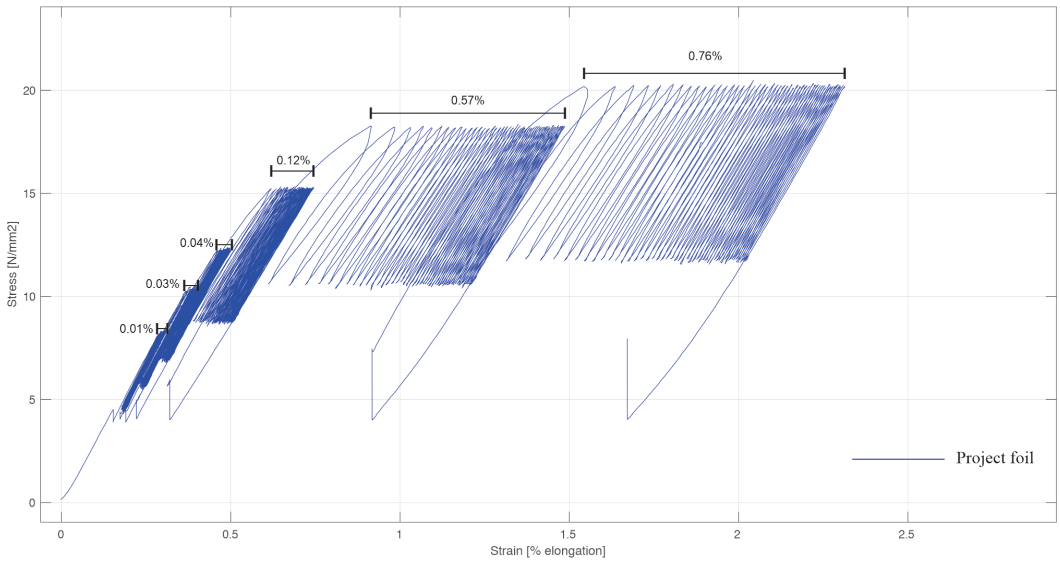


Figure 3. Measuring the hysteresis loops of Chelsea Hospital Project bottom foil (150µm) [source: author]

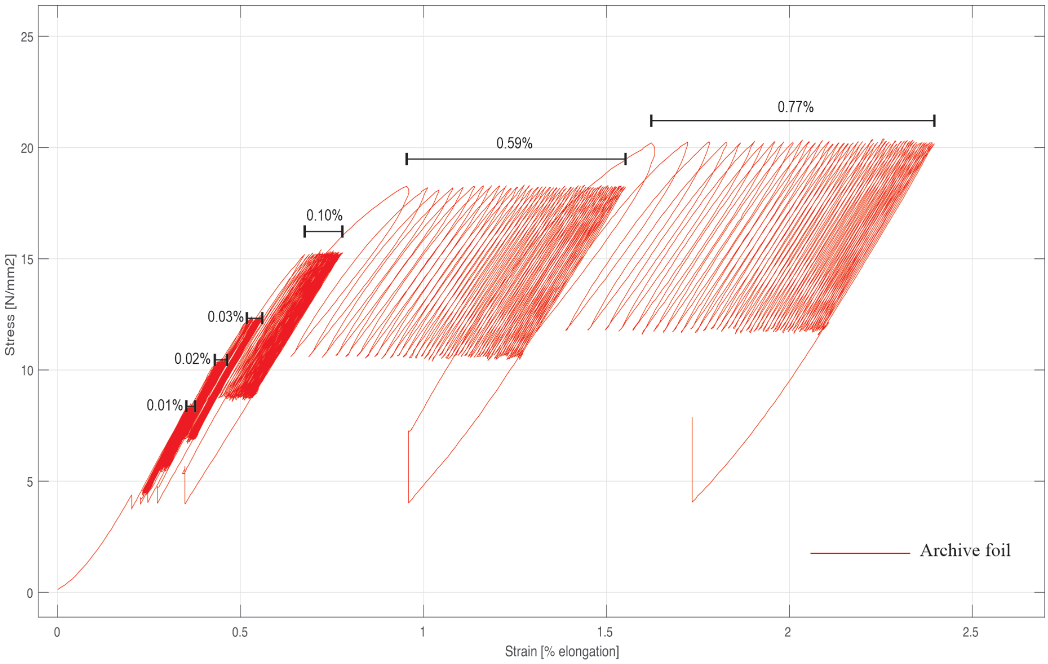


Figure 4. Measuring the hysteresis loops of Archive foil (150µm) [source: author]

Figures 6 and 7 respectively represent the strain rate between the second to tenth cycles of the fourth, fifth and sixth hysteresis loops for both the project and archive foil. The fourth hysteresis loops of load cycle 15.0-9.0 MPa experience strain of 0.03%, the fifth hysteresis loops of load cycle 18.0-10.8 MPa experience strain of 0.21% and the sixth hysteresis loops of load cycle 20.0-12.0 MPa experience strain of 0.27% for both project and archive foil (Table 2), ascertaining no wind loads have been experienced in the range. With the increased load cycles the reduction in elongation is visible. At the end of the fiftieth cycle, the load cycles are overlapping representing a condition of saturation.

| Foil type | Fourth hysteresis loop (15.0-9.0 MPa) [strain %] | Fifth hysteresis loop (18.0-10.8 MPa) [strain %] | Sixth hysteresis loop (20.0-12.0 MPa) [strain %] |
|---|---|---|---|
| Project foil | 0.03 | 0.21 | 0.27 |
| Archive foil | 0.03 | 0.21 | 0.27 |

Table 2. Comparison of strain rate of second-tenth load peak for project and archive foil [source: author]

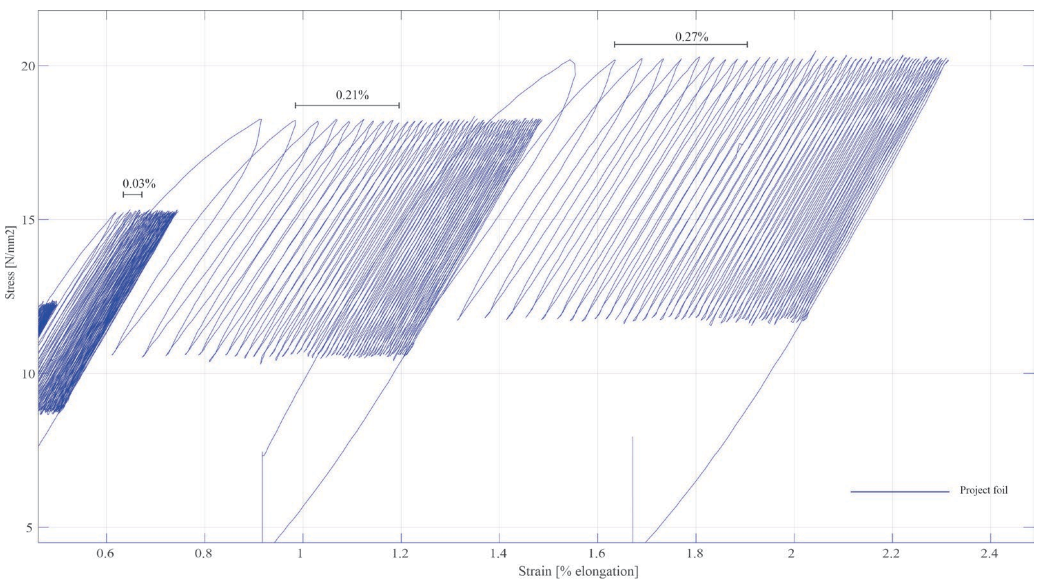


Figure 6. Measuring the Strain rate between 1st and 2nd cycle of 5th and 6th hysteresis loops of Chelsea Hospital Project bottom foil (150µm) [source: author]

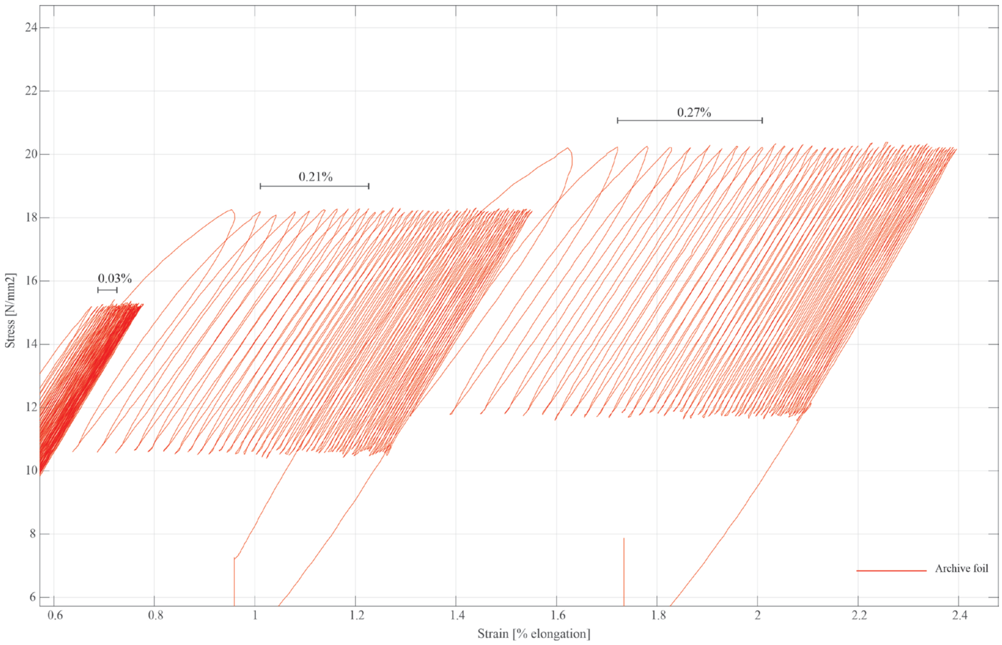


Figure 7. Measuring the Strain rate between 1st and 2nd cycle of 5th and 6th hysteresis loops of archive foil (150µm) [source: author]

## 5. Conclusion

The present comparison between uniaxial hysteresis tests carried out on the reclaimed bottom foil (150µm) of the Chelsea and Westminster Hospital project (UK) and the archive foil (1988) sample from Nowofol elucidate the history of experienced wind loads within the project life span of 33 years. From the analysis of the hysteresis curve, it is evident that most of the loads experienced by the bottom foil are within the range of 4 MPa- 12.5 MPa, identified by the strain difference between the project and archive foil in the first, second and third hysteresis loops. The experienced load range on the project foil suggests that a lower thickness of bottom foil also can be used. It signifies further reduction in overall weight of the ETFE foil system. The hysteresis test also shows a consistent ageing effect on project foil, showing enhanced stiffness than the retaining archive foil sample that has experienced no loads. The results of uniaxial hysteresis tests to analyse the wind load behaviour of ETFE foils are in the similar range of the bi-axial hysteresis tests developed therefore the study also suggests that uniaxial hysteresis tests developed within this manuscript can also be used to elucidate the behaviour of ETFE foils however for quantitative results determining the actual scenario on site, bi-axial hysteresis tests shall be performed.

## Acknowledgements

The research funded by the European Union under the Horizon Europe-Marie Skłodowska-Curie Actions (MSCA) Grant ID 101072598 for the 'Acoustic and Thermal Retrofit of Office Building Stock in the EU*'* is gratefully acknowledged. Special thanks to Delche Lazarev and Maher Al Abboud for their valuable assistance in the Lab.

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Paper Title: Evaluation of the wind load history of environmentally exposed ETFE foils

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