Bending performance of glass fibre reinforced polymer sandwich panels subjected to combined thermal cycling and load

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ABSTRACT

There are many examples of Fibre reinforced polymer (FRP) materials in the broad field of construction, but only a few in façade applications. FRP sandwich panels in facades are highly bespoke elements, thus leading to the lack of representative data on long-term durability behaviour of FRP sandwich panels subjected to natural weathering conditions as found in façade applications. This paper investigates the flexural properties of Glass fibre reinforced polymer – Polyethylene terephthalate foam (GFRP–PET) foam sandwich panels subjected to 100 and 200 freeze-thaw (F/T) cycles with and without sustained loading of 15% and 35% of their ultimate static failure load using a 4-point bending set up. It was found that the effect of F/T cycles and the sustained loading have only minor effects on the structural performance such as stiffness and strength, whereas with prolonged ageing a shift in failure modes was observed; after 100 F/T cycles, 90% of all tested specimens exhibit a core shear failure and only one failure due to face sheet crushing was recorded. However, for 200 F/T cycles only 56% of all specimens failed in shear, but 44% in face sheet crushing.

INTRODUCTION

Geometrically complex building envelopes are typical in contemporary architecture. The conventional approach during their design is to provide a succession of layers and materials in their build-up, each one addressing a particular requirement (thermal, structural, water tightness etc.). This approach often becomes problematic and costly. Sandwich panels consisting of FRP face sheets bonded to lightweight cores have successfully been used in aerospace and marine industries and can potentially provide an integrated, loadbearing and lightweight solution for geometrically complex building envelopes. The design life of facades is not exactly specified in the current design standards; it is generally suggested to be part of the design life of the entire building which is deemed to be a minimum of 50 years [1]. However, this is rarely achieved without major means of refurbishment. Hence, materials used in façade systems should be designed to withstand significant visual and mechanical deterioration under varying weathering conditions for the given period of time; incorporating regular inspections and maintenance cycles. These cycles depend on the materials response to façade-like natural weathering such as the simultaneous influence of several environmental agents, e.g. UV radiation, humidity/ moisture, heat and freeze-thaw cycles.
FRP's have been researched for the military, aerospace and maritime sectors since the early 1960's [2,3], however applying these outcomes directly to the building industry is problematic. Materials and manufacturing processes used in the construction industry (e.g. engineered thermoplastics vs. thermosets, Autoclaves vs. Vacuum Assisted Transfer Moulding) reflect the industry's requirements for low cost designs, non-repetitive freeform geometries and comparably low or one-off production volumes, and are often of lower quality than those found in aerospace and marine applications [4,5]. In order to enable a wide spread use in façade systems, research which primarily ensures long-term structural integrity and secondarily an adequate visual appearance is required. One inevitable environmental influence on façade systems is sunlight exposure, however UV radiation is excluded from this study because it typically only results in superficial deterioration of the resin matrix and limited to a few microns from the surface its effect on the structural performance of the FRP is deemed to be negligible [6]. Other environmental conditions such as exposure to moisture are relevant to this study. Research by others shows that FRPs are sensitive to harsh aqueous exposures e.g. immersion into saline solutions, which is representative of de-icing salts on road bridge applications, but the reported outcomes have to be considered carefully because of the artificial ageing conditions and materials used (commonly FRP pultrusions) as they are not necessarily representative of FRP sandwich panels in façade applications [7,8]. Similar problems are faced evaluating the outcomes of research carried out on the individual sandwich panel's constituents such

as face sheets only [9,10] or panels with different core materials, e.g. balsa [11] or honeycomb [12]. Elevated temperatures (incl. temperature cycles) is another key consideration for façade applications, but research on the effect of extreme temperatures/temperature cycles is excluded from this preliminary review as these conditions are exclusively intended for aerospace applications; the state-of-the-art review in this study is therefore limited to moderate temperature levels. Given the high variability of FRP composites, the following paragraph will cover research undertaken on a range of different polymer resins and foams which differ from the material tested in the experimental program. It is deemed to give a generic overview on methods used to evaluate the materials degradation and to provide a general trend of the material's response rather than to quantify the performance of GFRP – PET composites specifically.

Sousa et al. [8] investigate the effects of thermal cycles from -5 to 40 °C for up to 190 cycles on the mechanical response of pultruded GFRP profiles (unsaturated polyester-UP/ vinylester-VE). Viscoelastic properties did not degrade, tensile and interlaminar shear properties changed only slightly (UP-10% and VE-13%), but flexural properties suffered a significant loss (UP 24% and VE 25%). Similar behaviour was found by *Dutta* [13] who tested glass-epoxy FRP coupons in dry air freeze thaw cycling from -40 to +23 for 150 cycles and determined a reduction in tensile strength by 10%. As thermal cycling introduces failures such as matrix microcracking as well as adhesive rupture, e.g. fibre-matrix debonding, matrix dependant properties like stiffness are expected to degrade faster than those dominated by the fibre's performance. Opposing results were published by *Wu et al.* [9]. His research investigates the durability of unloaded and pre-strained GFRP (VE) composite bridge deck face sheet coupons under freeze-thaw (4.4°C to -17.8°C) and low temperature (constant -17.8 °C) conditions in media of dry air, distilled water and saltwater for an ageing period of 625 cycles (~1250h). No statistically relevant changes in the flexural strength was recorded. Varying the cycling length (2h and 5h) had no measurable impact, assuming that the total number of cycles induces greater deterioration than the total exposure time. A similar behaviour was established by *Tam et al.* [10] who tested CFRP and GFRP coupons at dry air under F/T, sustained loading and combined exposure. Although strength and stiffness degradation occurred for CFRP laminates (up to 13% degradation); GFRP specimens were virtually unaffected (< 3%). Moreover, other researchers have found a greater and more deleterious trend when superposing F/T with moisture. *Karbhari et al.* [14] investigate FRP (VE) laminates at different temperature levels at dry and wet conditions and found that low-temperature thermal cycled coupons deteriorate faster than exposed to constant immersion at sub-zero temperatures. It was concluded that moisture absorption causes plasticisation and hydrolysis of polymer chains, resulting into a greater molecular mobility hence enhancing the material deterioration. These chemical reactions are accelerated by micro cracks in the resin that happen at lower temperatures that facilitates the water ingress at higher temperatures. The collected water in turn expands at sub-zero temperatures and leads to additional matrix fibre debonding [9, 14]. *Hollaway* [15] further established that sustained loading during the conditioning process reduces the durability of the composite, which was also found by *Gibson* [16] who established that moisture

Sandwich panel deformations are, given its composite nature and distribution of material properties, dominated by the core's, in this case, foam's stiffness. Changes in the shear modulus G of the foam, e.g. due to environmental influences but also as a result of a constant stress state induced by the structural build up, can significantly affect the overall performance of the sandwich panel and requires careful consideration during the design process. *Toubia et al.* [17] tested closed cell Polyvinyl chloride (PVC) foam-Vinylester/E-Glass Sandwich panels after environmental conditioning compromising freeze-thaw (-20°C to +20°C) and immersion into a saline solution for 200 cycles (~100 days). Core shear strength showed a slight increase by 3.2% whereas the core shear modulus reached an increase of approx. 30%. This significant rise in stiffness was further investigated using the measured storage modulus; however no microstructural changes of the PVC foam network were detectable when further investigated under the microscope. *Garrido et al.* [18] investigated the effects of different temperature levels on the shear response of PET and Polyurethane PUR foams used in composite sandwich panels. Shear modulus was determined for temperatures ranging from -20 to 120°C. Increased temperature causes considerable reductions of the shear resistance for both PET and PUR foams, i.e. a drop of 66 (or 24) % for a rise from ambient temperature to 80°C was measured. In [19] GFRP-PET sandwich panels subjected to a sustained loading (4%&15% of maximum shear strength capacity of the foam $\tau_{foam,max}$) were tested in a 3PB set-up; shear creep behaviour was evaluated by recording mid-span deflections Δ for a loading period of 1080h. PET (100 kg/m^3) reaches an increase of Δ_{tot} of 14%, whereas PUR (68kg/m^3) achieves 47% [20]; *Huang et al.* [21] even established an

increase by 124% for PUR (96 kg/m^3). Once unloaded the recovery of flexural creep deformations was recorded; approx. 35% of the total deflections were non-recoverable viscoelastic deformations.
The design of FRP sandwich panels used in façade applications is stiffness-driven, and assumes a perfect bond behaviour between face sheets and foam core. The above-mentioned experimental programs have shown degrading behaviour of the constituents. Freeze thaw cycles reduce the material properties of FRP laminates, based upon different thermal expansion coefficients resulting in micro-cracking of the resin matrix which in turn is accelerated if combined with sustained loading and high levels of humidity, e.g. 90% rH up to water immersion enhancing capillary water ingress and hydrolysis. On the other hand, the response of foam to freeze-thaw cycles, sustained loading and their superposition is reported to vary from no measurable changes over increased stiffness to significant reductions in the shear modulus. Moreover, to the authors best knowledge, the phenomena of an increased stiffness is lacking a scientific explanation on the material's level. The inconsistences and gaps in existing research make it impossible to draw any meaningful engineering design guidelines for FRP sandwich panel in façade applications. Therefore it is essential to perform research on the FRP sandwich structure subjected to realistic ageing conditions with a particular focus on the performance of foam – face sheet interface. This paper considers the combined effect of freeze-thaw and sustained load, but excludes the effect of variations in environmental moisture levels. This is equivalent to assuming that the event of rain is too short to allow water ingress via diffusion; standing water should be structurally avoided. However, for future work this assumption needs to be considered more carefully, particularly in view of the *Tuttle* [12] findings that the RH in the core already doubles (24% to 46%) only via face sheet diffusion for an ageing period of 9 months at 40°C and 55% RH; leading to a higher moisture level, which in turn would favour micro-cracking.

EXPERIMENTAL METHOD

The experimental program aims to quantify the effect on the structural performance of GFRP-PET sandwich panels subjected to façade-like natural ageing. The investigated sandwich panel consist of GFRP face sheets (Formax Multiaxial stitched E-Glass fibres/ Gurit Ampreg 21FR Epoxy) and a PET foam core (Gurit – G-PET™ 75FR); panels were manufactured by Premier Composite Technology® (PCT) using Vacuum Assisted Resin Transfer (VARTM) process. The panels are artificially aged by subjecting them to 100 and 200 freeze-thaw (F/T) cycles (~48/96 days) with and without sustained loading of 15% and 35% of the ultimate failure load P_{ult}. This is followed by mechanical destructive testing in a 4-point bending set-up. The first stage of the artificial ageing program (100 F/T cycles) complies with ASTM D7792 [22]; a test program originally designed for FRP pultrusions. Additional 100 F/T cycles are performed for a better understanding of the materials long-term response. A direct translation into real life exposure is not possible as the average annual freeze thaw cycles exclusively depend on the climate zone for which the building is designed. However, 200 F/T cycles is deemed to correspond to an expected life span loading for a building exposed to northern European climate. The thermal cycle ranges between ±2 -14°C and ±2 23°C (ambient temperature). Each temperature level is maintained for 2.5h followed by a 2.5h period to transition between the temperature levels; the duration of one full cycle is 10h [
Figure 1 (a)]. Sustained load is introduced via a forced central displacement of the sandwich panel with self-reacting steel frame (in 3PB configuration) [
Figure 1 (b)]; load cells and displacement transducer are installed at each end of the frame to monitor creep and relaxation of the FRP panel during the ageing period.

The FRP panels were manufactured in the same batch and are supposedly identical. Pre-loaded panels measure 1000x300x25 mm and are sealed around the edges with aluminium tape to prevent direct exposure of the foam core to the environment; replicating realistic application conditions. The environmental chamber used for the F/T- conditioning consists of an "Interlevin LHF620" chest freezer equipped with 4 silicone band heating elements (50Watt each); the interior temperature is recorded using 6 thermocouples type K (TK1,2,4,5,8) [
Figure 1(c)] and ambient temperature is obtained from the reference TK7. Fans close to the heating and cooling elements ensure a constant airflow and steady internal temperature profile throughout the cooling and heating cycles. Labview [23] was used to control the freeze-thaw cycles; the programmed temperature was calibrated according to the temperature within the environmental chamber and not directly of the specimen. However, additional measurements showed only an insignificant discrepancy between the specimen's surface and chamber's air temperature.

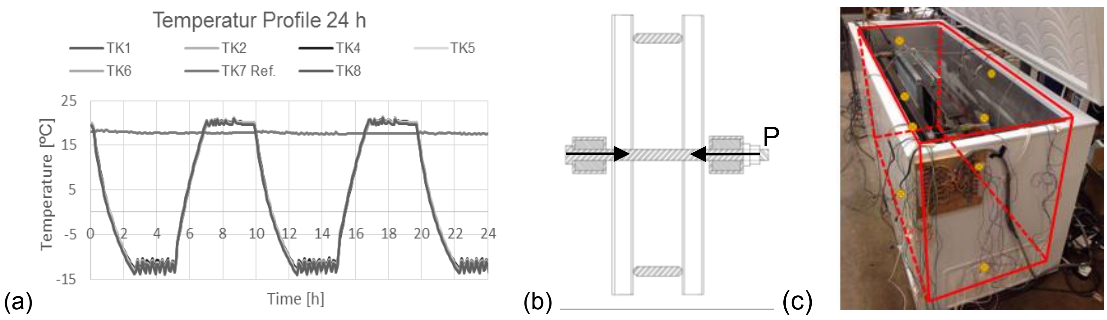


Figure 1. (a) Achieved temperature profile for a time frame of 24h, monitored by 7 Thermocouples (TK); (b) side-view self-reacting frame; (c) Environmental chamber with thermocouple (TK) location.

The specimens are dry cut into the required dimensions (300x75x25 mm) using a diamond wheel cutter and then tested to failure in a 4-Point-Bending (4PB) test with a span of 250mm using an electromechancial universal testing machine fitted with a calibrated 30kN load cell. The central displacement is recorded using a laser extensometer (precision 0.001mm). The four different testing series are referred to as follows: “as-received” with NA-4PB, F/T aged series with 1M-0%-4PB, 1M-15%-4PB, 1M-35%-4PB (or 2M-0%-4PB, 2M-15%-4PB, 2M-35%-4PB) for the unloaded and with 15%/ 35% of maximum failure load preloaded series; 1M and 2M stand for the time frame the series has been aged (1.5 or 2.5 months respectively). As suggested in ASTM 7025 [24] a minimum number of 5 specimens per series was tested; the exact number of specimens is reported in .

RESULTS AND DISCUSSION

For the first testing round after 100 F/T cycles only core shear failure was observed in all but one tested specimens; latter failed in face sheet crushing. The only pronounced difference was found to be the total mid-span deflection, i.e. the panel’s stiffness, of the 1M-0% Series [Figure 2] in comparison to the other three testing series. Further investigation showed that, although from the same patch and with an identical face sheet orientation the build-up differed in the orientation of its foam block alignment. Specimens of the 1M-0% Series exhibit their foam block glue line perpendicular to the loading direction, whereas for the remaining specimens have the glue line orientated in parallel to it. As the adhesive used to glue the foam blocks is of higher stiffness than the foam itself, the glue line acts as a thin web connecting top and bottom face sheets and significantly increasing the panel’s stiffness; results of 1M-0% Series are not further considered. Additional 100 F/T cycles had a major impact on the failure mode; almost 50% of the second testing round failed in crushing of the top face sheet instead of core shear failure. A third round of F/T cycles is currently undertaken in order to determine extent to which the failure mode depends on the ageing degree.

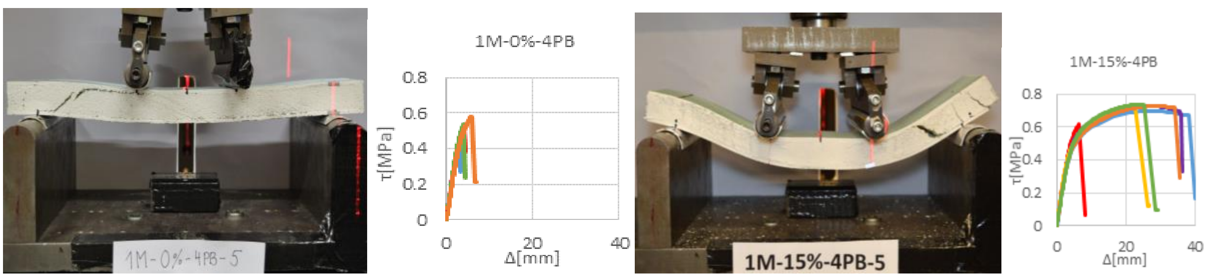


Figure 2. Comparison of failure modes between (a) non-loaded and (b) 15% loaded sandwich panels, both after 100 FT cycles.

Error! Reference source not found. shows the core shear modulus and strength before and after 100 and 200 F/T cycles (with and without preload) for all four testing series. Initial calculations for the bending stiffness and shear modulus based on ASTM D7250 [24] were discarded as the formulae were found to be very sensitive to minor experimental inaccuracies. Instead, the shear modulus *G* was determined from an analytical approach based on fundamental Sandwich beam theory according to

$$\Delta = (PL^3/48D) + (PL/4AG) \quad (1)$$

where Δ is the total deflection, P is the failure load, L is the loading span, D is the bending stiffness, A is the shear area and G is the shear modulus of the core. Stiffness of the face sheet is considered constant for all conditions, assuming that the temperature difference ΔT of the F/T cycles is too small to cause fibre matrix cracking due different thermal expansion of the constituents.

Figure 3 and show and summarise the obtained experimental data for the foam's shear stiffness G and shear strength τ for all tested series but 1M-0% series. The number of tested specimens per testing series (n), the failure modes (C, D, SC) and where applicable the coefficient of variation (CoV) according to the statistical analysis in [24] are reported. It was found, that sustained loading has no significant effect on the overall stiffness and strength of the sandwich panel. Specimens subjected to the different loading scenarios (0%, 15% and 35% of P_{ult}) exhibit after 100 (or 200) F/T cycles similar values for G and τ across all three testing series. It was further observed, that the environmental ageing has only little influence on the material properties. A slightly decreasing trend, supposedly resulting from the material degradation induced by the F/T cycles, was observed. However, the changes are minor and when considered in the scope of experimental errors negligible. Considering the mean value of all three loading scenarios, the shear strength decreased by 8.7% after 200 F/T cycles, whereas the shear stiffness even only dropped by 4.5% for the same number of ageing cycles. A good match between the experimentally obtained data and the material properties provided by Gurit [25] (G = 14 MPa, τ = 0.6 MPa; according to ASTM C-273) is found; the as-received testing series (NA) only differs by -3% and +15% for the G and τ respectively.

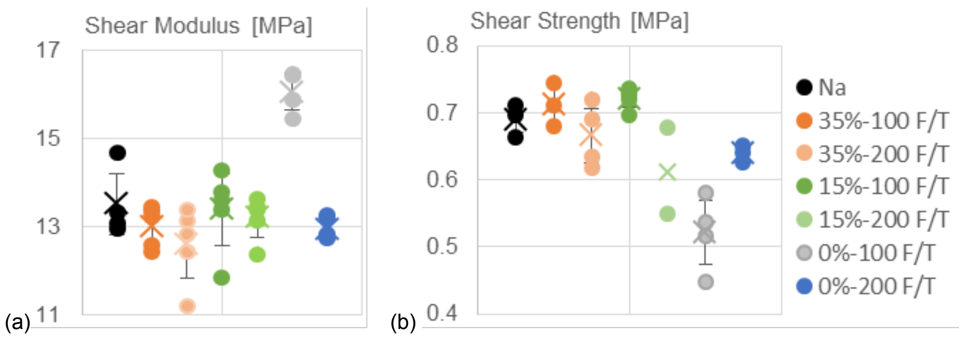


Figure 3. (a) Core shear modulus (b) shear strength: Data scatter, standard deviation and mean value.

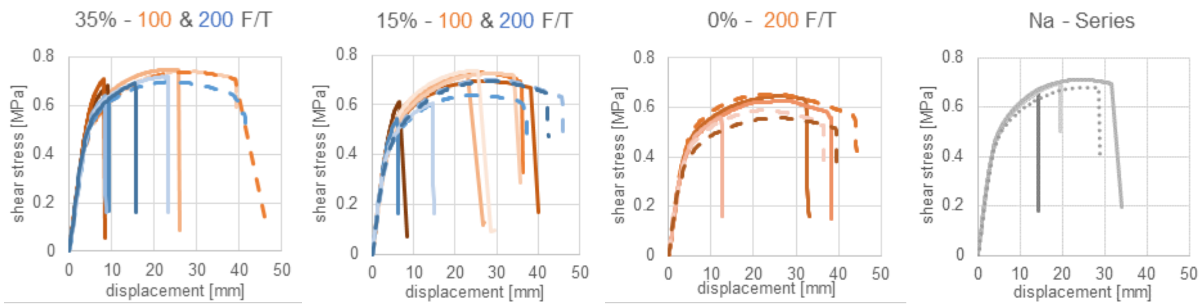
Table 1. Summary of experimental data: core shear modulus G, core shear strength τ, number of tested specimens n and coefficient of variation CoV for as received, 100F/T and 200 F/T cycled series.

		G	n	CoV	τ	n	CoV
NA		13.52	4	5.06	0.69	3 - C*	2.88
					0.69	1 - D**	-
100 F/T	(0%	16.07	4	2.67	0.52	4 - C	9.15)
	15%	13.39	5	6.17	0.72	5 - C	1.91
	35%	13.01	5	3.21	0.71	3 - C	3.7
					0.74/0.74	1 - D/ 1 - SC***	-
200 F/T	0%	12.94	6	1.79	0.64	3 - C	0
					0.57	3 - SC	2.06
	15%	13.21	5	3.71	0.58	2 - C	-
					0.68	3 - SC	4.15
	35%	12.6	5	6.8	0.67	4 -C	6.2
					0.7	1 - SC	-

*C – Core shear crack, **D – Delamination, ***SC – Skin compression

As already briefly mentioned, the only remarkable difference was observed in the change of failure modes with increasing number of F/T cycles. It appears that F/T cycling causes a shift of failure mode from core shear cracking to face sheet crushing (i.e. local buckling of the fibres) at the load introducing point, given that the identical testing 4PB set-up for both 100 and 200 F/T cycles testing series was used. This observation needs to be confirmed with further testing.

All testing series expect the 1M-0% Series, follow a similar load-deflection-pattern. Figure 4 shows the core shear stress τ vs. the total panel deflection Δ for every testing series (excl. 1M-0% Series). The initial linear-elastic initial material response is followed by a non-linear deformation state until failure is reached. This behaviour is governed by the foam response to loading; foam follows an initial linear elastic stress-strain behaviour, which replicates the loading of the cell walls followed by a plateau, where the structure of the cell walls begins to fail. No consistent relationship between the length of the ‘plastic’ plateau and pre conditioning of the testing series was found. Shear crack failure occurs when maximum shear capacity of the foam is reached. Face sheet crushing perquisites that the supporting stiffening effect of the underlying foam locally vanishes, e.g. through cell wall crushing, allowing the fibres to buckle and resulting into crushing of the laminate crushing. It is observed that core shear failure happens for a wider range of mid-span deflection (6.2 to 38.9 mm), whereas face sheet crushing only occurs at higher deflection values, which across all testing series range from 40 to 44 mm. Specimens that failed in face sheet crushing are indicated by the dashed graphs in Figure 4.



*dashed line – face sheet crushing; dotted line – delamination.

(a) (b) (c) (d)

Figure 4. Shear stress vs. mid-span displacement for (a) 35% of P_{ult}, 100 (orange colour scheme)&200 (blue colour scheme) F/T cycles, (b) 15% of P_{ult}, 100&200 F/T cycles (c) unloaded (0% of P_{ult}) , 200 FT cycles and (d) as received (Na-series).

CONCLUSIONS AND FUTURE WORK

- Sustained loading has even after 200 F/C cycle (~90 days) no measurable effect on the stiffness and strength of the sandwich panel. This suggests that the magnitude of sustained loading does not significantly affect the foam. This is in conflict with research by others and needs confirmation.
- A minor decreasing trend in shear modulus and in shear strength (-4.5% and -8.7% respectively) is measured after a total exposure to 200 F/T cycles. However, the absolute values are too close together, hence the resulting variations can be considered within the boundaries of experimental errors.
- Prolonged ageing provokes a shift in failure modes. For 100 F/T cycles, 90% of all tested specimens exhibit a core shear failure and only one specimens failed in face sheet crushing. However, after 200 F/T cycles a significant change in failure modes is observed: only 56% of the specimens failed in shear, whereas 44% exhibit face sheet crushing. This phenomena needs further experimental investigations.
- The limited test results suggest that face sheet crushing results from a prolonged deformation plateau of the sandwich structure when loaded to destruction; plateau length almost doubled. This needs further experimental testing in order to establish this observation.
- Despite the recommendation in [22] of only 100 ageing cycles, a third set of testing series will be evaluated after additional a total exposure to 300 F/T.
- A more elaborated testing program combining the current ageing program with high-cycle fatigue loading replicating localised high wind turbulences on façade systems is in progress.

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