ETFE Membrane Structures: and What About Hail Impact Resistance?

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Doorways to the Future
ABSTRACT
Ethylene-tetra-fluoroethylene (ETFE) membrane structures have become very fashionable in Europe since large, light-transparent buildings like the Eden Project in Cornwall, the Space Centre in Leicester, England, and the Masoala Rainforest Building (MRF) in Zurich and others became very popular. In Europe, increasing hail intensity and frequency might be the result of climate changes. Alpine countries such as France, Switzerland, Germany, Italy, and Austria are increasingly hit by hailstorms. Therefore, buildings must exhibit increased resistance against hail impact. Current test procedures often require a hailstone size of 40 mm (approximately 1.6 inches) and higher. Experiences during the recent hailstorms will be explained with reference to the MRF building, where, after the first hailstorm in 2002, a protection system was mounted. In another hailstorm occurring two years later, the installed system proved its efficiency.

SPEAKER
PETER H. FLÜELER has 26 years experience in polymer technology of building materials and their long-term performance. He has done extensive hail resistance and polymer material testing and evaluation. Flüeler has lectured to architects and engineers at the Swiss Federal Institute of Technology ETH, Zurich.
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INTRODUCTION
In the last ten years, many large sculptural buildings with special optical effects were designed and built for park decks, gardens, museums, exhibitions, sports facilities, etc. Spectacular examples in which ethylene-tetrafluoro-ethylene (ETFE) was used for roof and wall coverings are the Eden Project in Cornwall, Great Britain; the Air and Space Center, Leicester, GB; the Masoala Rainforest MFR building in Zurich, Switzerland; and Allianz Arena, Munich, Germany. More such buildings are under study or in the stage of realization in China and in other countries.

Important requirements of such buildings are high transparency, light weight, visual effects, sculptural tolerance, or possibilities of unconventional shape, long service life, and low cost. It seems that ETFE membranes combined with steel framework constructions do meet most of these requirements.

In this article, the experiences of the MRF building at the Zurich Zoo during two hail-storms in 2002 and 2004 will be discussed. The study and realization of a protection against hail impact will be presented.

ETFE MEMBRANE PROPERTIES AND MANUFACTURING OF AIR CUSHIONS

Material Properties
ETFE is the abbreviation of a semi-crystalline thermoplastic polymer usually composed of polyethylene (PE) and tetra-fluoro-ethylene (TFE) in a ratio of 1 to 3. By inserting P-segments into the stiff TFE molecular chain, good melting properties are achieved, facilitating the extrusion process. Hence, thin foils can be manufactured with a slightly bluish color if not filled with pigments. Such foils are light- and UV-transparent. They have a high tear resistance, high melting temperature, excellent surface properties, good aging behavior, outstanding resistance against chemicals, and good fire properties. They can be colored and the surface treated for special appearance. The main properties are listed in Table 1.

Drawbacks are point and shock loadings because of their thinness. Special attention is required to mechanical influences from installation and maintenance. Vulnerability to vandalism and sound transmission of such structures must be respected during design, construction, and use. At present, the membranes can be welded by hot air or high frequency techniques only under controlled factory conditions. Repairs

<table>
<thead>
<tr>
<th>General properties</th>
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<tbody>
<tr>
<td>Density</td>
<td>1.73 g/cm³</td>
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<tr>
<td>Mass of 0.1 mm membrane</td>
<td>0.173 kg/m²</td>
</tr>
<tr>
<td>Appearance, non-pigmented</td>
<td>glossy, transparent, slightly bluish</td>
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<tr>
<td>Surface</td>
<td>smooth, water repellent</td>
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</tbody>
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<table>
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<tr>
<th>Main mechanical properties (0.2mm thick)</th>
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<tbody>
<tr>
<td>Tension: E-modulus (long./perp.)</td>
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<tr>
<td>Tension: stress at stretching (long./perp.)*</td>
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<tr>
<td>Tension: elongation at stretch (long./perp.)*</td>
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<tr>
<td>Tension: stress at rupture (long./perp.)</td>
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<tr>
<td>Tension: elongation at rupture (long./perp.)</td>
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<tr>
<td>Tear resistance (500 mm/min)</td>
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<tr>
<td>Point loading (500 gr. drop test)</td>
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<td>Stress/ elongation (50 mm/min.)</td>
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<tr>
<th>Physical-chemical properties</th>
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<tr>
<td>Melting range</td>
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<tr>
<td>Coefficient of thermal expansion</td>
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<tr>
<td>Transparencies of 0.1 mm foil (4 mills)</td>
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<tr>
<td>UV-Transparency</td>
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<tr>
<td>Fire: classification</td>
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<tr>
<td>Weathering, aging</td>
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<td>Chemical resistance</td>
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*Initiation of stretching starts earlier!

Table 1 – Main properties of ETFE foils.
are done by compatible adhesive tapes. Sound transmission from inside to outside or inversely should be studied carefully.

**Manufacturing**

**Membrane:** ETFE membranes are made of granular raw material and extruded in a die of a size of 1.55 m (status 2005). Regular membranes are produced in a thickness range from 0.08, 0.10, 0.15, and 0.2 to 0.25 mm. For air cushions, a membrane thickness of 0.2 to 0.25 mm (8 - 10 mills) is common.

**Air cushions:** The 1.55-m-wide (5.1 foot) membranes are joined by hot air and high frequency welding techniques. The cushion elements are cut out of the rolled material by CNC-controlled machines according to their geometrical shape. The borders of two or three membranes are folded in loops and then welded, and a flexible rod is inserted in the loop. In a last step, the rubber profiles are mounted and then prepared for shipment. On the construction site, the prefabricated cushions are pulled into a slotted metal profile so that the loads are linearly transferred to the supporting main structure. A fault-free installation is required to avoid stress concentrations.

**Masoala Rainforest Building, Zurich Zoo**

The Masoala Rainforest Building (MRF) at the Zurich Zoo has a steel framework construction covering an area of 120 x 90 meters (2.5 acres). Ten Virendeel steel arches span 90 meters with a flashing height of 31 meters. Between the main arches, the roof loads of the membrane structure are supported by two lighter steel trusses. Longitudinal loads are transferred to the main structure by interconnecting wind struts (Figures 1, 2, and 3).
The building envelope consists of an inflatable triple membrane made of ETFE foils jointed to load-carrying air cushions bridging the 4-m gap from the bearings to the arc top. The border cushions span the entire arc from bearing to bearing with a total length of 100 meters. The air cushions are formed by a wind-adaptive pressure of 250 - 350 Pa (approx. 1 - 1.5% of a car tire pressure). Also, the front sides are sealed by air cushions. For maintenance and cleaning, a mobile framework provides access to the inside surfaces of the air cushions. Lateral steel flaps at the bearings and nine large skylights in the roof provide ventilation and support the climate conditioning system.

THE CONCEPT OF HAIL IMPACT PROTECTION

Hailstorm 2002

The hailstorm of June 24, 2002, one week after the installation and one year before the official opening of the MRF, damaged the exterior membranes of the building envelope. All air cushions of the roof except the front sides had to be replaced. The damage was caused mainly by the size, shape, and intensity of that hailstorm. Knobbed and strangely shaped hailstones sized up to 70 mm caused the pressure drop of the cushions and water intrusions due to multiple perforations. Repair of such heavy damage was extremely time consuming, costly, and risky.

Development of a Protection Plan

Within a very short time, a plan to avoid future hail damage had to be established, evaluated, and tested in order to guarantee the opening date in June 2003. In order to maintain insurance coverage, a protection system of the air cushions was mandatory. At that time, no membrane build-

![Figure 4 - Lateral bearings of the steel arches with three air cushions and lateral air flaps for the ventilation. Distance between the main beams, 12 meters.](image)

![Figure 5 - Typical hail size and shape of hailstorm June 2002. Swiss 2-franc coin with diameter of 27 mm (about 1.1-inch diameter). Photo, U. Spreiter, Wallisellen.](image)
ing worldwide had such a protection. Also, experiences about achieved protection effects of such systems were missing. The following installations were taken in consideration: for temporary or permanent use, stiff (transparent plates) or flexible systems (nets, foils, etc.).

After studying pros and cons, costs estimation, and the available timeframe of only four months (the planting of the forest was already underway), the zoo decided to install a permanent protection system in the form of an additional membrane. The membrane of the same thickness covers the air cushions and is inflated by a separate pressure system. It is mounted to the framework, avoiding interference with the sub-laid membrane structure. Therefore, replacement is possible at any time.

EXPERIMENTAL EVALUATION OF THE PROTECTION CONCEPT

Procedures

The efficiency of the protection system was tested in two steps: as single-layered and double-layered membranes with varying spacing pressurized at 150 Pa. The hail impact was simulated by polymer and ice balls of 40 and 50 mm with a velocity range of 5 - 60 m/s. The displacement of the membrane was measured by a high-speed camera. Typical characteristics such as stretching initiation, crack appearance, perforation of the top and bottom membranes were recorded.

**Figure 6 – Realized hail protection with an additional ETFE layer, exchangeable without interference to the main building envelope.**

**Figure 7 – Experimental arrangement for hail impact tests on the inflated ETFE membrane, size 2.0 x 1.7 m².**
equal showed rated Joules, cushions. increasing placement.

Results

The optimal thickness of the membrane was found by testing with impacting polymer balls of Ø 40 mm. Figure 8 shows the kinetic energy for various velocities in relation to the membrane displacement. At a velocity of 30 m/s equal to 13.6 Joules, impacting ice balls caused indents with increasing stretching to the air cushions. At 50 m/s, equal to 36 Joules, the top membrane perforated and the bottom membrane showed stretching phenomena. However, impacting with polymer balls caused similar phenomena already at 20 m/s and respectively at 52 m/s. The difference results from friction, surface temperature, and its heat transfer.2

INSTALLATION AND FULL-SCALE PROOF TEST — HAIL STORM OF AUGUST 7, 2004

Installation of the Protection System

First, the perforated air cushion of the building envelope had to be replaced and re-pressurized. Then, the protection membranes equipped with the EPDM profiles were installed. Due to the arch shape of the trusses, the boundaries of the protection membrane had to be screwed to the existing Alu-profile with a spacing of 15 cm (6 inches). Special attention was paid to waterproofing and to wind forces. The air pressure generators were mounted on the top of each main steel arch (12 systems connecting three protection membranes).

Full-scale Hail-proof Test

On July 8, 2004, the region of Aargau in Zurich was struck again by a severe hailstorm. Compared with 2002, the hailstones were of smaller size, but again, they were knobbed and sharply edged, causing higher impact energy per unit area (Figure 11).

The protection membrane of the MRF building was impacted and perforated by numerous hits - mainly on the exposed northwest faces. It fully served its protection purpose and no air cushions were damaged. Until now, the protection membrane has not yet been replaced, for ecological reasons. It will provide sufficient protection during future hailstorms.

CONCLUSION

European regions such as the Alps, the Pyrennes, the Apennine, the Carpats, as well as other areas, are frequently hit by hailstorms. Due to the climate changes, their frequency has increased. Hailstones have changed to more frequent irregular shape and bigger size.3 Very often, the hailstone size exceeds 40 mm (1.6 inch), the recommended size for hail impact resistance in Switzerland. Insurance companies are aware of the new risks. They are in the process of changing their compensation policies accordingly and pressing for stricter building codes.4 The Swiss standards have

Figure 8 – Kinetic energy vs. deflection of 40 mm PA-balls for different membrane thicknesses.

Figure 9 – High-speed sequence of a Ø 40 mm PA sphere impacting a single 200 µm ETFE-membrane. At a velocity of 50.8 m/s, a total deflection of 108.5 mm was observed causing small cracks after extended stretching. Background: 10 and 50 mm grid.
already implemented hail impact as a regular load as well as protection measures. Also, a classification of hail impact resistance for building materials will be introduced soon. It will describe the damage-free range for relevant hailstone sizes. Engineers, architects, and building owners are well advised to evaluate the hail impact risks already in the design stage.

ETF membrane constructions and similar thin building envelopes are susceptible to impact loads. The shape and nature of the striking object play an especially important role. At the MRF building, it was demonstrated that an efficient protection can be installed without change in appearance and major limitations in use. In addition, limited protection against flying, wind-driven objects is also achieved. Extended test series showed that a spacing of 100 mm (4 in) between the protection layer and the air cushion with a minimal pressure of 150 Pa is sufficient. It withstands hailstones up to 50 mm without damaging the bottom membrane.

Furthermore, the experiments have shown that the hailstorm conditions are simulated more realistically by using ice balls. During impact, the heat dissipates faster with the use of ice balls, due to a large contact surface with the membrane, a high stretching rate during an impact, and the surface friction. In hail impact experiments, it is therefore highly recommended to use ice balls of constant quality.

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Figure 12 – Protection membrane after hailstorm of July 8, 2004. It suffered numerous perforations and indents but air cushions were undamaged.

REFERENCES


