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TEC – Thin Environmental Cladding

Glass as functional facade element

Alan Tomasi[a,*], Danijel Mocibob[a], Bert van de Linde[a], Frank Wellershoff[b]
and Kristian Koldtoft[c]
[a]*Permasteelisa Group, Vittorio Veneto, Italy*
[b]*HafenCity Universität Hamburg, Germany*
[c]*Fiberline Composites, Middelfart, Denmark*

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Abstract. Permasteelisa Group developed with Fiberline Composites a new curtain wall system (Thin Environmental Cladding or TEC), making use of pultruded GFRP (Glass Fiber Reinforced Polymer) material instead of traditional aluminum. Main advantages using GFRP instead of aluminum are the increased thermal performance and the limited environmental impact. Selling point of the selected GFRP resin is the light transmission, which results in pultruded profiles that allow the visible light to pass through them, creating great aesthetical effects. However, GFRP components present also weaknesses, such as high acoustic transmittance (due to the reduced weight and anisotropy of the material), low stiffness if compared with aluminum (resulting in higher facade deflection) and sensible fire behavior (as combustible material). This paper will describe the design of the TEC-facade, highlighting the functional role of glass within the facade concept with regards to its acoustic, structural, aesthetics and fire behavior.

Keywords: Facade design, structural design, structural analysis, building envelopes, curtain walls, glass facades, structural panels, building materials, glass, day-lighting, sustainable development, performance assessment

1. Introduction

TEC, Thin Environmental Cladding, is the latest technological development completed by the Permasteelisa Group R&D department. This is part of Permasteelisa's Alter Technology, which looks at innovative design systems and materials. More specifically, TEC represents a curtain wall system entirely composed of pultruded composite material. The expert knowledge of pultrusion techniques and GFRP (Glass Fibre Reinforced Polymer) properties was provided by Fiberline Composites with a common and challenging objective: the development of a high performing, top quality product characterized by a unique architectural appearance. Figure 1 shows the final product applied in the full-scale test area. As can be seen, GFRP material (and chosen insulating material for cavity filling) allows for high-diffused light transmission levels. This results in great aesthetic effects during night-time and in natural lighting during day-time.

*Corresponding author: Alan Tomasi, Group R&D Project Manager, Permasteelisa S.p.A., viale E. Mattei 21/23 | 31029 Vittorio Veneto, Treviso, Italy. Tel.: +39 0438 505207; E-mail: a.tomasi@permasteelisagroup.com; www.permasteelisagroup.com.

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Fig. 1. TEC views: mock-up panels during day-time (a) and during night-time (b); demonstrator panel exposed at Palazzo Giustinian Lolin in Venice (c).

As can be seen, in order to give to TEC this unique and innovative light skin appearance, Permasteelisa decided to openly show the GFRP on both facade faces, designing large, translucent framing and infill elements. This peculiarity – important for the characterization of the product – implied a challenging design work to keep the facade performance to the reference high levels. Within the TEC, glass has been applied not only as simple frame infill, but also as functional component to pass over the GFRP disadvantages and, at the same time, to improve the facade performances assuring the desired aesthetics.

Thin translucent GFRP surfaces need to be made heavy to achieve the desired sound insulation values. The only transparent material with adequate weight is glass, which has been included as an aesthetic shield on the external surface. To achieve the desired aesthetics, glass on framing has been laminated to GFRP plates using a cold lamination process (due to the maximal temperature that the GFRP can sustain, standard autoclave processes are not feasible).

Due to acoustic insulation, the decoupling of internal and external skins was mandatory, although coupling them would result in higher structural stiffness, increasing the effective inertia due to the composite effect. An intensive investigation on structural adhesives has been conducted with the purpose to find the best compromise (not too rigid, not too weak – acoustic decoupling vs. sandwich effect). The best solution has been found in a high modulus silicone, which assures sufficient stiffness, stable and durable, which allows reducing the thicknesses of the framing, proportionally reducing the cost and environmental impact of the product.

Another aspect where glass was exploited is to improve the fire reaction property of the facade skins. Being a combustible material, the burning behaviour of GFRP is sensitive to its thickness. The glass pane laminated with the GFRP increases the capability of conducting the heat away from the burning area (glass is more conductive than GFRP), which decreases the burning rate, which allows reducing the GFRP plate thicknesses, maximizing the light transmission of framing and spandrel areas.

2. TEC-facade design

The TEC-facade research project began with the idea of developing a simple and unique unitized facade system entirely composed by GFRP pultruded profiles. The pultrusion process allows very large shapes to be produced with good tolerances. This possibility pushed the design toward a solution

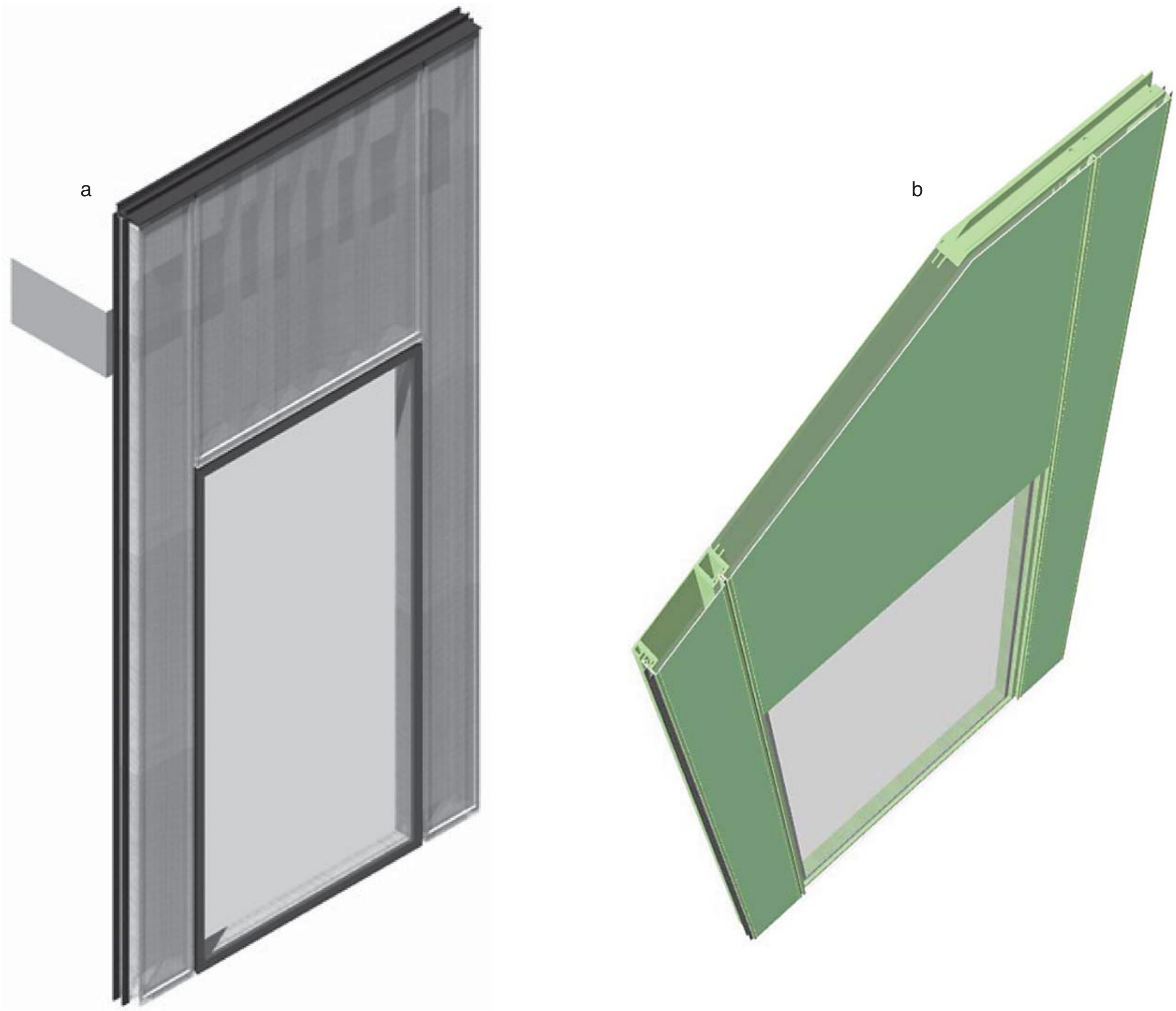

Fig. 2. TEC design: preliminary design (a) and final design (b).

composed by large, hollow mullions and a spandrel area composed by one entire hollow profile (Fig. 2a). This solution, despite the intrinsic lack of flexibility in panel width (given by the width of each profile), would have given to the facade concept a unique and personal design, completely exploiting the possibilities given by the innovative material and production process. However, the design solution presented a few lacks, which caused a challenging design work to be improved.

Pultruded composite profiles are characterized by an important anisotropy, which become even more important when large sections are considered. Material stiffness in orthogonal direction to the pultrusion is about 1/3 of the stiffness in parallel with the reinforcements (mono-directional glass fibres). This property led to inadequacies of the design system considered as a whole. Even if all the profiles considered alone appeared to be correctly designed, the results of simulations performed on the panel as a whole were poor. Due to material anisotropy, in addition to the vertical component of deflection (usual governing factor in unitized CW design), a horizontal one has to be superimposed, which exceeds the total deflection above the limits.

Beyond structural inadequacy, also the acoustic behaviour of the preliminary TEC resulted poor. GFRP material is in fact characterized by very low specific weight which is, regarding the acoustic, a disadvantage: at low frequencies the sound insulation values of a homogeneous partition is proportional to its mass. Moreover, in large hollow profiles, profile ribs act as sound transfer mean, rigidly connecting internal and external facade skins. For acoustic, decoupling of internal and external skins is as much important as the high surface mass.

Driven by the need to solve acoustic and structural performances, the preliminary concept was redesigned to a solution which implements the three exposed principles: increased stiffness in panel width, increased surface weight and decoupling of the external and internal skins, maintaining at the same time the characteristic appearance. The final design solution consists of an external glass/GFRP laminate skin structurally bonded to a main GFRP frame. The float glass pane, 12 mm thick, would assure the right surface weight, contributing also to the panel stiffening in the width, while decoupling of facade skins would have been assured by the structural adhesive used to fix the external laminates (Fig. 2b).

3. Structural analyses

First step was the validation of structural adequacy of the facade concept. In this particular case, because of the slenderness of the facade frame, the contribution of glass stiffness and glass/GFRP sandwich effect is crucial. Structural calculations have been performed on the entire panel, considering strength and stiffness of the adhesive joint, connecting the external skin as a parameter. Facade deflection and tensile stresses on external glass skin, detected as the most critical points, have been monitored with high accuracy and is presented further on.

Numerical simulation is done, using FE (Finit Element) software Straus7 (Straus7, 2004). Isotope plate elements are used for modelling the glass panel and aluminium bracket, while orthotropic plate element is used for simulating the GFRP mullion. Beam elements are used to model the GFRP transoms, while the adhesive was modelled using brick elements (Fig. 3a). Being an anisotropic material, pultruded GFRP profiles are characterized by different mechanical characteristics in different directions, in accordance with manufacturer guidelines (Fiberline, 2002).

A panel is restrained at bracket position, while connections between GFRP mullion and transom are modelled using master-slave links, joining a pair of nods in all directions (Fig. 3a). Due to panel and

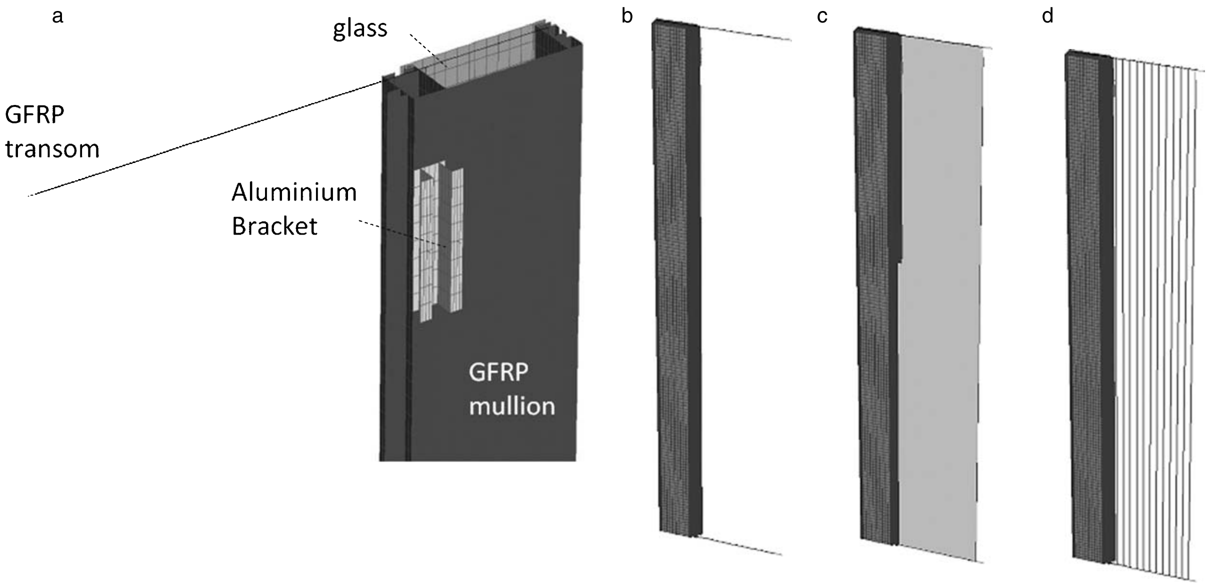

Fig. 3. FE modelling: (a) connection details (b) symmetrical model (c) load path (d) Gerber effect.

load condition symmetry, only one half of the facade is modelled (Fig. 3b). The governing load for serviceability limit state of facade is the wind load. A reference value of 2.4 kPa (240 kg/m^2) has been considered; which is typical for high-rise buildings, corresponding to maximal wind gust (duration of three seconds) with a return period of fifty years. Wind load has been implemented in the FE model as surface pressure on plate elements (Fig. 3c). Normal to plane displacements of top and bottom transoms is linked to simulate the shear transfer (from one panel to the panel above) at stack joint position (Fig. 3d).

A parametrical study varying the stiffness of the adhesive, starting from an Elasticity modulus of 1 MPa (typical for structural silicones) to 1500 MPa (typical for rigid Epoxies) have been studied. Furthermore, different bracket positions (distance from the restraint to the top edge of the panel) at 200 mm, 400 mm and 800 mm have been investigated, to simulate various solutions that can occur during the facade design.

Parametrical study results on the influence of the adhesive elasticity modulus E_a on TEC-facade out-of-plane deflection f_y can be seen in Fig. 3a. Due to the increase in the glass/GFRP sandwich effect, using stiffer adhesive, out-of-plane deflection is decreasing, reaching almost constant value for adhesives with elasticity modulus higher than 200 MPa (once the sandwich effect reaches 100% – glass and GFRP act as rigid component: further increase of adhesive stiffness would not lead to further improvement. The serviceability limit here is settled to be 18.3 mm which for spanning length greater than 3000 mm correspond to the allowable deflection of L/300+5 concerning the (CWCT, 2005).

Figure 4b is showing the influence of the adhesive elasticity modulus E_a on the principal tensile stresses in the glass. It can be noted that principal tensile stresses in the glass are increasing slightly with higher modulus adhesives, and more evidently when the bracket is moving to the central span (800 mm) then toward the ends (299 mm). Here, allowable tensile stress limit for glass is according the standard ASTM E1300-09a (ASTM 2009), where for float annealed glass strength limit on the edge is 18.8 MPa.

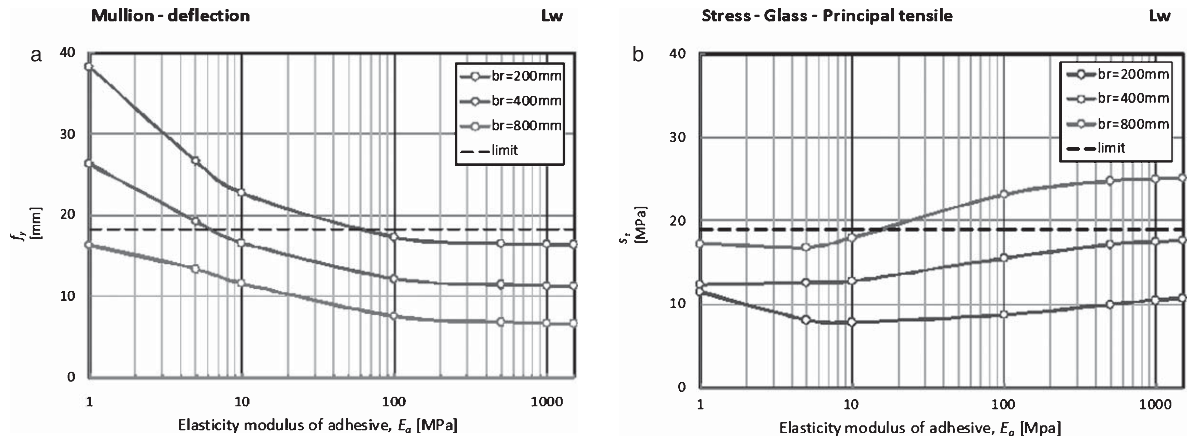

Fig. 4. FE results – influence of elasticity modulus of adhesive E_a on (a) out-of-plane mullion deflection f_y (b) principal tensile stress in glass σ_t.

Deformation shapes of the facade mullion are highly dependent on mullion restraint/bracket position. As can be seen in Fig. 5a, with the bracket placed close to mullion end, bigger rotation happens at mid span, while for bracket position at 800 mm from the mullion end it happens close to fixing point. This has direct influence on principal tensile stresses in the glass, because glass through the adhesive is forced to follow the mullion deformation. Maximum stress on glass occurs at glass edge, for which reason chamfering and polishing of glass edges is strongly recommended. For cost and safety reason (post breakage behaviour), annealed float glasses can be considered and an upper bound has been defined for the adhesive elasticity modulus.

4. GFRP/glass composite behaviour

Based on the obtained numerical results, an adhesive screening phase took place. The following requirements have been defined of primary relevance: elasticity modulus between 10 and 100 MPa, elongation at failure higher than 200%, elasto-plastic or hyper-elastic behaviour, relatively fast curing time, high moisture and UV resistance, mechanical stability at extreme temperatures (from −20°C to +80°C) as well as compatibility with GFRP substrate.

Literature screening, data sheet collection and manufacturer interviews have been done, considering at the early stage many adhesive types (acrylics, silicones, epoxies, polyurethanes and MS polymers). With the collaboration of the manufacturer, preliminary tensile and shear tests on the most promising adhesives were done. The following adhesives have been considered as the most promising:

- mono-component acrylic adhesive (cured by UV exposure)
- bi-component acrylic adhesive (fast curing)
- high modulus structural silicone

Tensile test, performed in accordance to ISO 527-1 (ISO, 2012), on mono-component acrylic adhesive shows very good stability in the defined temperature range, maintaining a high deformation at failure also at −20°C (Fig. 6). Although having elongation at break higher than 300%, due to elasto-plastic material behaviour, with limited elastic phase and large ductility, this adhesive was considered as a

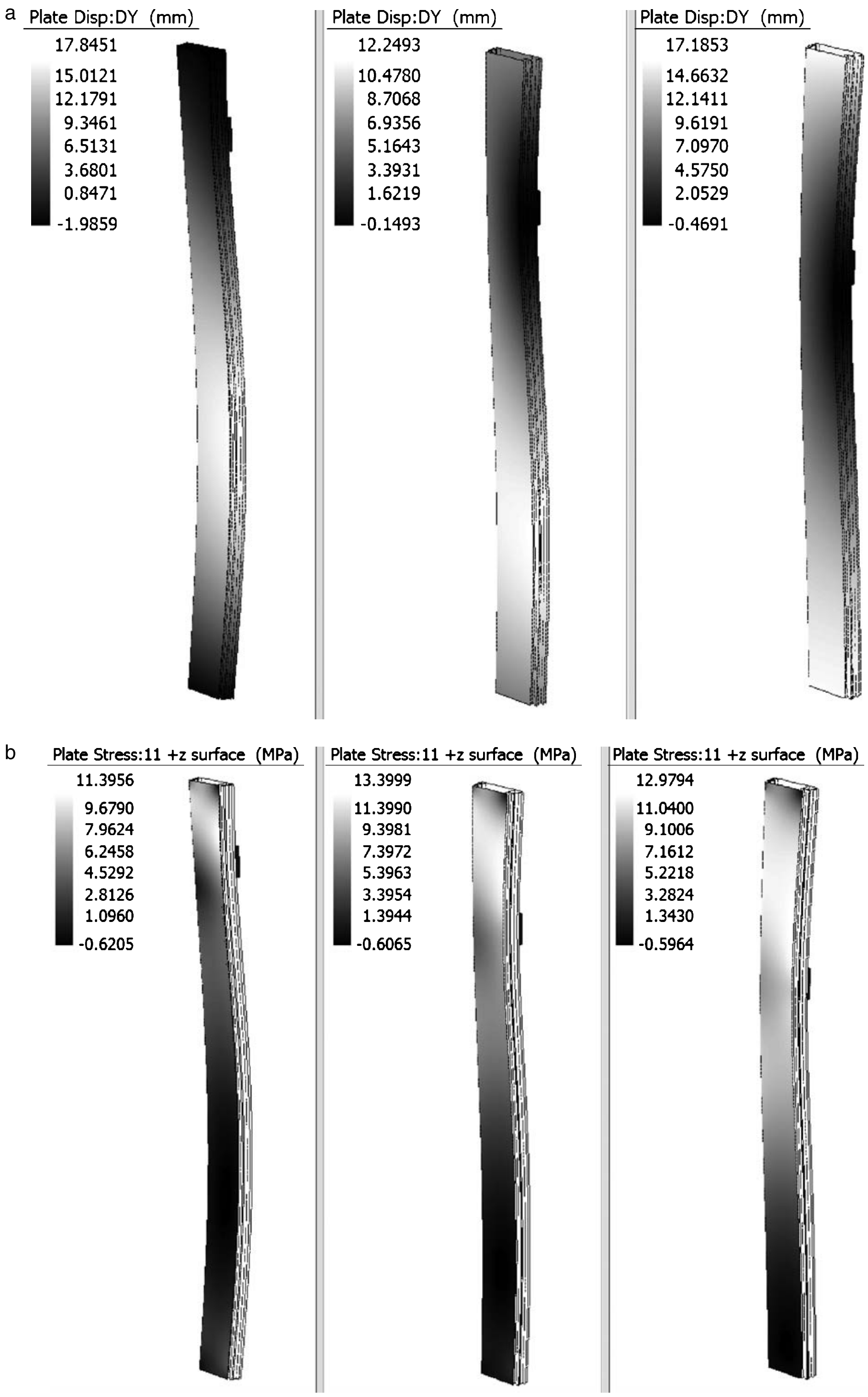

Fig. 5. FE results – influence of bracket position (from left, 500 mm, 850 mm and 1200 mm below the stack joint) on (a) deformation shape (b) distribution of principal tensile stress in glass.

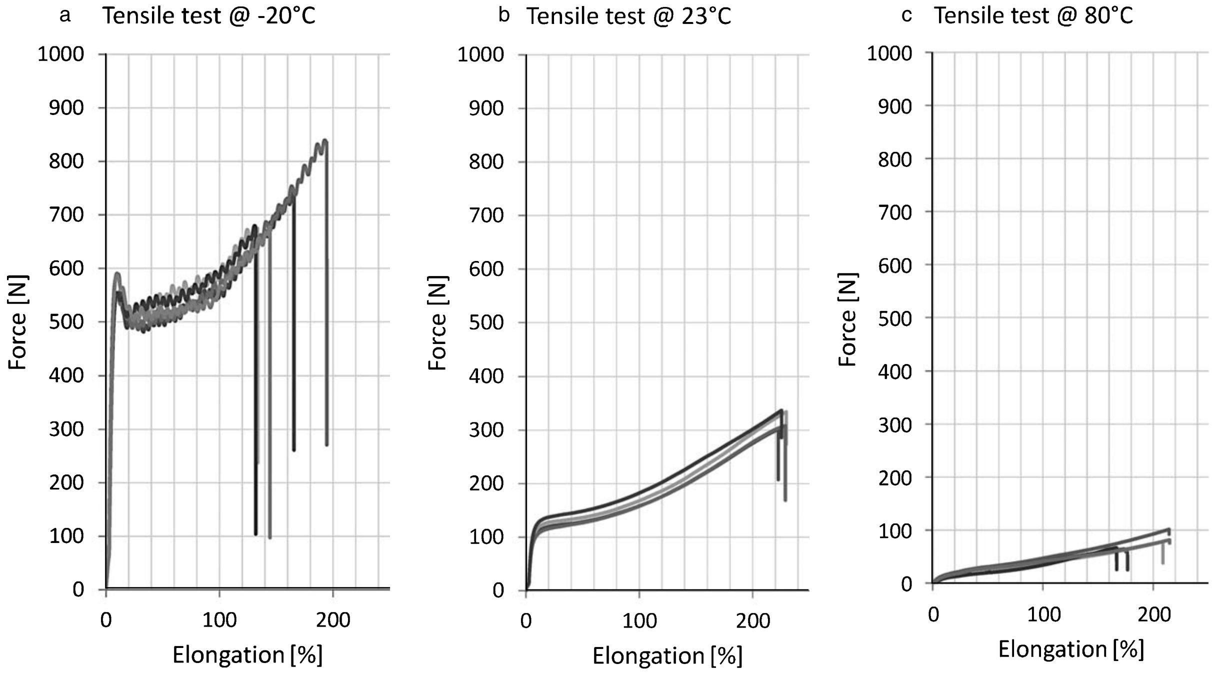

Fig. 6. Tensile test of mono-component acrylic at (a) −20°C, (b) +23°C and (c) +80°C.

risk due to irreversible elongation that can occur due to differential thermal expansion between GFRP and glass. Furthermore, thin design thickness (1.5 mm), has been considered as disadvantage, due to difficulty of thickness control during the production.

The bi-component acrylic showed good adhesion to glass/GFRP substrates as well; however, due to quite low glass transition temperature at around 50°C, mechanical properties drop immediately, reaching at 80°C values comparable with standard structural silicone, which can be seen from the DMA test results on Fig. 7a. Similar elasto-plastic behaviour with its disadvantages explained earlier, can be noted from the tensile test in Fig. 7b.

As a conclusion, the high modulus structural silicone has been chosen. It proved good adhesion performance, compatibility with the GFRP substrate and the typical stability and durability of silicones. However, elasticity modulus of 2.5 MPa, is lower than what was defined in the preliminary requirements. This has no influence on glass stresses because the diagram is almost flat in that region (Fig. 4b), but the panel deflection limit is exceeded (Fig. 4a). It has therefore been chosen to reinforce the GFRP structure and to consider, for the worst cases (maximum wind load and maximum panel dimensions), an alternative bracket system which allows fixing the panel bracket at 400 mm below the panel-to-panel joint. It can be noted that the slightly increase of silicone stiffness (from standard structural to high modulus structural silicone) has in this particular case a big influence in reducing the panel deflection.

Long-term durability tests have successfully been performed with structural silicone, fulfilling requirements prescribed by ETAG002 part 1 (ETAG, 1999). Figure 8 is showing the failure modes of the peeling tests and tensile tests. In both cases, a cohesive failure of the adhesive can be noted. GFRP substrate demonstrated to be compatible with silicone; several surface pre-treatments were tested before suitable cleaner and primer were selected.

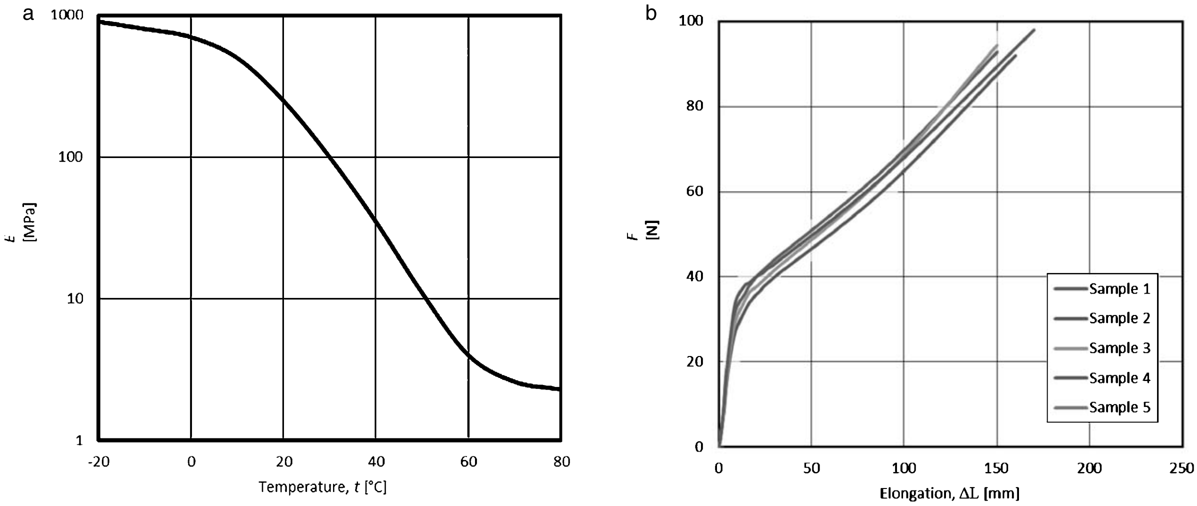

Fig. 7. Test results of bi-component acrylic adhesive (a) DMA test (b) tensile test at 23°C.

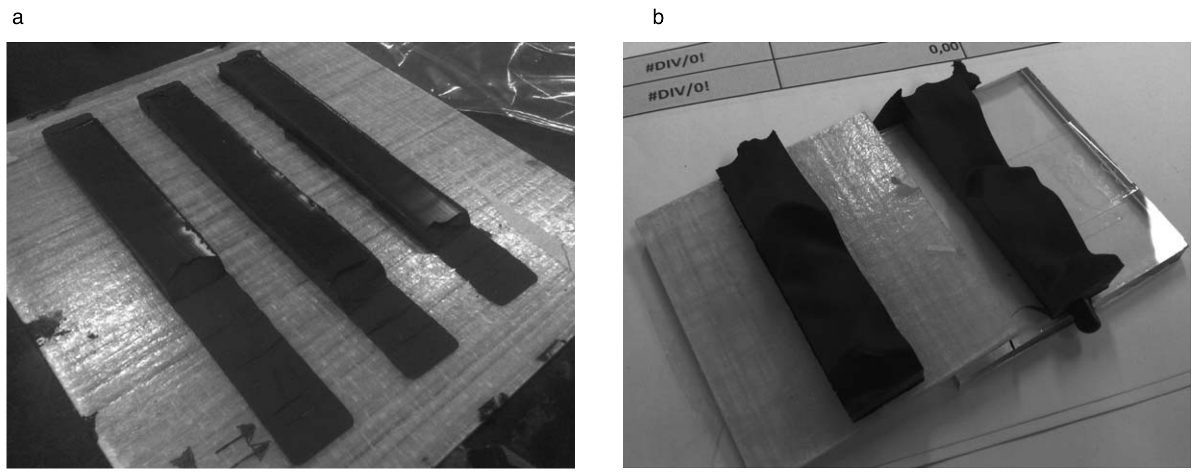

Fig. 8. Failure mode (a) peeling test (b) tensile test.

5. Acoustic analyses

If structural performance can be accurately determined upfront through simulations, the same cannot be said for acoustics. Acoustic software allows evaluation of sound insulation values of relatively simple systems with tolerances not lower than 2 dB. Moreover, good experience is required in order to properly set software parameter and to consequently understand the results. Since acoustic behaviour of GFRP was not known, it has been chosen to proceed via testing.

While final GFRP profiles were not available (test done in pre-production stage), a similar system has been built with existing pultruded profiles: actual profiles have been obtained bonding different GFRP parts with an epoxy adhesive (thin, stiff adhesive joints), while for bonding the laminate skin, a

b

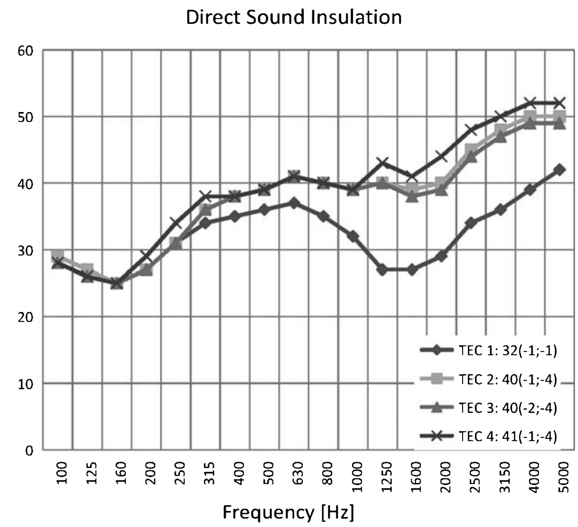

Fig. 9. Acoustic test (a) specimen set-up (b) direct sound insulation test results.

a medium modulus acrylic adhesive has been chosen. Figure 9 shows the acoustic test set-up as well as results from the tests.

Four configurations have been tested, changing panel joint sealing. Last configuration (TEC4) represents the insulation of the facade with the IGU shielded (hence, sound insulation of mullion and spandrel areas). Results show very good improvements given by the float glass application: direct sound insulation value passed from 36 dB to 40 dB. The improvements given by the glass is much more evident at low frequencies: performance with correction for traffic noise (second parameter between brackets) passed from 26 dB to 36 dB. Considering that 3 dB of difference in sound level corresponds to a double sound intensity, this can be considered a huge improvement. As a conclusion, the float glass skin added on the new design proved to satisfy acoustic and structural requirements.

A test done at the end with the real pultruded profiles confirmed the results estimated, achieving very high sound insulation even with the limited wall thickness.

6. Glass/GFRP lamination

In order to maintain the characteristic aesthetics defined at an early stage of development, GFRP plates have to be added externally to the glass skin. Given the limited thermal expansion coefficient of pultruded GFRP, which is similar to float glass, because high percentages of reinforcement fibres are used, development focused immediately on industrial glass/glass lamination processes. The following interlayer materials have been considered and tested:

- Standard autoclave lamination with PVB interlayer: not applicable because of elevated temperatures required by the process (140°C) which is not sustainable by the GFRP;
- Vacuum bag lamination with PVB, EVA, PU and SentryGlass: purpose to study the adhesion properties of the interlayer and influence of a low oxygen atmosphere on GFRP. At process

a b

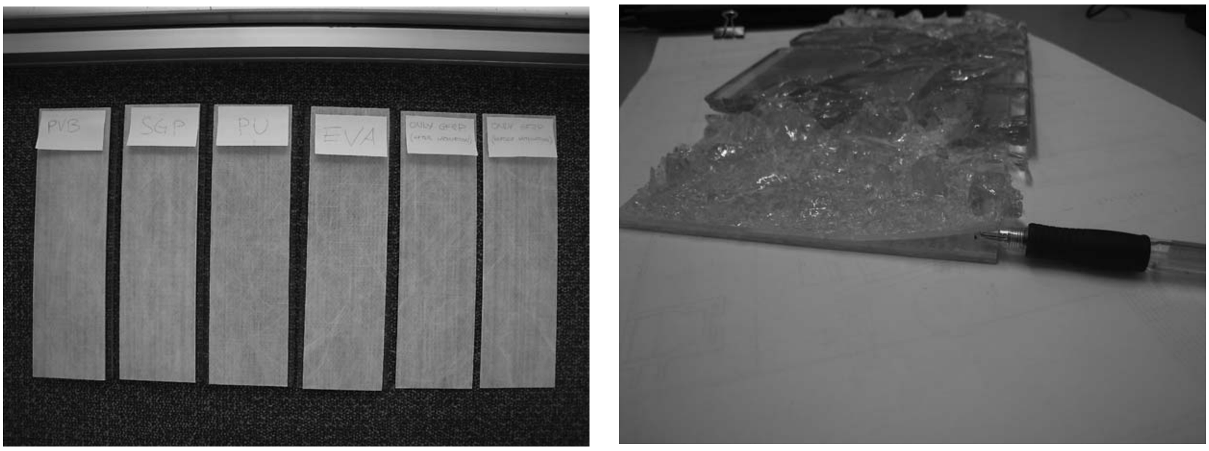

Fig. 10. Vacuum bag lamination process (a) delamination after pummel test (b) colour degradation at different temperature.

temperature of 95°C GFRP, preliminary pummel test shows promising results for PU and EVA interlayers, but GFRP yellowish. At the process temperature of 80°C, the GFRP did not deteriorate in colour, but adhesion problems between interlayer and GFRP occurs (Fig. 10);

- Cold lamination processes using resins: three products have been considered: a 2-component polyurethane, a mono-component acrylic (UV cured) and a 3-component acrylic. The latter demonstrates better performances than the others (durability and adhesion) and has been considered for the next steps of the project.

The technical feasibility of the lamination of large GFRP plates using a liquid product had to be tested. Indeed, GFRP plates with a thickness of 3 mm are not perfectly flat, due to residual stresses in the structure, caused by the simultaneous pulling and cooling actions during the process (Fig. 11a). A full size production test has been internally manufactured to check whether the resin, once cured, can flatten the GFRP. Tests proved that the hydrostatic pressure rising in the resin due to the weight of the glass alone (hence, glass pane placed on top of GFRP plate during curing) is sufficient to flatten the GFRP (Fig. 11b).

7. Fire analyses

Further aspects considered in TEC-facade design are the fire reaction properties of the final product. The GFRP material, if applied with a 4 mm thickness, is classified classB-s3-d0 (reference target for TEC-facade) defined by tests previously performed according to EN 13501-1 (EN, 2007). However, decreasing the GFRP thickness from 4 to 3 mm negatively influences the fire reaction property. Indeed, the material burns quicker than in the thicker version and the peak of heat release rate exceeds the threshold set for class B classification.

Cone calorimeter tests have been performed to better understand how the heat generation is influenced by the thickness of the GFRP, by the presence of the back glass pane and by the contribution of the laminating resin (that is also a combustible material).

Pre-tests showed that a laminate composed by a 3 mm GFRP plate and a 4 mm glass (conservative choice) has performance very similar to a 4 mm GFRP plate alone. Indeed the glass helps reducing

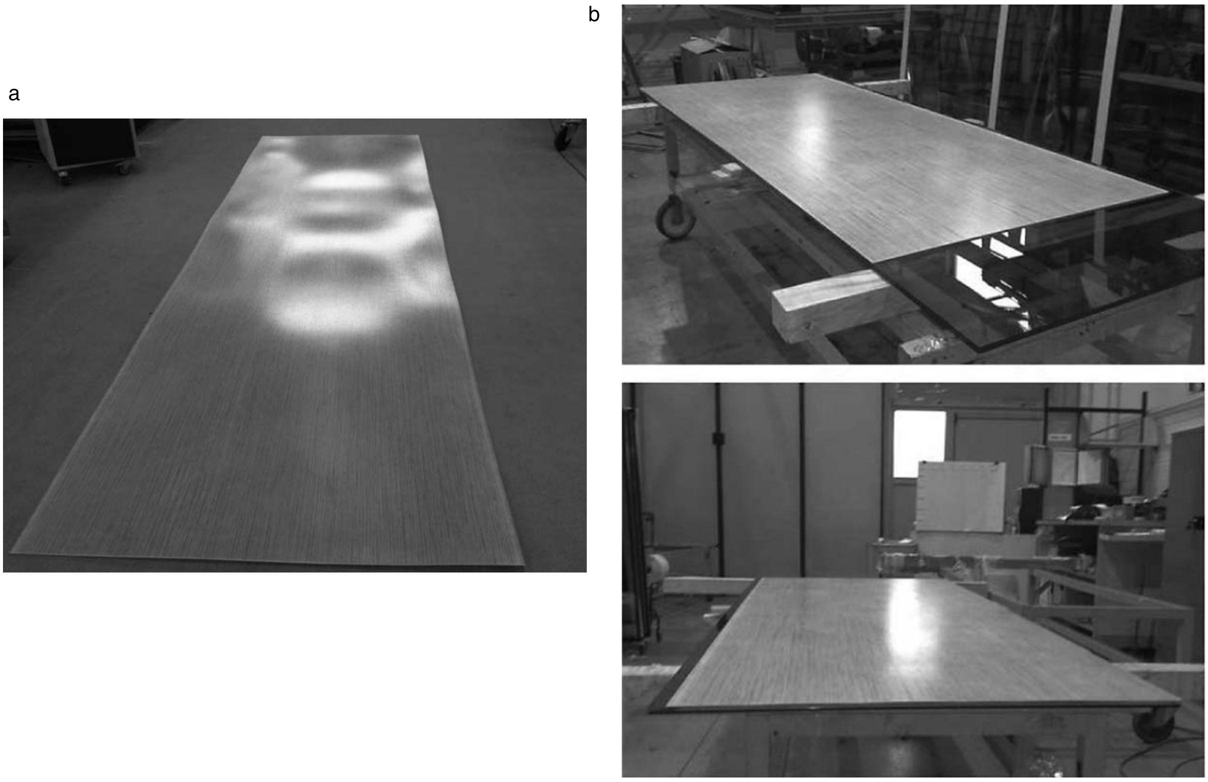

Fig. 11. 3 mm GFRP plate flatteners (a) before lamination (b) after lamination.

the temperature at the burning area (inertia and heat conduction). On the other hand, the glass did not give any advantage if laminated to a 4 mm GFRP plate. Indeed, the total amount of combustible material (GFRP and laminating resin) is too high, resulting in an excess of total heat released by the material. Optimal performance is given by a balance between low burning rate (which require higher mass) and low total heat released (which require lower mass).

SBI corner tests have been performed in the final configuration (Fig. 12), hence with a surface exposed to flames composed by a 3 mm GFRP plate laminated with 1.5 mm of laminating resin to a 10 mm thick glass pane (a cavity of 60 mm has been provided at the back, according to the real application conditions). Class B-s3-d0 according to EN 13501-1 has been achieved, confirming the estimation made through the cone calorimeter pre-tests.

8. Conclusions

This paper describes the holistic functional role of glass in the newly developed TEC with regards to its acoustic, structural, aesthetics and fire behaviour.

The acoustic insulation of the TEC-facade has been improved by using two measures: surface weight increase and facade skin decoupling. These allowed the achievement of the imposed requirements, but as a consequence, made facade design more difficult.

a b

Fig. 12. SBI corner test performed with the final facade configuration. As can be seen, with materials of limited combustibility (class B) there is very limited fire spread in vertical direction and none in horizontal direction.

In particular, decoupling of internal and external skins, mandatory due to acoustic insulation, influenced the overall structural behaviour of TEC-facade, making the GFRP weak to resist the imposed loads. This led to study the possibility of composite action of structurally bonded glass/GFRP. Parametric numerical analyses demonstrate high influence of adhesive stiffness on GFRP mullion deflection and slight influence on principal tensile stresses in glass. Based on obtained parametrical results and laboratory testing, the suitable adhesive has been selected: a high modulus structural silicone, which met all the imposed requirements, allowing for a stable and durable composite action between glass and GFRP.

In order to maintain the desired aesthetics (showing the translucent GFRP on both sides), GFRP plates have been laminated to the added glazed skin. Several interlayer materials as well as lamination techniques have been investigated and tested. GFRP material, not sustainable for high temperature applications, did not allow for application in standard autoclave lamination and vacuum bag processes. Cold lamination process using 3-component acrylic demonstrated best performances in durability and adhesion and has been considered for the application.

Testing concerning the fire reaction properties of the TEC-facade showed that glass helps reducing the temperature closed to the burning area (thermal inertia and heat conduction). Added glass allowed a slight reduction of GFRP plate thicknesses, hence a maximization of facade light transmission, without increasing the burning rate.

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