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Design of a 5m Span All-Glass Walkway

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Abstract

For a residential building in the French Alps, Vitroplena designed and installed an all-glass walkway. The structure connects the upper platform of the stairwell and the master bedroom spanning a distance of 5.28 m. The width of the bridge is approximately 1 m. The structural performance of the walkway relies on a 101010.4(TTG,sPVB) floor plate supported by 200 mm high 101010.4(TTG,sPVB) structural glass beams. The accompanying 1010.4(TTG,sPVB) balustrades are laminated to these structural glass beams. A key feature of this design is the adhesive bonding of the floor plate to the balustrades and the structural glass beams using a transparent acrylic adhesive. The bonding process was executed entirely in situ. The end supports of the all-glass walkway take the form of discrete steel shoes with neoprene elements to avoid hard glass-steel contact. These supports are concealed behind a wooden cladding. The design process encompassed finite element modelling, implementing viscoelastic behaviour of the interlayers and hyperelastic behaviour of the transparent acrylic adhesive. The innovations introduced in this project come in several dimensions: only three glass components are used, which are bonded together to form a cohesive structural entity using a transparent acrylic adhesive, which maximises transparency by eliminating conventional steel connectors. This paper elucidates the design principles, the challenges encountered during installation and the intricacies of the in situ bonding. This project serves as a reference of all-glass applications using structural adhesive bonding, and therefore contributes to the advancement of structural glass engineering.

Keywords

all-glass, walkway, laminated, adhesives, in-situ bonding

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1. Introduction

Vitroplena has designed and installed an all-glass walkway for a residential house in the French Alps. The structure is located in the living room, and connects the upper platform of an open stairwell with the master bedroom. The walkway spans 5.28 m and has a width of approximately 1 m. The entire structural entity consists of three pieces: a floor plate and two structural beams with the balustrades laminated to them. All glass elements are made from thermally toughened glass (TTG) in combination with structural PVB-interlayers Saflex® DG41 (sPVB). The floor plate has a 101010.4(TTG,sPVB) glass configuration with a width of 955 mm and a length of 5277 mm. The load-carrying beams are 200 mm high and consist of 101010.4(TTG,sPVB) laminates. The balustrades, which have a total height of 1250 mm, have a 1010.4(TTG,sPVB) glass configuration. These balustrades are directly laminated to the glass beams using the same structural PVB-interlayer, i.e. Saflex® DG41. Using a transparent acrylic adhesive, the walkable floor plate is structurally bonded to the glass beams and balustrades resulting in a structural entity in which all glass elements cooperate to transfer the imposed loads. Figure 1 depicts a sketch and a picture of the all-glass walkway after installation.

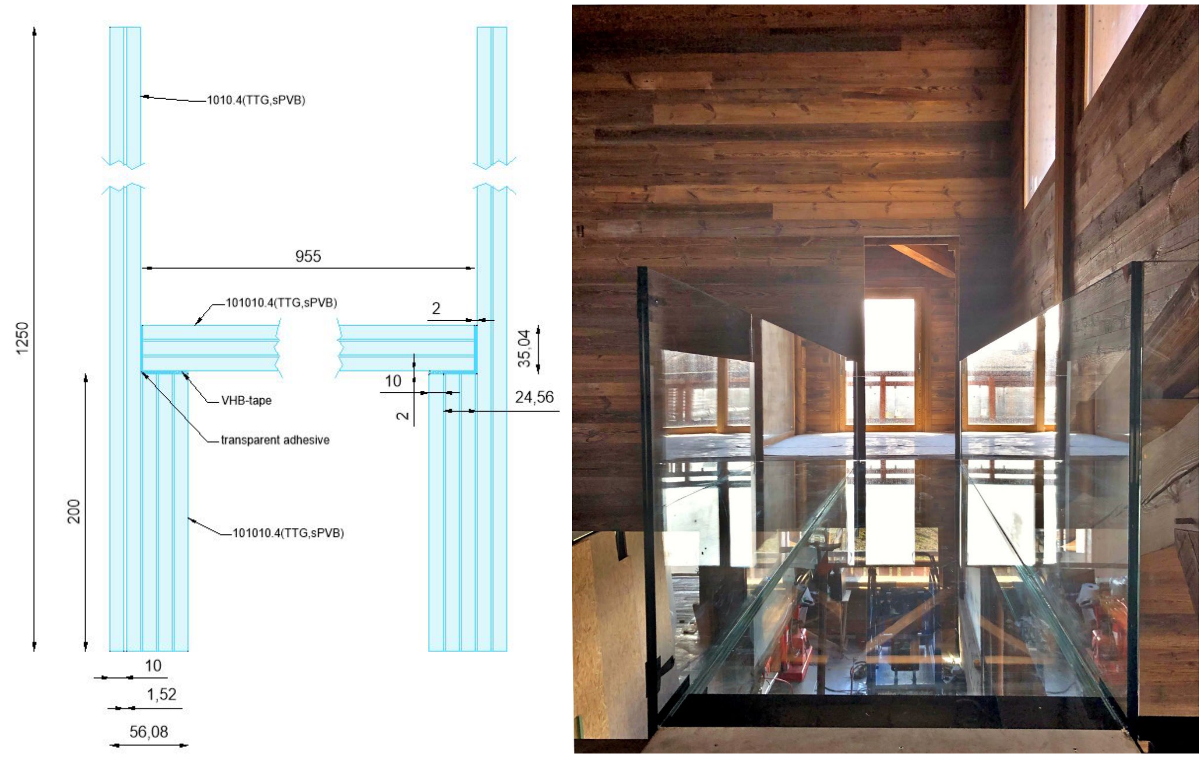

Fig. 1: 5m span all-glass walkway (left: sketch with dimensions in mm; right: walkway after completion).

2. Design calculations

The structural design of the all-glass walkway made use of the standards EN 1990 (+ French National Annex), EN 1991-1-1 (+ French National Annex), NF DTU 39, SIA 2057, EN 16612 and CEN/TS 19100. First, the floor plate and the structural beams are calculated using finite element modelling and analytical approaches. Using a full three-dimensional finite element model of the entire all-glass walkway, the balustrades and the adhesive bonds are designed. The structural performance of the entire bridge is investigated using this model as well. Modal analyses also allow to determine the natural frequency of the structure.

2.1. Loads, load combinations and criteria

The entire glass walkway was designed as a primary load-carrying structure, taking into account a fracture limit state (FLS) and post-fracture limit state (PFLS) in addition to the traditional ultimate limit state (ULS) and serviceability limit state (SLS).

Conform EN 1990 (+ French National Annex), the building is categorised as *category A: residential*, resulting in a uniform line load $q_{k,h}$ of 0,6 kN/m applied at barrier height.

For the floor plate, category A results in a uniformly distributed load $q_{k,v}$ of 3 kN/m² and a point load $Q_{k,v}$ of 4 kN (100 mm by 100 mm).

Additionally an *accidental* wind load is considered to compensate for open doors. The peak wind velocity pressure q_p equals 775 Pa. Considering the wind pressure coefficient $c_{p,net}$ equal to 1.28 and an accidental load combination factor ψ of 0.2, the characteristic value of the wind load w_k equals 198 Pa. Table 1 summarises the imposed loads.

Table 1: Loads

Load		Value	Description
Category A: residential	$q_{k,h}$	0.6 kN/m	Line load at barrier height
	$q_{k,v}$	3 kN/m²	Uniformly distributed load
	$Q_{k,v}$	4 kN	Point load (100 mm by 100 mm)
wind	w_k	198 Pa	Uniformly distributed load

The criteria in ULS and PFLS are related to the strength of the glass. All elements consist of thermally toughened glass. The design value of the strength of thermally toughened glass is determined according to EN 16612 (CEN, 2019) and equals 87.5 MPa. In the SLS, deflections of the individual elements are limited to:

- beams: L/300 (NBN B03-003)
- floor plate: L/200 (SIA 2021)
- balustrade: 35 mm at barrier height (NF DTU 39)

With respect to the FLS, thermally toughened glass is used in laminated configuration using structural interlayers. Hence, when a glass ply breaks, it breaks into small pieces and sticks to the interlayer. When all glass plies would break, the structural interlayer ensures a residual capacity of the laminated element. The PFLS considers a VB3A scenario according to the Swiss standard SIA 2057 (SIA, 2021) in which structural calculations for accidental load combinations are made with one glass plie broken. This PFLS also tackles the potential breakage of a glass ply due to nickel sulfide inclusions, although that risk is reduced as heat soak testing of all elements is prescribed.

For the adhesive bonds, the design took into account a safety factor of 6 with respect to the strength of the adhesive. This value is prescribed in ETAG 002 (2012) and can even be considered too high as manufacturers themselves usually settle for a safety factor of 4. Based on the boundary conditions of the project and the in situ bonding, a safety factor of 6 was assumed to be more appropriate.

Besides strength and stiffness of all-glass walkway and its individual elements, also the natural frequency of the entire structure was determined. The natural frequency was kept above the value of 5 Hz, which is considered to be safe based on NBN S23-002 (2020).

2.2. Structural analyses

2.2.1. Floor plate

Stresses and deflections in the floor plate, with composition 101010.4(TTG,sPVB), under the effect of the load combinations in ULS, PFLS and SLS are calculated using geometrically non-linear finite element analyses. The floor plate is modelled as a 2D rectangular plate of 5277 mm by 955 mm consisting of three thermally toughened glass plies with a nominal thickness of 10 mm separated by 4 structural PVB-interlayers, i.e. 4 · 0.38 mm = 1.52 mm. A quasi-static viscoelastic material behaviour was considered for the structural PVB-interlayers. The adopted load scenario was an exposure temperature of 40°C and a load duration of 30 minutes, corresponding to a Young's modulus of 1.2 MPa and a Poisson coefficient of 0.49. The two 5277 mm long edges are simply supported by the glass beams. The mesh of the model contains S9 multi-layered elements (9 Gauss points, full integration, use of modified shear interpolation functions). The lateral displacement of each layer is set equal. Transverse strains are neglected, hence plate like stress behaviour occurs (expressed with internal forces and moments for each layer).

Figure 2 depicts the principal tensile stresses in the 101010.4(TTG,sPVB) for the most onerous load combination in the ULS and PFLS, i.e. one ply is broken, and the vertical deflection for the most onerous load combination in the SLS.

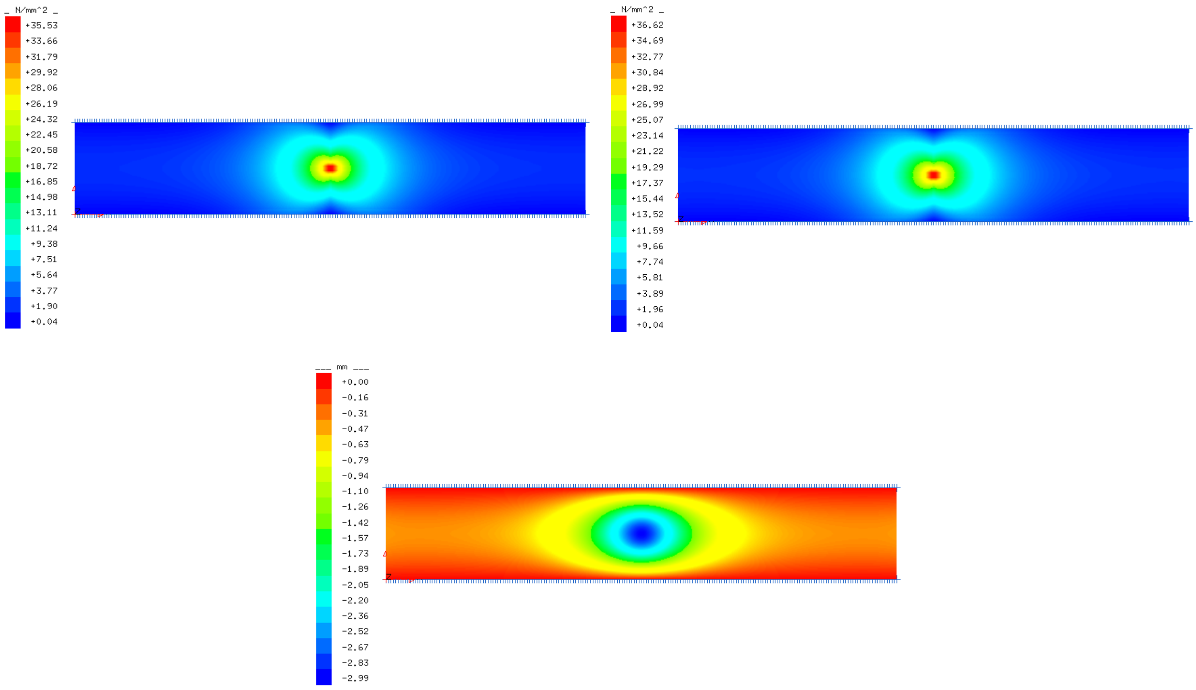

Fig. 2: Principal tensile stresses in the floor plate for the most onerous combination in ULS (top left) and PFLS (top right), and maximum deflections for the most onerous combination in the SLS (bottom).

As the principal tensile stress in ULS and PFLS equal 35.5 MPa and 36.6 MPa respectively, and as such remain below the threshold of 87.5 MPa, the design can be considered safe in ULS. In SLS, the maximum deflection equals 3.0 mm, i.e. smaller than the allowed value of L/200 = 955/200 = 4.8 mm.

2.2.2. Beams

For the preliminary design, the 101010.4(TTG,sPVB) beams are calculated by hand using the basic principles of beam theory. The presence of the balustrades, laminated to the beams, is not taken into account in the initial design, which is a conservative approach. To take into account the shear interaction between the individual glass plies, the Enhanced Effective Thickness Method for beams (CEN, 2021) is applied for the load scenario of 40°C and 30 minutes to determine the equivalent thickness t_{eq} of the beam. The glass (E = 70000 MPa and G_t = 28689 MPa) beam elements have a length of 5277 mm, but the free span L equals 4737 mm. The height h of the beams equals 200 mm. Lateral torsional buckling of the individual beams is checked using a simplified method to determine the critical bending moment M_{cr} and by taking into account a partial safety factor γ_M equal to 1.8 to determine the design bending moment M_{Rd}.

$$M_{Rd} = \frac{M_{cr}}{\gamma_M} = \frac{\pi t_{eq}^3 h \sqrt{E G_t \left(1 - \frac{0.63 t_{eq}}{h}\right)}}{6L} \tag{1}$$

Applied to the beams in this project the design bending moment M_{Rd} equals 10.2 kNm. For the most onerous load combination in the ULS, the maximum occurring bending moment M_{Ed} equals 9.7 kNm resulting in maximum principal tensile stresses of 49.1 MPa (< 87.5 MPa). In the SLS, the maximum deflection under the action of the most onerous load combination equals 12.8 mm (< 15.8 mm).

Remark that the calculation in principle occurs backwards, i.e. the height of the beam for the given configuration is determined to fulfil the requirements in ULS and SLS.

2.2.3. Balustrades

To determine the structural performance of the balustrades and to design the adhesive joints (cfr. infra) in ULS and SLS, a three-dimensional finite element model of the entire bridge is developed. Symmetry along the longitudinal axis is considered. The glass elements and the interlayers are modelled using solid shell elements. The mechanical properties of the interlayers are determined for a load scenario of 40°C and 30 minutes conform EN 16612 (CEN, 2019). The adhesive bonds are modelled using quadratic tetrahedral elements and mechanical properties derived from material characterisation tests. The supports in the model, as in reality, are 12 mm thick neoprene pads on 15 mm thick POM blocks. The glass balustrades are restricted to move out-of-plane at the free ends.

Figure 3 depicts the maximum principal stresses in the glass and the maximum deflections for the most onerous load combinations in ULS and SLS.

The maximum principal tensile stress in the balustrades equals 25.1 MPa (< 87.5 MPa) for the most onerous load combination in the ULS. The maximum deflection equals 18.2 mm (< 35.0 mm) for the most onerous load combination in the SLS. The principal stresses in the interlayer between the glass balustrades and the structural glass beams remain limited as the stiffer transparent acrylic adhesive connecting the floor plate, balustrades and beams attracts the forces acting on the balustrade.

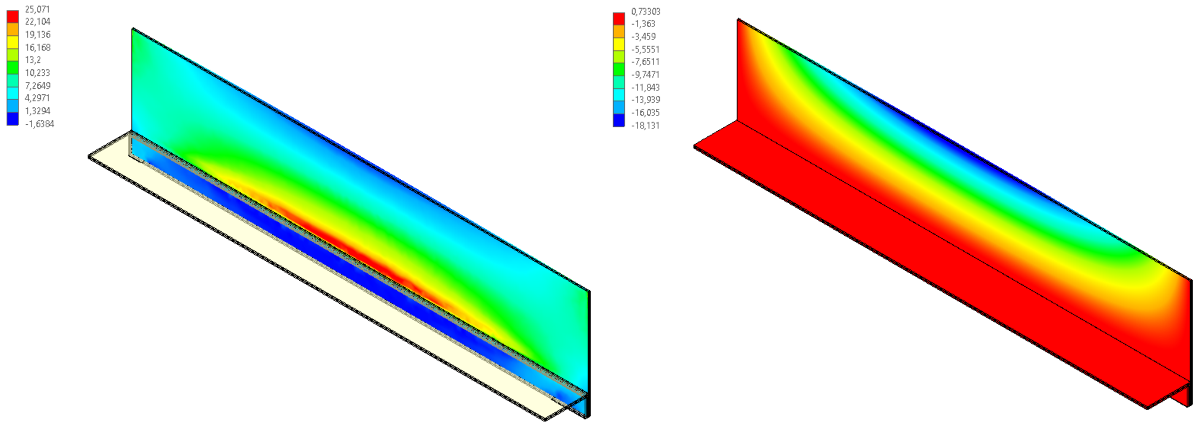

Fig. 3: Maximum principal tensile stress in ULS and maximum deflection in SLS of the balustrades under action of the most onerous load combination.

2.2.4. Adhesive bonds

The 3D finite element model as described in the previous paragraph is used to check the principal tensile stresses and the shear stresses in the adhesive layer connecting all the glass elements. The occurring stresses under the most onerous load combinations in the ULS are compared to design values which take into account a safety factor of 6 as mentioned in one of the previous paragraphs. The conclusion of this study is that the transparent acrylic adhesive fulfils all requirements with respect to strength. The durability of the adhesive is confirmed based on tests performed by the manufacturer.

2.3. Modal analysis

A modal analysis of the entire all-glass walkway results in a first and seventh mode as presented in Figure 4. The lowest natural frequency of 10.0 Hz (> 5 Hz) corresponds with a mode corresponding to deflecting balustrades, whilst mode 7 corresponding to a frequency of 44.7 Hz is related to a deflecting floor plate. The criterium with respect to natural frequency is fulfilled.

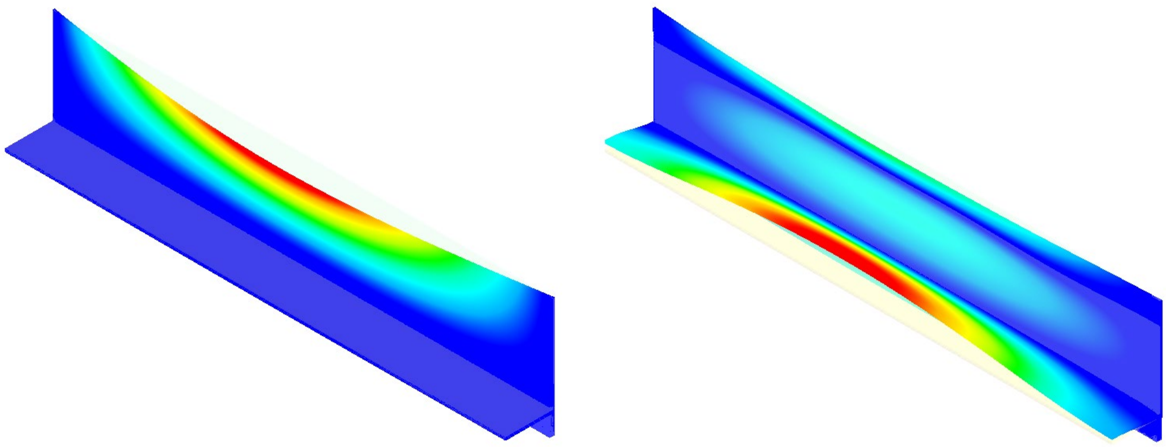

Fig. 4: Mode 1 (10.0 Hz) and mode 7 (44.7 Hz).

3. Installation

The installation took place in March 2023. The three pieces out of which the entire all-glass walkway consisted were manipulated using glass suction lifters. Before installation, everything was cleaned properly using acetone, isopropyl alcohol and foam cleaners in combination with lint-free cloths. During the entire process of installation, bonding and curing, no other works could be performed. This to ensure a dust-free environment. Adhesive bonding and curing occurred at room temperature and ambient relative humidity.

First, the beam-balustrade elements, i.e. the 101010.4(TTG,sPVB) structural beams with 1010.4(TTG,sPVB) balustrades laminated to it using a structural interlayer, were installed in their steel support shoes at both ends. Neoprene pads and POM blocks avoided direct glass-steel contact in the supports. One such element was fixed and avoided to move out-of-plane. The second element could move freely in the horizontal direction perpendicular to the span of the walkway. This to allow a correct positioning of the floor plate between the beam-balustrade elements, hence to control the relative horizontal position between the elements and as such the thickness of the adhesive bond between floor plate and balustrade. Next, the floor plate, 101010.4(TTG,sPVB), was positioned between the beam-balustrade elements using glass suction lifters and a pulley system. As such the floor plate hovered above the beam-balustrade elements. The horizontal position of the moveable beam-balustrade element was adapted to result in the necessary void between floor plate and balustrade. The distance between the floor plate and the beams was ensured using transparent VHB-tape. The floor plate was lowered using the pulley system until it rested onto the tape resulting in a void with correct dimensions between floor plate and beam, and floor plate and balustrade. Once all glass elements were cleaned again, the transparent acrylic adhesive could be poured into the cavities. After curing, excessive adhesive was removed and the structure could be completed.

The main challenges encountered during installation and the intricacies of the in situ bonding are:

- the tolerances of the finished glass products are minimal, i.e. the dimensions of the individual glass plates and the relative positions of individual glass plies in laminates;
- the manipulation of large glass elements in a residential setting is not straightforward;
- positioning of the elements relative to each other requires a precise planning and an accurate execution;
- environmental conditions are hard to control in case of in-situ bonding, although in this project the bonding took place inside which implies a certain level of control;
- quality control is essential to ensure a good and durable bond between the elements;
- in-situ installation/bonding/curing must be prepared down to the smallest detail. Although contingencies are probably part of each of such projects, there is only one chance to bond and cure everything properly.

Figure 5 depicts the all-glass walkway during construction. Figure 6 depicts the walkway serving as a reference for all-glass applications using structural adhesive bonding. Transparency is maximised by using a transparent acrylic adhesive and by eliminating conventional steel connectors.

Fig. 5:all-glass walkway during construction.

Fig. 6:all-glass walkway after completion.

4. Conclusions

For a residential house in the French Alps, Vitroplena designed and installed a 5m span all-glass walkway. The structure consisted of three pieces: two 200 mm high beams with a 101010.4(TTG,sPVB) glass configuration to which the 1010.4(TTG,sPVB) 1.25 m high balustrades were laminated using the same structural interlayer Saflex® DG41, and the floor plate, 101010.4(TTG,sPVB). The latter was adhesively bonded to the structural beams and the balustrades using a transparent acrylic adhesive. The structural design was performed taking into account the ultimate limit state, serviceability limit state, fracture limit state and post-fracture limit state. A combination of analytical calculations, finite element analyses of individual elements and numerical analyses on a full 3D finite element model were used. As such the principal tensile stresses in the glass and the adhesive layers, and deformations of the entire walkway could be limited below the design thresholds. The installation and bonding occurred on-site, and was as such accompanied by additional challenges. The installation began by positioning the two beam-balustrade pieces in steel shoes at the supports. Next, the floor plate was positioned between the balustrades as such that the distance between the floor plate and balustrades was exact. Using VHB-tape, a cavity between the floor plate and the beams was created. The gap was filled with a transparent acrylic adhesive and cured. In this project, transparency is maximised by using a transparent acrylic adhesive and by eliminating conventional steel connectors. The finished walkway serves as a reference for all-glass applications using structural adhesive bonding.

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