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# Research on Thin Glass-Polycarbonate Composite Panels

Thorsten Weimar, Sebastián Andrés López
*Universität Siegen, Institute of Structural Design, Germany,*
*tragkonstruktion@architektur.uni-siegen.de*

Glass, particularly in architectural design, expresses lightness and modernity. By rising glass surfaces of facades in buildings with high safety requirements, glass works as security glazing. Requirements of security glazing increase constantly. However, single glass panes do not fulfil the demands on these high technology products. Thereby, laminated glass or insulated glass are used to solve problems of the specifications in view of fire, heat, noise, sound and sun protection as well as safety, energy, design or media. The combination of different materials in a composite panel permits the optimisation in consideration of requested structural or mechanical properties. In this case, the lamination of brittle glass with ductile polycarbonate enables innovative composite panels, which extends the range of glazing with security relevant applications. Glass-polycarbonate composite panels are generally defined with two outer glass panes and one or more inner polycarbonate sheets, laminated with polymeric interlayers. The combination of these two materials demonstrates a more efficient alternative to common security glazing. Continuous developments in the field of thin glass result in more and more applications beyond the usage in smartphones or tablets. Large-sized thin glasses with a nominal thickness of 2 mm or less are for some time available and already used in science and technology. Applications of thin glass in the building sector demand to analyse the required material properties and to combine thin glass panes with additional layers due to its low geometrical stiffness. An option for applications of large-sized thin glass panes presents the lamination with polycarbonate. Thin glass substitute the two outer glass panes in glass-polycarbonate composite panels. Therefore, thin glass-polycarbonate composite panels are slighter than common security glazing. Several options for using thin glass in architecture and the lamination with polycarbonate are described as well as the required tests for using as laminated safety glass and security glass with resistance against manual attack.

**Keywords:** thin glass, laminated safety glass, composite panel, security glazing, polycarbonate

## 1. Introduction

Since at least by the development of curtain walls, the application of glass with large dimensions becomes a matter of course. At the same time, mechanical, structural, physical and optical requirements are constantly increasing. EN 13830 (2015) describes required characteristics for curtain walls in terms of weather, sound, fire and heat protection. Information about the resistance against usual external loads completes the composition. Modern facades aim at the integration of several functions in one glazing. Mike Davies already introduced in 1981 the concept of a polyvalent wall designed to break the boundaries between a solid wall and a transparent facade due to the interaction of various functional layers. The building envelope adjusts adaptively to the respective requirements and is therefore called an intelligent facade with nine different functions in individual layers connected between two glass panes. Based on this idea, the requirements for today's transparent facades can be arranged into different aspects. These include fire, heat, noise, sound and sun protection as well as design, energy, media and security. Up to today, this concept represents the unachieved ideal of multifunctional glazing in facades (Davies 1981).

These high requirements are often not met by a single glass pane. Therefore, laminated glass is used primarily in multifunctional glazing of curtain walls. According to EN ISO 12543-1 (2011), a laminated glass consists of at least one or more glass panes or plastic glazing material laminated by an interlayer. The interlayer of laminated safety glass should guarantee the passive safety like bonding of splinter, limiting of the opening angle, sufficient post-breakage behaviour and avoiding cut and stab injuries. The protection of people and objects against external impact is called active safety and provided by security glazing. A composite panel made of different materials allows further optimisation with regard to the desired properties in case of security and heat protection. A combination of the brittle material glass with the ductile material polycarbonate leads to innovative composite panels in the field of safety as well as heat insulation (Weimar 2011).

Continuous developments in the production of thin glass generate additional fields of utilisation beyond the application as special glazing. Large-sized composite panels made of innovative thin glass and polycarbonate offer an advantageous alternative to conventional laminated safety glass and security glazing. The usage of the impact-resistant polycarbonate in combination with the high surface strength of thin glass reduces significantly the cross-sections and the dead load of the composite panel in comparison to laminated safety glass as security glazing.

This paper focuses on the experimental investigation of thin glass-polycarbonate composite panels as security glazing. The laminate is made of chemically strengthened thin glass panes, polycarbonate sheets and a thermoplastic polyurethane interlayer. Furthermore, research on the lamination with the ball drop test and on the resistance against climatic stress as well as manual attack fulfil the test methods. The structural behaviour and additional the post-breakage behaviour are analysed with the four point bending test.

## 2. Thin glass-polycarbonate composite panels

### *2.1. Material*

Common security glazing consists of laminated safety glass with several glass panes. Depending on the resistance class, thick cross-sections with high dead load might result. In order to optimise security glazing, composite panels based on thin glass and polycarbonate are used. Thin glass-polycarbonate composite panels consist of two outer thin glass panes and at least one inner polycarbonate sheet, which are laminated with a polymeric interlayer. Thin glass-polycarbonate composite panels for the highest resistance class P8B against manual attack are up to 51 % thinner and up to 72 % lighter than common security glazing. This enables a thinner design for frames and support structures. Retrofitting into existing buildings and further processing to double glazing will be easier. Figure 1 shows the cross-section of a thin glass-polycarbonate composite panel.

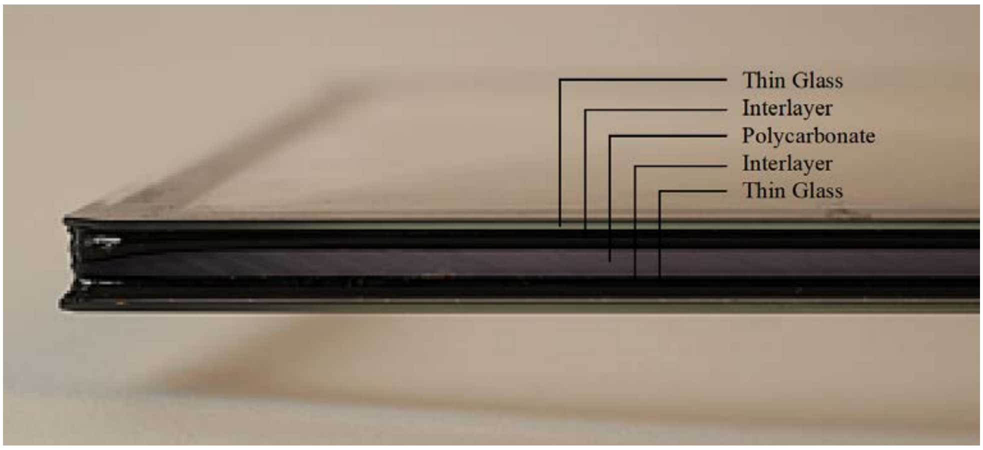



Fig. 1 Cross-section of a thin glass-polycarbonate composite panel made of two outer 0.85 mm thin glass panes, one 2.00 mm inner polycarbonate sheet and two 2.00 mm thermoplastic interlayers.

The design and construction of glass in buildings are currently limited to glass products with a nominal thicknesses of 3 mm to 19 mm in accordance with DIN 18008-1 (2010). Thin glass is considered under a thickness of 3 mm, preferred under 2 mm. Generally, thin glass is very common on smartphones and mobile devices. The development of these products pushes the industry to produce thinner and larger glass panes. This results in higher scratch and fall resistance as well as in a lower weight. Borosilicate glass, aluminosilicate glass and soda lime glass are typical glass types used for thin glass. Borosilicate glass shows an excellent chemical durability and thermal resistance, aluminosilicate glass possesses an extraordinary high mechanical durability and advantageous properties for chemical strengthening and soda lime glass indicates the typical glass properties of float glass (EN 1748-1-1 2004; EN 15681-1 2016 and EN 572-1 2016). Due to the resistance against mechanical influences, aluminosilicate glass is typically used in the electronic industry or in laboratories and biotechnology. In comparison to float glass or borosilicate glass, aluminosilicate glass is stronger and optical brighter.

Thin glass can be produced by different processes. First of all, with the well-known float process. The overflow-fusion process or the down-draw process complete the manufacturing technologies. By melting and mixing the raw materials, homogeneous molten glass is produced. During the overflow-fusion process, the molten glass flows over the outer surfaces of the bath and join each other at the bottom of the bath. The down-draw process is similar to the overflow-fusion process. The molten glass is pulled down of a hole at the bottom of the bath. Due to the development of these processes, it is possible to produce glass rolls over 100 m. Thin glass is usually pre-stressed by chemical strengthening with an ion exchange. This strengthening allows a high surface compression. Stress differences between the outer and inner glass layer are introduced by placing the panes in a hot salt bath. Smaller ions in the glass surface are replaced with ions with a larger radius. Thus, compressive stress is induced at the surface and, because of the equilibrium of stresses, tensile stress results in the core. The maximum size for chemically strengthened thin glass is limited by the dimensions of the salt bath tubs (Albus et al. 2015). However, thin glass allows large deformation without breaking because of its low geometrical stiffness in combination with high quality and surface strength.

Polycarbonate is a thermoplastic polymer containing carbonate groups in its chemical structure. The material is produced by a reaction of bisphenol A and phosgene. The transmission coefficient of polycarbonate shows a similar value than of glass. Additionally, the heat conductivity of polycarbonate is five times lower. This results in advantageous thermal protection of the composite panel. It is necessary to protect the polycarbonate sheet from ultraviolet radiation because it becomes brittle. Anyway, the favourable properties in reference to high impact resistance and transmittance as well as its low dead weight in comparison to glass, polycarbonate is frequently used as an alternative for glazing in the building envelope. A comparison of different polycarbonate products shows no significantly differences in properties like transmittance, density, thermal expansion, strength, stiffness as well as notch toughness and impact strength (Lexan 2015, Makrolon 2013).

The thermoplastic polyurethane interlayer is an essential part for lamination of brittle thin glass and ductile polycarbonate in consideration of the shear transfer. In addition, the interlayer has to compensate the different thermal temperature expansions of the two materials. The thermal expansion coefficient of polycarbonate is seven times higher than of glass. The Young's modulus of the interlayer with 0.76 MPa is significantly lower than of polycarbonate or thin glass. This results in the required flexibility of the interlayer. The thermoplastic polyurethane does not contain any softener, but ultraviolet radiation blockers for protection in the critical ultraviolet wavelength spectrum.

Table 1 shows the relevant material properties of the used thin glass, polycarbonate and thermoplastic polyurethane interlayer.

Table 1: Relevant properties of the used thin glass, polycarbonate and thermoplastic polyurethane interlayer.

| Property | Thin Glass | Polycarbonate | Interlayer |
|---|---|---|---|
| Product | Leoflex™ (2015) | Lexan® 9030 (2014) | Thermoplastic Polyurethane (Weimar 2011) |
| Density | 2.480 g/cm$^3$ | 1.200 g/cm$^3$ | 1.035 g/cm$^3$ |
| Young's Modulus | 74,000 MPa | 2,300 MPa | 0.76 MPa |
| Bending Strength | 260 MPa | 90 MPa | - |
| Thermal Expansion Coefficient | $9.8 \cdot 10^{-6}$ 1/K | $70.0 \cdot 10^{-6}$ 1/K | $223.5 \cdot 10^{-6}$ 1/K |

### *2.2. Requirements and applications for thin glass-polycarbonate composite panels*

Thin glass-polycarbonate composite panels represent an innovative alternative to conventional laminated safety glass and security glazing. The basic function of laminated safety glass is to provide passive safety. Additional requirements lead to security glazing with active safety. Security glazing is classified into resistance against manual attack according to EN 356 (2000), resistance against bullet attack according to EN 1063 (2000) and resistance against explosion pressure according to EN 13541 (2012). An essential aspect for laminated safety glass is the analysis of lamination. The durability test methods are realised at high temperature, in humidity and under radiation in order to study the composite panel under extreme climatic conditions (EN ISO 12543-4 2011). The test method for the bonding strength under consideration of mechanical stress is given by the ball drop test (EN 14449 2005).

The German glass design standard DIN 18008 regulates the usage of laminated safety glass. It is generally used in linearly supported or in point fixed glazing. It is used as vertical glazing, for example, in barrier glazing, curtain walls or in sport halls. Thin glass-polycarbonate composite panels are generally suitable for these applications. Horizontal glazing, but also walk-on glazing or walk-on glazing in case of maintenance procedures, are also made of laminated safety glass (Haese 2016). Generally, by increasing demands on security glazing, additional layers of glass are required. Thin glass-polycarbonate composite panels offer an enhanced serviceability and durability caused in its robustness and lightweight. Applications in the field of glazing with a resistance against manual attack are shop windows and all-glass doors but also glazing in security areas at airports, embassies, banks or museums.

### *2.3. Manufacturing process of thin glass-polycarbonate composite panels*

The lamination between the individual layers of thin glass-polycarbonate composite panels take place in a cast resin process with a multicomponent, thermoplastic polyurethane. The more complex process is recommended for the manufacturing of thin glass-polycarbonate composite panels because of its low bending stiffness. Therefore, individual and complex dimensions or requirements for thin glass-polycarbonate composite panels are easier to take into account in the manufacturing process. As a result, no constraint stresses occur in the cross-section which results during the autoclave process from the required lamination temperatures due to the different thermal expansion coefficients of the individual layers. In the used cast resin process, the interlayer crosslinks with a chemical reaction at room temperature within a period of 24 h without further radiation or moisture.

## 3. Research on lamination and resistance against manual attack

### *3.1. Bonding strength of the interlayer under consideration of mechanical loads*

The analysis of the bonding strength of the interlayer against mechanical loads is based on EN 14449 (2005) with the ball drop test. A steel ball with a diameter of 63.5 mm and a mass of 1,030 g falls from a height of 4.000 mm without any initial pulse centrally on the specimen. The composite panel with the dimensions of 500 mm by 500 mm is clamped four sided line-shaped on a steel frame. Overall, five specimens are tested. The number of the penetrated specimens, the number of the specimens which are broken but not penetrated and the mass as well as the size of the glass fragments detached at the lower surface are documented. Table 2 shows the results of the ball drop test. The steel ball does not penetrate any specimen. Only the top thin glass pane breaks and shows damage and crack formation. After the impact, no fragments of glass above the critical size of 40 mm detached from the bottom side or the top side of the composite panel. In one case, both thin glass panes are intact after the impact. The analysed specimens comply with the requirements for the mechanical load by a hard impact and ensure a sufficient adhesion of the interlayer according to EN 14449.

Table 2: Results of the ball drop test according to EN 14449. The cross-section consist of two outer 0.85 mm thin glass panes, one inner 2.00 mm polycarbonate sheet and two 2.00 mm thermoplastic interlayers.

| Specimen | Nominal Thickness | Real Thickness | Penetration | Damage | Splitter Mass |
|---|---|---|---|---|---|
| 1 | 7.70 mm | 7.38 mm | no | top glass pane | - |
| 2 | 7.70 mm | 7.37 mm | no | top glass pane | - |
| 3 | 7.70 mm | 7.33 mm | no | top glass pane | - |
| 4 | 7.70 mm | 7.38 mm | no | no damage | - |
| 5 | 7.70 mm | 7.28 mm | no | top glass pane | - |
| Average Value | 7.70 mm | 7.35 mm | | | |
| Standard Deviation | 7.70 mm | 0.04 mm | | | |

### *3.2. Resistance against climatic stress*

Test methods for a resistance against climatic stresses are described in EN ISO 12543-4 (2011) to verify the durability of the interlayers. The test at high temperature analyses the temperature influence of +100 °C over a period of 16 h on the composite panels. Testing in humidity determines the influence of the air humidity of 80 % RH and a temperature of +50 °C over a period of 2 weeks. The radiation test proves the effects of radiation in a sun-like spectrum on the thin glass-polycarbonate composite panel. Additionally, the light transmission value of the specimens is detected before and after the radiation. Due to the tests, the interlayer should not change in a visual rating with appearance of blisters, delamination or clouding. All tests methods for durability are performed on 3 specimens with the dimensions 300 mm by 150 mm and a nominal cross-section of two outer 0.85 mm thin glass panes, one inner 2.00 mm polycarbonate sheet and two 2.00 mm interlayers. All specimens passed the tests without the appearance of any defect. The requirements of the resistance against climatic stress as test methods for durability are passed.

### *3.3. Resistance against manual attack*

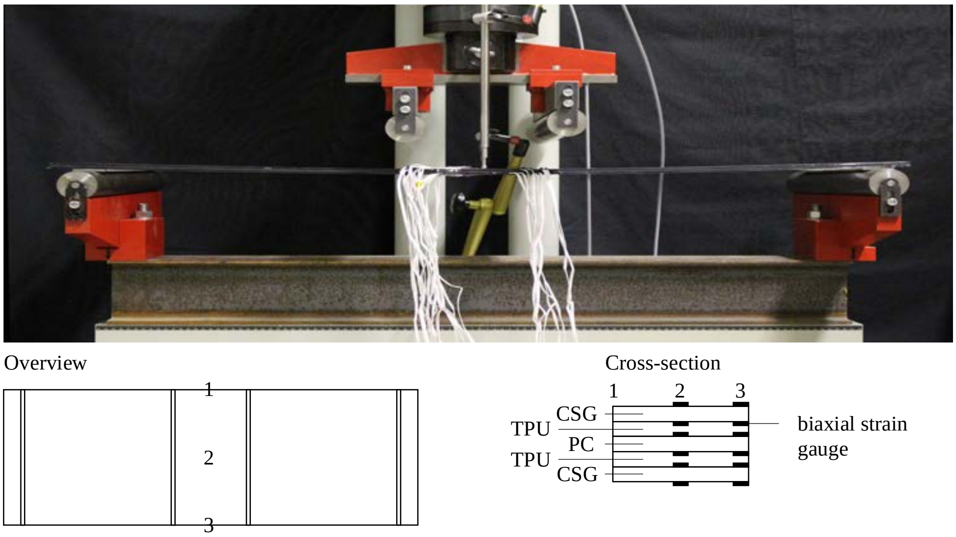
EN 356 (2000) describes security glazing with a resistance against manual attack. The test needs an experimentally procedure on a defined minimal cross-section according to the required resistance class. Test results are independent of the bearing behaviour as well as of the dimensions of the structural design. Subsequently, the minimum cross-section may be modified with additional glass panes, polycarbonate sheets or with sheets of a higher nominal thickness. Depending on the resistance class, a difference between P1A to P5A and P6B to P8B is made. The test of a break-through glazing utilizes a 2 kg machine-guided axe with an impact speed of 11 m/s and an impact force of 300 J on a specimen of 1,100 mm by 900 mm. The resistance class depends on the number of loosening strikes and axe strikes until the formation of a 400 mm by 400 mm opening in the middle of the specimen. Table 3 describes the minimal cross-sections for a thin glass-polycarbonate composite panel with resistance class P6B and P8B. The resistance class P6B requires a 5 mm polycarbonate sheet. The resistance class P8B is achieved by two inner polycarbonate sheets with a thickness of 5 mm, connected with an additional interlayer.

Table 3: Cross-section and resistance class against manual attack of thin glass-polycarbonate composite panels consisting of chemically strengthened thin glass (CSG), polycarbonate (PC) and thermoplastic polyurethane interlayer (TPU).

| Cross-Section | Nominal Thickness | Resistance Class |
|---|---|---|
| 0.85 mm CSG \| 2.00 mm TPU \| 5.00 mm PC \| 2.00 mm TPU \| 0.85 mm CSG | 10.70 mm | P6B |
| 0.85 mm CSG \| 2.00 mm TPU \| 5.00 mm PC \| 2.00 mm TPU \| 5.00 mm PC \| 2.00 mm TPU \| 0.85 mm CSG | 17.70 mm | P8B |

## 4. Research on the structural behaviour

The shear bond of the interlayer has a significant influence on the structural behaviour of the thin glass-polycarbonate composite panels. According to DIN 18008-1 (2010), a favourable shear bond may not be used except under constraining conditions. The two limit cases »no composite« and »full composite« can be determined by analytical or numerical calculations. In reality, there is a »partial composite« which transmits the shear forces. Based on the four point bending test according to EN 1288-3 (2000) an experimental method is available to investigate the shear bond of the interlayer and the resulting structural behaviour of thin glass-polycarbonate composite panels. The specimens with the dimensions of 1,100 mm in length and 360 mm in width lie on two support rollers and are symmetrically loaded to the centre by two load rollers. Biaxial strain gauges measure the elongation in the centre of the composite panel and along the longer edge in longitudinal direction and in transverse direction. Linear variable differential transformers detect the deformation at the two longer edges in the centre of the plate. Figure 2 shows the experimental setup.




1 linear variable differential transformer (LVDT)

2 biaxial strain gauge (longitudinal and transverse direction)

3 linear variable differential transformer (LVDT) and biaxial strain gauge (longitudinal and transverse direction)

Fig. 2 Experimental setup of the four point bending test for determining the deformation and strains in the cross-section of a thin glass-polycarbonate composite panel consisting of chemically strengthened thin glass (CSG), polycarbonate (PC) and thermoplastic polyurethane interlayer (TPU).

### *4.1. Structural behaviour*

To study the structural behaviour of thin glass-polycarbonate composite panels, specimens are loaded force-controlled for 120 s with a load of 300 N. In total, 3 specimens with polycarbonate sheets of 4 mm, 8 mm and 12 mm are available. The nominal thickness of the two outer 0.85 mm thin glass panes and the 2.00 mm thermoplastic polyurethane interlayers are constant for all specimens. Table 4 shows the results of deformation, ratio of load to deformation and longitudinal strains in the centre of the plate as the average value from the experimental tests for the structural behaviour of the thin glass-polycarbonate composite panels.

Table 4: Results of deformation, ratio of load to deformation and longitudinal strains for a load of 300 N. The upper values of strains describe the measured values on the top side; the lower values represent the measured values on the bottom side of the corresponding layer. The bracket term presents the standard deviation. The specimens consist of two outer 0.85 mm thin glass panes, two 2.00 mm interlayers and one inner 4.00 mm (PK 04), 8.00 mm (PK 08) or 12.00 mm polycarbonate sheet.

| Measurement | PK 04 | PK 08 | PK 12 |
|---|---|---|---|
| Nominal Thickness | 9.7 mm | 13.7 mm | 17.7 mm |
| Real Thickness | 9.5 mm | 13.4 mm | 17.3 mm |
| Deformation | 59.5 mm<br>(8.3 mm) | 25.7 mm<br>(3.5 mm) | 12.3 mm<br>(0.6 mm) |
| Load / Deformation | 5.1 N/mm (0.7 N/mm) | 11.8 N/mm (1.5 N/mm) | 24.3 N/mm (1.1 N/mm) |
| Strains Top Glass | -505 µm/m (55 µm/m)<br>-147 µm/m (46 µm/m) | -309 µm/m (11 µm/m)<br>-87 µm/m (26 µm/m) | -209 µm/m (7 µm/m)<br>-102 µm/m (7 µm/m) |
| Strains Polycarbonate | -728 µm/m (139 µm/m)<br>+673 µm/m (435 µm/m) | -908 µm/m (190 µm/m)<br>+877 µm/m (72 µm/m) | -664 µm/m (32 µm/m)<br>+636 µm/m (46 µm/m) |
| Strains Bottom Glass | +141 µm/m (74 µm/m)<br>+492 µm/m (23 µm/m) | +84 µm/m (14 µm/m)<br>+305 µm/m (29 µm/m) | +53 µm/m (5 µm/m)<br>+163 µm/m (15 µm/m) |

The ratio of load to deformation describes a specific value which draws conclusions from the non-linear behaviour of the composite panels. A high value suggests a higher resistance against deformation and an evaluation by the linear plate method. In contrast, a low value results in the non-linear method. By increasing of the nominal thickness of the polycarbonate sheet, the ratio of load to deformation increases with a reduction of deformation under constant load. However, a thick polycarbonate sheet laminated with two thin glass panes possesses a smaller influence of the non-linear method referring to the strains as well as to the total bending stiffness. The specimens with the smallest nominal thickness of 9.7 mm show a value of 492 µm/m for the strains in the centre of the composite panel at the bottom of the lower glass pane. In comparison, the strains on the bottom side of the lower glass pane are reduced by the factor of 3 for the specimens with a 12 mm polycarbonate sheet. The participation of the two outer thin glass panes in the load transfer decreases with increasing of the nominal thickness of the polycarbonate sheet. A comparison of the measurements with the values determined by the geometrically non-linear calculation with the program SJ Mepla 4.0.6 for the two limit state »no composite« and »full composite« shows a partial composite for the interlayers of thin glass-polycarbonate composite panels. The relationship between the ratio of load to deformation and the nominal thickness of the polycarbonate sheet of the tested thin glass-polycarbonate composite panels are shown in Figure 3.

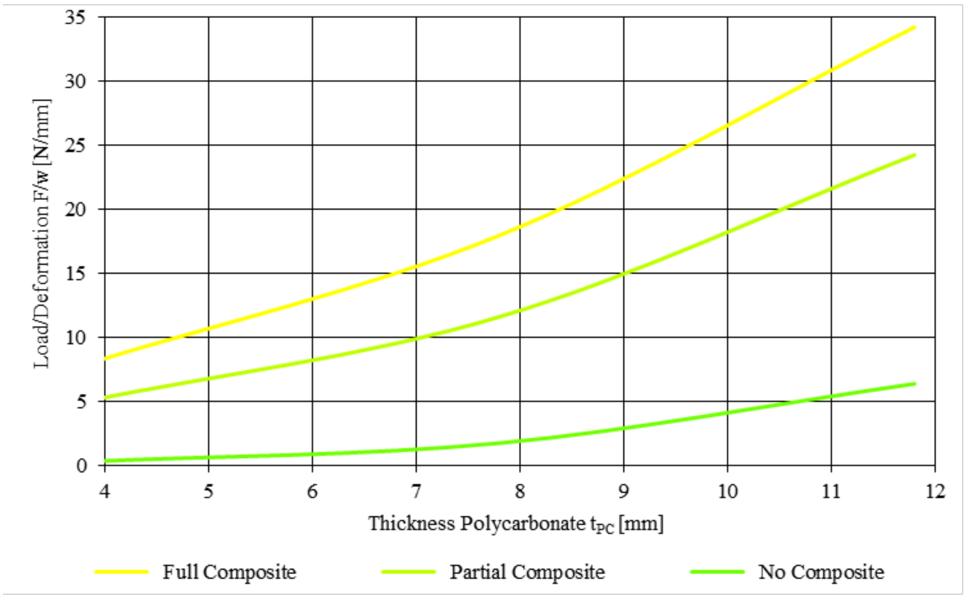



Fig. 3 Comparison of the measured ratio of load to deformation depending on nominal thickness of polycarbonate sheets for thin glass-polycarbonate composite panels with numerical calculated limit states »full composite« and »no composite«.

Additional studies with the four point bending test are aimed at the ultimate load. The thin glass-polycarbonate composite panels do not break with test setup showed in Figure 2. Thus, the limit value of the permissible deformation for determining the ultimate load is set to 10 times of the normative limit value with L/100. However, the ultimate load is limited as the load value of a deformation of 100 mm. If the nominal thickness of the polycarbonate sheet increases, the ratio of load to deformation of the composite panel also increases analogously to the results of the structural behaviour. Thinner composite panels show larger standard deviations especially for the polycarbonate sheet. The connection of the interlayer to the thin glass and the polycarbonate influences directly the strain distribution in the cross-section. Nevertheless, the average value of strains of the surfaces are analogously with small standard deviation. For this reason, the thin glass-polycarbonate composite panels achieve an almost equal crosslinking in the two interlayers. Table 5 shows the results of deformation, ratio of load to deformation and longitudinal strains in the centre of the plate as the average value from the experimental studies.

Table 5: Results of deformation, ratio of load to deformation and longitudinal strains. The upper values of strains describe the measured values on the top side; the lower values represent the measured values on the bottom side of the corresponding layer. The bracket term presents the standard deviation. The specimens consist of two outer 0.85 mm thin glass panes, two 2.00 mm interlayers and one inner 4.00 mm (PK 04), 8.00 mm (PK 08) or 12.00 mm polycarbonate sheet.

| Measurement | PK 04 | PK 08 | PK 12 |
|---|---|---|---|
| Nominal Thickness | 9.7 mm | 13.7 mm | 17.7 mm |
| Real Thickness | 9.5 mm | 13.4 mm | 17.3 mm |
| Load | 535 N<br>(33 N) | 1,163 N<br>(142 N) | 2,378 N<br>(77 N) |
| Deformation | 99.5 mm<br>(1.6 mm) | 100.6 mm<br>(0.3 mm) | 100.6 mm<br>(0.2 mm) |
| Load / Deformation | 5.4 N/mm (0.4 N/mm) | 11.6 N/mm (1.4 N/mm) | 23.6 N/mm (0.7 N/mm) |
| Strains Top Glass | -822 µm/m (44 µm/m)<br>-279 µm/m (85 µm/m) | -1,158 µm/m (111 µm/m)<br>-315 µm/m (129 µm/m) | -1,509 µm/m (37 µm/m)<br>-629 µm/m (49 µm/m) |
| Strains Polycarbonate | -1,117 µm/m (252 µm/m)<br>+975 µm/m (625 µm/m) | -3,317 µm/m (267 µm/m)<br>+3,423 µm/m (244 µm/m) | -5,126 µm/m (32 µm/m)<br>+5,442 µm/m (167 µm/m) |
| Strains Bottom Glass | +274 µm/m (126 µm/m)<br>+804 µm/m (19 µm/m) | +360 µm/m (69 µm/m)<br>+1,184 µm/m (51 µm/m) | +543 µm/m (32 µm/m)<br>+1,375 µm/m (49 µm/m) |

### *4.2. Post-breakage behaviour*

The post-breakage behaviour describes the structural behaviour of laminated safety glass with destroyed glass panes and depends on material properties, adhesion of the interlayers, fracture pattern as well as boundary conditions. Laminated safety glass with broken glass panes can be seen as stiff glass fragments connected by elastomeric bridging ligaments. This is accompanied by a neglect of the strain energy in the glass fragments as well as a rigid position of the glass fragments. By increasing glass fragments, the errors are negligible. (Overend 2014). As it is seen after the destruction of the outer thin glass panes, the fragments of the destroyed chemically strengthened thin glass has similar dimensions like heat strengthened glass. However, due to the fracture pattern the consideration of broken thin glass panes in the pressure zone is possible and analysed with the investigation of the post-breakage behaviour.

The thin glass-polycarbonate composite panels are systematically destroyed with 12 impacts on the top and the bottom to analyse the post-breakage behaviour. Subsequently, the specimens are force-controlled loaded with 200 N for 120 s. The tests are realised with the same specimens from the studies of the structural behaviour. Table 6 shows the results of deformation, ratio of load to deformation and longitudinal strains in the centre of the composite panel as the average value from the experimental studies of the post-breakage behaviour. Having regard to a flexible thin glass-polycarbonate composite panel, it is not possible to adjust the aimed load. PK 04 achieve the maximum deformation according to the test setup showed in figure 2 with a small load. In this case, the study of the post-breakage behaviour of thin glass-polycarbonate composite panels also needs a limitation of the deformation. The limit value is set to 10 times of the normative limit value of L/100 analogously to the tests of the structural behaviour.

The strains of the polycarbonate sheet show lower values on the pressure stressed top side than on the tensile stressed bottom side. This illustrates a sufficient post-breakage behaviour of the thin glass-polycarbonate composite panels. The broken glass pane at the bottom fails under tensile and is no longer involved in the load transfer. The glass fragments at top interconnect under compressive stress and form an enhanced pressure zone. The polycarbonate sheet and the glass fragments handle the load transfer in the pressure zone. The tensile zone is located in the lower part of the polycarbonate sheet. In case of specimen PK 04, the polycarbonate sheet is totally under tensile strain due to favourable acting transverse strains. Depending on the nominal thickness, transverse strains are favourable for the post-breakage behaviour of the thin laminated glass (Blank 1994).

Table 6: Results of deformation, ratio of load to deformation and longitudinal strains. The upper values of strains describe the measured values on the top side; the lower values represent the measured values on the bottom side of the corresponding layer. The bracket term presents the standard deviation. The specimens consist of two outer 0.85 mm thin glass panes, two 2.00 mm interlayers and one inner 4.00 mm (PK 04), 8.00 mm (PK 08) or 12.00 mm polycarbonate sheet.

| Measurement | PK 04 | PK 08 | PK 12 |
|---|---|---|---|
| Nominal Thickness | 9.7 mm | 13.7 mm | 17.7 mm |
| Real Thickness | 9.5 mm | 13.4 mm | 17.3 mm |
| Load | 140 N<br>(11 N) | 201 N<br>(1 N) | 199 N<br>(1 N) |
| Deformation | 101.9 mm<br>(6.2 mm) | 49.1 mm<br>(7.7 mm) | 19.4 mm<br>(1.3 mm) |
| Load / Deformation | 1.4 N/mm (0.0 N/mm) | 4.2 N/mm (0.7 N/mm) | 10.3 N/mm (0.7 N/mm) |
| Strains Polycarbonate | +502 µm/m (84 µm/m)<br>+3,406 µm/m (634 µm/m) | -1,187 µm/m (296 µm/m)<br>+2,265 µm/m (261 µm/m) | -804 µm/m (25 µm/m)<br>+1,126 µm/m (7 µm/m) |

Figure 4 shows the non-linear distribution of the ratio of load to deformation for the thin glass-polycarbonate composite panel as a function of the nominal thickness of the polycarbonate sheets. The results of the experimental measurements in the four point bending test show the structural behaviour in state I with undestroyed thin glass panes in comparison to the post-breakage behaviour in state III with systematically destroyed thin glass panes.

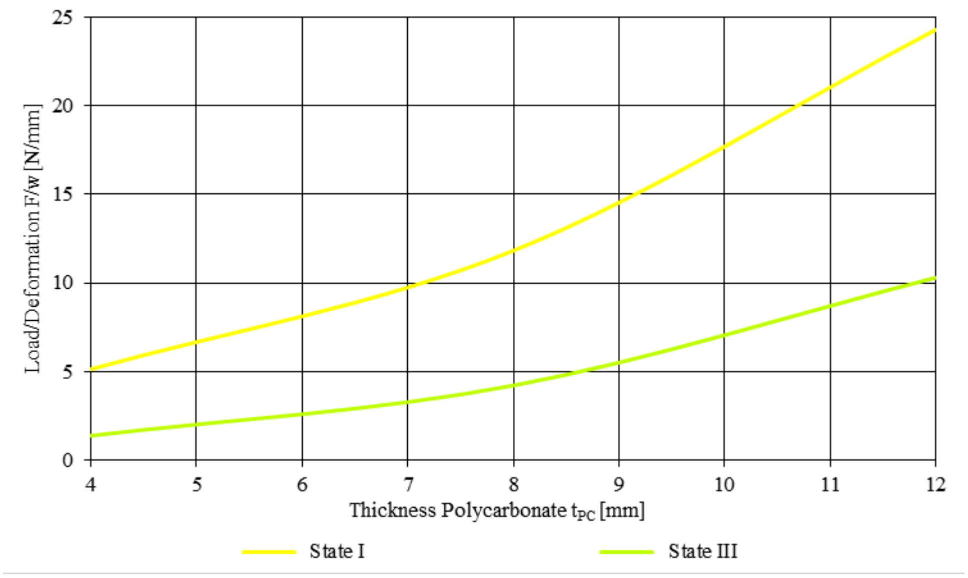



Fig. 4 Ratio of load to deformation depending on the nominal thickness of polycarbonate sheets for thin glass-polycarbonate composite panels analysed with the four point bending test in state I with undestroyed and in state III with systematically destroyed thin glass panes.

## 5. Conclusion

The research on thin glass-polycarbonate composite panels provides practical applications of innovative thin glass in combination with polycarbonate. The composite panels offer a wide range of applications as laminated safety glass as well as security glazing. The adhesive bond of the interlayer consist of thermoplastic polyurethane is identified with the ball drop test. The tests for durability to demonstrate a resistance at high temperature, in humidity and under radiation are fulfilled. The classification as security glazing with a resistance class P6B against manual attack achieves a thin glass-polycarbonate composite panel with a nominal thickness of 10.7 mm. The requirements for the resistance class P8B are met with a nominal thickness of 17.7 mm. Analyses with the four point bending test illustrate a partial shear transfer of the polyurethane interlayer. The structural behaviour of the composite panels shows reduced participation of the thin glass panes in the load transfer with increasing thickness of the polycarbonate. The bending stiffness of the polycarbonate sheet in combination with the glass fragments in the pressure zone ensures a sufficient post-breakage behaviour. Nevertheless, the composite panels show low geometrical stiffness accompanied by large deformation. The laminate does not break under a deformation with 100 mm and more. Therefore, the study limits the maximum deformation for thin glass-polycarbonate composite panels with a value of L/10. Structural design of these composite panels in the ultimate limit state and particularly in the serviceability limit state should consider the fact of low geometrical stiffness connected with large deformations. The studies of thin glass-polycarbonate composite panels are currently being supplemented by tests with other thin glasses, for example with a thickness of 2 mm. A continuing step is aimed to compare the measurements to analytic and numerical results.

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