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Glass in Architecture and Structural Engineering

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Foreword

The conference »Engineered Transparency« was founded in 2007 at the Columbia University in the City of New York and has accompanied the »glasstec« in Düsseldorf – the world's leading trade fair of the glass industry – since 2010. The unique liaison of research, novel developments and built examples always meets the demands of a broad expert audience.

The conference covers various subjects ranging from conceptual design, to planning and realization as well as to relevant research topics in glass and facade constructions. Additionally, the mini-symposia »embedded functions« and »glass technology« address current trends in the field of glass in building. Those special sessions were initiated in close collaboration with the professional associations Hüttentechnische Vereinigung der Deutschen Glasindustrie e.V./ Deutsche Glastechnische Gesellschaft e.V. (HVG/DGG) and Bundesverband Flachglas e.V. (BF) as well as Fachverband Konstruktiver Glasbau e.V. (FKG).

More than 60 peer-reviewed contributions received from authors more than 20 different nations create this exceptional spectrum of topics. We want to express our sincerest thanks to all contributing authors and speakers who share their ideas and knowledge with great commitment and often in addition to their day-to-day business. It is a great pleasure to welcome Werner Sobek, Werner Sobek Group, Stuttgart, Tom Minderhoud, UNStudio, Amsterdam, Juan Lucas Young, Sauerbruch Hutton, Berlin and Johann Sischka, Waagner-Biro, Wien as keynote speakers who lead to the conference with their inspiring ideas.

We would like to thank the members of the scientific committee for their valuable suggestions and the review of all papers. Particular thanks are due to Mrs. Stürmer and her team at Ernst & Sohn and Mrs. Horn and the staff at Messe Düsseldorf for their understanding and active support.

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Inhaltsverzeichnis

Facade – Architectural Design

Facade – Structural Design

Facade – Projects

Solar Technologies

Glass – Structural Glass

Glass – Structural Design

Glass – Composites and Coatings

Glass – Projects

Photovoltaic glass in building skin. A tool for customized BIPV in a BIM-based process

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Building Integrated Photovoltaics (BIPV) means today the possibility for the building skin to produce renewable energy in a safe, reliable and affordable way. Façade engineering and planning plays a fundamental role in this challenge and BIPV, along with other innovative technologies and solutions, opens a concrete opportunity to address the target of nearly-Zero or Plus-Energy Building. Most of the BIPV applications in façades concern glazed systems where PV cells are included within a laminated glass (e.g. in curtain walls or structural façade). Integrating photovoltaic in surfaces of the building envelope, involves a strong integration of energy, electrical, architectural and construction requirements during the whole process, from early-design phase till to manufacturing and operation. A collaborative and integrated planning approach by architects, engineers and manufacturers becomes essential, so that the development of methods, models and tools oriented to optimally support an integrated planning and construction process (i.e. the BIM approach) is a crucial aspect of growing interest. In the framework of the European project Construct PV, the authors collaborated in developing a web-tool aimed to support, since the early design phase, the integrated design of a customizable BIPV component for the integration into the building skin, within an interoperable process based on Building Information Modelling (BIM). The tool allows the customization of both physical (light transmittance, power,..) and constructive (dimensions, layers,..) features with the goal to cover all the main possibilities in terms of product design, such as the module's layering, the use of different materials (such as different glass types), the shape, the cell's arrangement, etc. with the result to define a 3D geometry of the component in a realistic graphic environment. The second step focused on developing a plug-in to create interoperability with a BIM-based process. The research is expected to cover a first step for supporting the design of advanced systems of building envelope including customized BIPV elements for transparent façade, in the perspective of an integrated approach ensuring quality, transparency and time/cost benefits.

Keywords: BIPV, building skin, semi-transparent photovoltaics, BIM, façade, tool

1 Introduction and motivations

1.1 BIPV and glazed façade: between product and process innovation

BIPV has always had a special relation with glass since its early usage. Conventional PV module requires transparent flat glasses in order to ensure strength, rigidity, environmental stability and high light transmission and also, with ultra-thin glasses, to reduce the

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module weight and the cost since glass is a moderately large part of the final cost for a solar module (Burrows & Fthenakis, 2015). But whereas research and manufacturing in conventional solar panels are mainly aimed to increase electro-technical requirements and energy performances, glass systems for BIPV are expected to evolve from relatively crude systems to a true integration of PV in glazed parts of the building skin (skylights, facades, spandrels, curtain walls and atrium roofing). BIPV glasses have been used so far almost entirely for prestige projects but today a market evolution is forecasted to shift towards a larger market of ordinary buildings (e.g. commercial, residential), with the challenge to integrate an attractive panel design (advanced optics, cell's arrangements, shape, etc.), to fit with new PV technologies (thin films, DSSC, organic PV, etc.) and to address cost-effectiveness (Gasman, 2012). In BIPV, the solar module becomes a constructive component of the building skin, language and material of its architecture. Such a different approach opens further issues in the use of glass, especially for façade, since aesthetics and building performances become an essential part of the expected requirements along with energy production, electrical safety and reliability (Frontini, Scognamiglio, Graditi, Pellegrino, & Polo Lopez, 2013). Moreover when BIPV glass is used for semitransparent elements, the solar façade acts as a key-element enabling the indoor comfort (solar gains, solar control and shadowing, daylighting along with acoustical and visual comfort) and the global building energy demand for heating and cooling (Lai & Hokoi, 2015) (Scognamiglio & Røstvik, 2012). In this framework BIPV urgently requires to complete the path of "technological transfer" in the building sector and, consequently, to overcome some barriers in terms of awareness, supporting tools, normative compliance and cost-effectiveness (Bonomo, Chatzipanagi, & Frontini, Overview and analysis of current BIPV products: new criteria for supporting the technological transfer in the building sector) (Bonomo, Frontini, De Berardinis, & Donsante, 2016). A different approach is required since the early Design Phase (EDP): PV becomes a "fundamental" of the design concept and of the envelope engineering, not only a multi-functional physical part of the building skin but also more and more part of an integrated and complex building process, both real and digitized, involving design, construction and information management. In this framework, the European project Construct PV (www.contructpv.eu) is aimed to develop and demonstrate customizable, efficient and low cost BIPV by means of a collaborative and integrated approach involving architects, engineers and manufacturers.

Innovative methods, models and tools oriented to optimally support an integrated design play a fundamental role in BIPV, since integrating PV involves a strong integration of energy, electrical, architectural and construction requirements during the whole process, from early-design phase till to manufacturing and operation. One of the practical reasons for which BIPV still today remains a niche market, along with other possible barriers (such as costs, normative framework, feed-in-tariffs), can be identified in the absence of supporting tools capable to overcome the gap between PV and building sector and to effectively integrate PV along the whole design and construction process. Goal of the work presented in the paper is to offer a versatile, flexible and effective software environment for design and evaluate a BIPV customizable component where energetic, architectural and construction aspects are jointly taken into account. The software platform, object of this document, has the general goal to facilitate the main stakeholders during the “process” of creation and implementation of a BIPV customized component, since the Early Design in connection also with BIM technology. Furthermore the web-tool allows a real time visualization of the BIPV object created by the user considering the different module’s materials. Different glass types and finishing are implement using different UNITY assets: transparency, reflectance and refraction are considered and represented and the relative influence on the final power is introduced.

1.2 Building Information Modeling (BIM) for design and engineering of BIPV glazed façade

Building Information Modeling is a methodology for the planning, construction and operation of a building. The continuous model-based process aims a continuous use of the digital representation of a product or a building component from the first planning phase to the construction phase and finally for the use of the product in the phase of the facility management. The key word for this procedure in the construction industry is Building Information Modeling or Building Information Management (BIM). STRABAG/Züblin developed this method further and defines internal processes based on these methods as 5D. 5D means: → 3D three dimensions: geometry; → 4D the fourth dimension: time; → 5D the fifth dimension: all other connected processes like estimating and logistics. So first of all BIM is a method to use the product data or building component data for the planning process. The data represents on the one hand geometrical data such as for example the height and the width of a BIPV-Element. On the other hand quality data is represented. This could be the material and detailed properties of an element. This data has to be used in different phases of the planning and construction process. Furthermore the data can be used by different stakeholders. The façade is the envelope of and for a building and it is responsible for the protection of the interior, for the representation, and thanks to newest developments it is also responsible for energy harvesting. Due to these functionalities and further different circumstances façades and façade-technologies become more and more complex. BIPV is such a new and highly complex technology. Why? In most cases BIPV is built by Glass. Glass has static properties, which makes this product highly regulated at least in Germany. Now, due to the integrated PV Cells it becomes also an electrical component. For the traditional construction industry a new interfaces between the trades of the façade engineering and the electrical engineering. To support the planning and engineering of BIPV, newest planning technology is necessary. In this perspective the motivation of the presented work, as described in the next sections, was to create interoperability between the BIPV design phase and a BIM-based process, allowing BIPV to enter a digital environment assisting the stakeholders (architects, owners, contractors, etc.) to make better-informed and shared decisions throughout the building lifecycle.

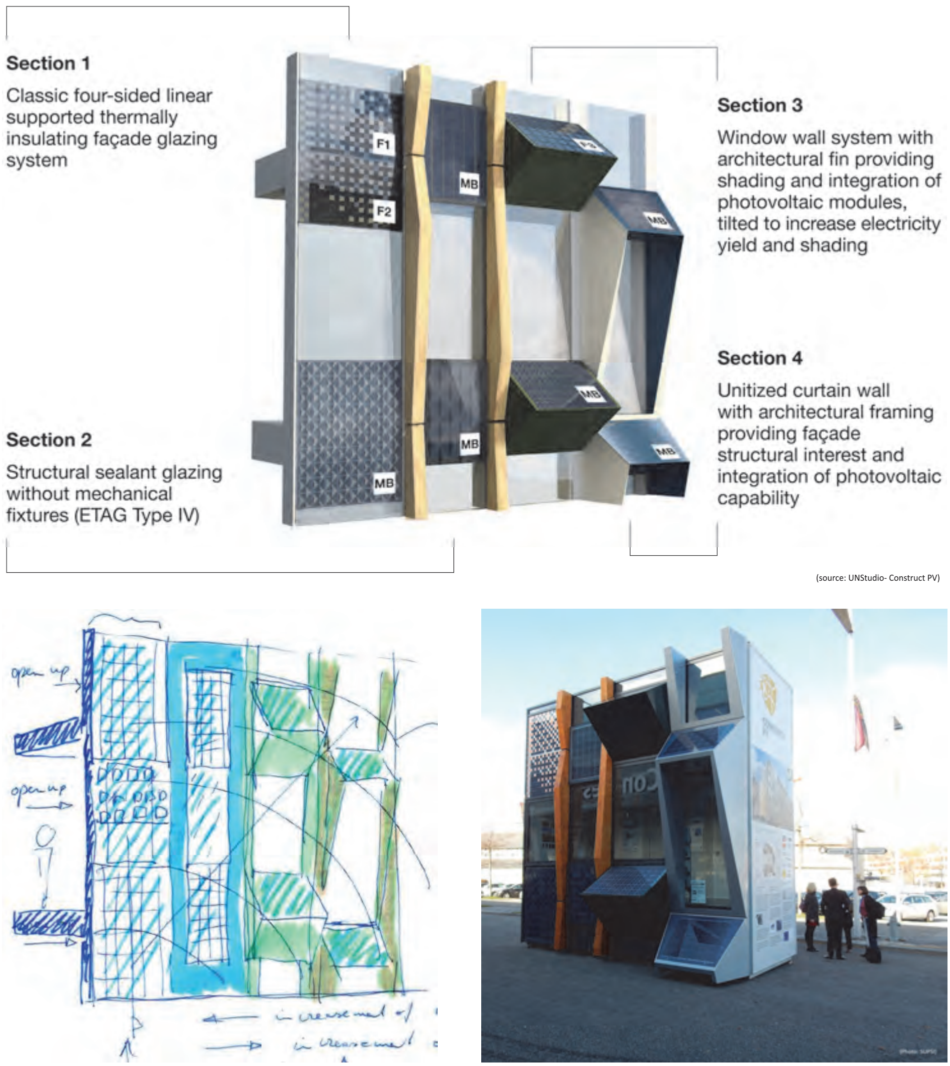

Figure 1-1 A mobile façade mock-up prepared by the coordinator of the project Züblin AG, will demonstrate in real-scale innovative BIPV glass-based technologies for the building envelope developed in Construct PV. The mockup, originated by the collaboration of Züblin with UN Studio, Fraunhofer ISE and Meyer Burger, demonstrates variants and possibilities in terms of architectural and technological design/manufacturing of BIPV systems for the building skin, showing different façade systems for glazed BIPV modules. It will be exhibited around Europe in the next years so that it will become a mobile demonstrative facility (more information at www.constructpv.eu).

2 Approach and methodology

The software platform, object of this document, has the general goal to facilitate the main stakeholders during the “process” of design, evaluation and implementation of a BIPV customized component within the design and building process. Since the architect is often the first key-player of the building process, the first step was the development of a platform with the function to flexibly support the **early design phase** for a customizable BIPV element. A **BIPV design web-tool** has been developed at this purpose as discussed in 2.1.1. Once that the configuration of the BIPV component has been established, in terms of architectural and constructive general layout, the development can move from a conceptual phase to the “design development” adding more details and information. The transition to a BIM-based process becomes strategic in order to really support the penetration of BIPV within the real Architectural, Engineering and Construction (AEC) process. Thus, the shift from a static component (such as an image, a CAD element, etc.) to a BIM parametric object was the second milestone of the work, as discussed in 2.1.2. The **Interoperability**, that is the interaction and information exchange of the design tool with Revit interface, has been defined through the development of a plug-in allowing effective and efficient exchange between the two software. As further discussed in 2.1.3, native **BIM objects** (Revit families) with specific features, parameters and behaviours (BIM objects adaptively working and customizable in BIM environment) have been predisposed to support this “transformation”.

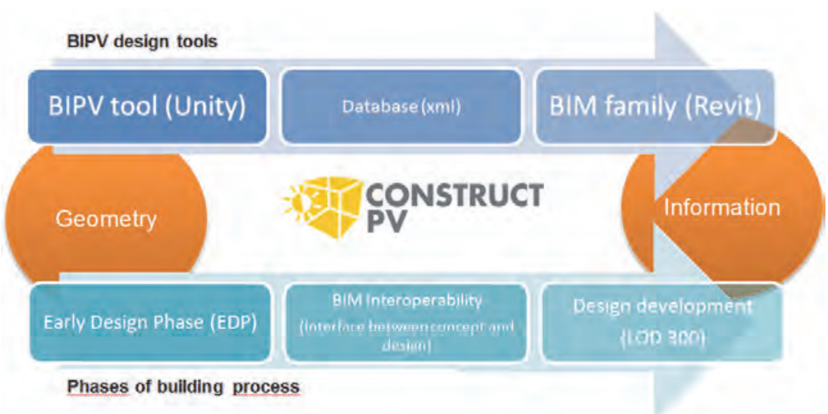

Figure 2-1 The possible levels of transfer of BIPV tools in the building process.

2.1.1 BIPV design web-tool for Early Design Phase

The main goal of the BIPV design web-tool is the development of an attractive web-platform with the function to support architects in creating customizable photovoltaic element to be used as part of the building skin. The tool has been developed on Unity platform that is a flexible and powerful development platform for creating multiplatform 3D games and interactive experiences. This software was chosen for the rapid iterative editing and the high visual fidelity, rendering power and ambience of the design environment (Real-time Global Illumination and physically-based shader) able to create an evocative dynamic platform. Thanks to this highly-flexible platform creating life-like images on the screen in real time, a high level of interactivity with the user (mainly architects, designers) is possible and BIPV design is transformed from a technical phase to the design concept of an architectural component in a scene looking relatively realistic. All the main architectural/constructive design possibilities for crystalline BIPV are available (module shape, layering, materials, type and material of solar cells, cell dispositions within the module, etc) thus offering a wide range of design opportunities to architects. In this “conceptual design” phase, even though the design creativity is an important goal, it’s essential to take into account all the rules of PV technology, taking care of a good final energy performance and considering, in each single case, the compatibility of the prototype with the industrial manufacturing possibilities. The main advantage is that a web-based software can be used over the internet with a web browser without installing any CDs, download any software, or worry about upgrades. Data are stored on secure, always-updated, backed-up servers and all data are centralized and accessible over the web from any computer at any time. The tool is placed on a web-link that can be directly connected with the project website (www.constructpv.eu). The tool generally allows to design and configure a crystalline module. It is possible to select the main design options at cell level. Mono or polycrystalline cells are available, in different colours and sizes. Also different electrical contact systems can be inserted in the module design (e.g. front or back contact and smart wire connection technology). Different grid dispositions of cells can be selected (rectangular uniform, rectangular exponential and hexagonal) as well as disposition type, spacing, etc. The layering of the module can be established adding or removing layers through the dedicated buttons and choosing the material and layer’s thickness. The material list provided in the database collects some main typologies and possibilities. For each material of the front layer is assigned a “Reduction Factor” parameter, linked to its energy transmittance (affected by colour, pattern and glass transparency) in order to estimate the final module power that is displayed in real time during the module design. The following correlation between the transparency/colours/patterns of the glass and the power has been introduced:

$$P_{max} = n \cdot PP_{cell} \cdot RF \tag{2.1}$$

2 Production of thin glass

2.1 Float glass process

Float glass is a sheet of glass made by floating molten glass on a bed of molten tin. After a controlled down process the glass is cut into certain sizes, as typically known as jumbo size. This method gives the sheet a uniform thickness and very plane-parallel surfaces.

2.2 Dawn draw process

The molten glass flows through a small gap at the bottom of the melting tank down and is cooled to ambient temperature by annealing furnaces. After this controlled down cooling process the glass is cut into certain sizes [1].

2.3 Overflow fusing process

The molten glass is poured into an overflow gutter. From this gutter the molten glass flows on both sides down and fuses at the bottom point of the gutter. After a down cooling phase the glass is cut into panels with certain sizes [1].

3 Pre-stressing of glass

3.1 Thermal treatment

Thermal treatment is a typical process of pre-stressing, according EN 12150 [2], of glass in which the glass is moved on rollers forwards into the heating zone and is heated up above the transition point. After this phase of heating, the glass is blown off with air. During the phase of cooling to ambient temperature, glass is permanently moved forwards and backwards on rollers in the furnace. The thinner the glass the bigger so-called roller waves can occur.

For this reason, the Austrian company LISEC has investigated a new process in which the glass is transported on air cushion. This technique gives the possibility to pre-stress thinner glass by thermal treatment without roller waves.

3.2 Chemical treatment – Ionic Exchange

Another possibility to pre-stress the glass is chemical treatment according EN 12337 [3]. The glass is immerged into molten potassium nitrate. At a temperature of approx. 370 - 450 °C the effect of ionic exchange takes place. The smaller sodium ions diffuse from the glass into the liquid potassium nitrate and the larger potassium ions penetrate into the glass matrix. Due to the larger ionic diameter of potassium ions compressive stresses in the close up range of the surface result. The depth of penetration is around 50 - 100 µm. [1]

The values for ultimate bending strength, which are the basis for a structural design, are still missing. Therefore a couple of different test scenarios were investigated for their applicability for determination of ultimate bending strength of thin glass. Due to the application one has to differ between test scenarios with and without the influence of the edge strength (edge quality) – the so called edge effect. In the following a couple of possible test scenarios were investigated with the help of a finite element program and the result are shown.

4 Determination of ultimate bending strength without influence of edge strength

All sides simply supported glass elements e.g. window glass, are good examples for application where the edge effect has not be taken into account. Because the maximum stress arises in the middle of the glass pane. At the edges tiny stresses arises and therefore the influence of the edge strength has not be taken into account.

4.1 Ring on ring test – EN ISO 1288

The test set-up is performed by placing the glass sample on a circular steel reaction ring (supporting ring) and applying on its upper surface a load transmitted through a steel loading ring, until the glass breaks, as shown in figure 4-1 below. The purpose of this test is to achieve a uniform tensile stress field inside of the loading ring that is independent of edge effects. This is described in Blank et.al [4]. Such test set-ups are defined e.g. in EN ISO 1288-1 fundamentals of testing glass [5], EN ISO 1288-2 for large surfaces [6] and EN ISO 1288-5 for small glass samples [8].

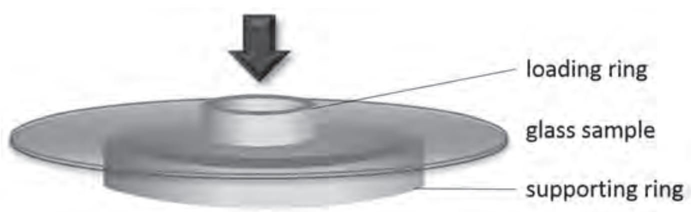

Figure 4-1 Ring-on-ring test set-up.

The test set-up for large surfaces defined in EN ISO 1288-2 is not usable for thin glass, because the deflection of the glass is much too high. The test scenarios (R 30, R 45, R 60 and R 105) defined in part 5 of EN ISO 1288 are more or less applicable for determination of bending strength of thin glass. But effects like as size effect, geometrical non-linearity or imperfections influences the results very much and have to be considered. Due to the thinness of the glass geometrical non-linear effects become dominant in these test scenarios, this is also mention in Wilcox [10].

Another effect, which has to be taken into account for thin glass is, that the stress has no constant distribution inside the loading ring as one assumption for the ring-on-ring test scenario which is stipulated in EN ISO 1288-5 [8]. Figure 4-2 below shows stress distributions for different ring-on-ring test set-ups (R30, R 45, R 60 and R 105) at different levels of stamp forces (0.10 kN up to 0.50 kN). The sizes of the quadratic glass samples are according EN ISO 1288 and the glass thickness is 1 mm.

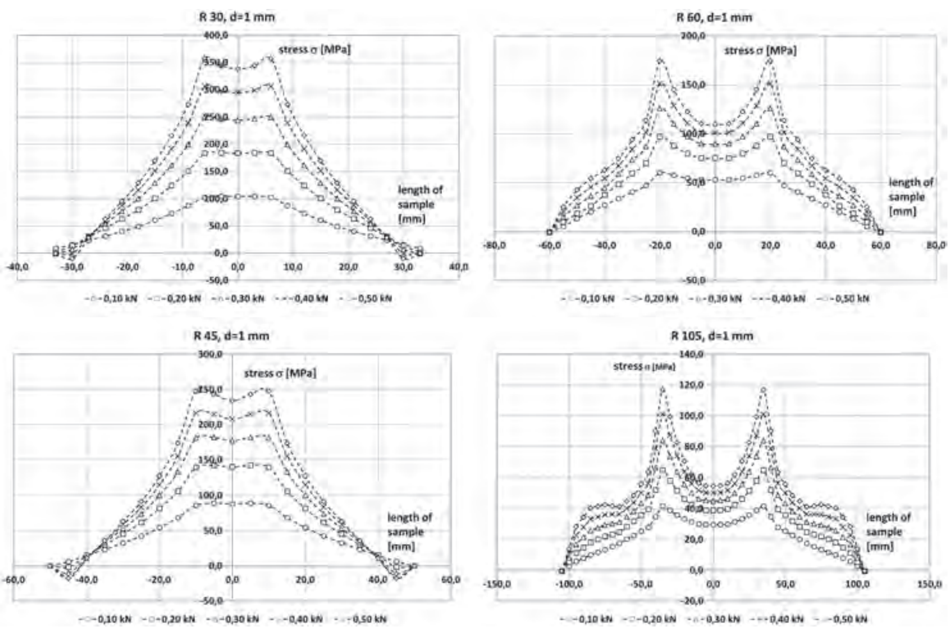

Figure 4-2 Ring-on-ring test – stress distribution along middle axis of glass sample.

Two effects can be summarized. The thinner the glass is the more difference between the stress in the middle of the glass sample and the area below the loading ring arises. The bigger the diameters of the loading ring is the more difference between the stress in the middle of the glass sample and the area below the loading ring arises.

4.2 Pressure pat on ring test

As a possible improvement of the ring on ring test a pressure pat on ring test was investigated. The test set-up is performed by placing the glass sample on a circular steel reaction ring (supporting ring) and applying on its upper surface a load transmitted through pressure pat instead of the loading ring, until the glass breaks, as shown in figure 4-3 below.

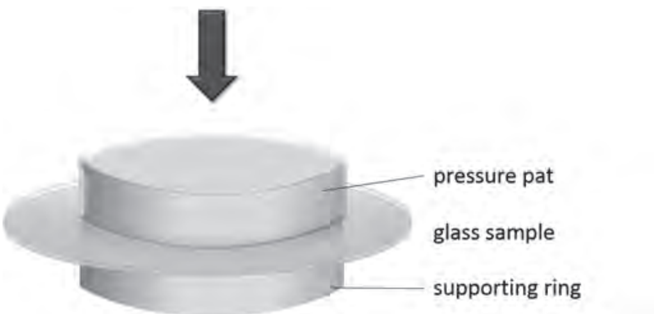

Figure 4-3 Pressure pat on ring test set-up.

The benefit of this scenario is that stability and buckling effects (described later in chapter 9 – effect of imperfections) are minimized and the area in which the stress can be assumed as uniform can be increased in comparison to a ring on ring test. A disadvantage is that the stress inside the supporting ring, as shown in figure 4-4, cannot be assumed as uniformly. Figure 4-4 below shows stress distributions for different diameters of supporting ring (105 and 190 mm) at different levels of stamp forces (0.10 kN up to 0.50 kN). Stress peaks in the area above the supporting ring arise. The thickness of the quadratic glass samples is 1 mm.

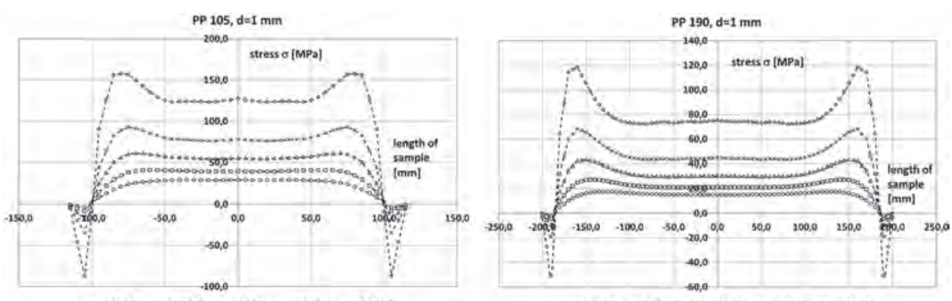

Figure 4-4 Pressure pat on ring test – stress distribution along middle axis of glass sample.

Two effects can be summarized. The thinner the glass is the higher stress peaks in the area above the supporting ring arise. The bigger the diameters of the supporting ring / pressure pat is the higher stress peaks in the area above the supporting ring arise in comparison to the stress in the middle of the glass sample.

5 Determination of ultimate bending strength with influence of edge strength

On two opposite sides simply supported glass elements e.g. room-high façade elements are good examples for application where the edge effect has be taken into account. The reason for this is that in such cases edges are bended and get bending stress at these edges.

5.1 Four-point bending test

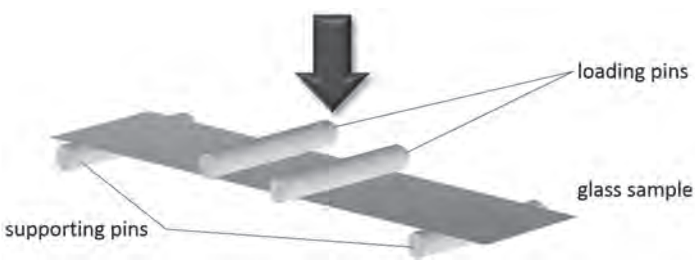

Figure 5-1 Four-point bending principle test set-up.

Figure 5-1 shows the principle test set-up for a four point bending test according EN ISO 1288-3 [7]. The test specimen with a length of 1100 mm and a width of 360 mm is supported on two supporting pins with a distance of 1000 mm. On its upper surface a load transmitted through two additional loading pins is applied until the glass breaks.

Large deflections result and the bearing forces are no longer vertical but inclined. The glass pane distributes its bearing force only by contact and eventually by friction between glass and rubber (EPDM). A simple resolution (breakdown) of the force to vertical and horizontal force shows that with increasing deflection also horizontal components are increasing. This has a growing influence on bending moment and therefore on the bending tensile stress. Due to the thinness no breakage of these thin glass panels can eventually be reached, because of slip from bearing pins due to bowstring effect (distance of pins is constant but end of panes move towards) or on some testing machines reach of maximum piston stroke.

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