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Mechanical Challenge of Frameless PV-Modules

Bernhard Weller, Lutz Tautenhahn
Technische Universität Dresden, Institute of Building Construction, Germany
www.bauko.bau.tu-dresden.de,

Frameless glass-to-glass PV-modules are exposed to a wide range of weather conditions, depending on their destined place of installation. Numerous aspects affect the mechanical stability as well as the mechanical durability under static and dynamic load conditions. These aspects are presented and discussed in detail. The structure of a glass-to-glass PV-module shows many similar features as a laminated glazing element in façades, which allows adopting knowledge from the structural use of glass in buildings. However, in some aspects, typical PV-modules show characteristic features, which significantly differ from standard laminated glass. The experience of using glass in buildings and the specific needs of the industry provide a fundamental basis for the development of innovative support and reinforcing systems. The research activities cover dynamic studies to assess the durability of PV-modules.

Keywords: Stability, Durability, Dynamic Testing, Adhesive, PV

1. Introduction

Glass-to-glass laminates are often used in glazed façades and for glass elements in structural applications. Less known is the production of PV-modules with thin-film technology on glass-to-glass laminates, which increased rapidly within the past years. The individual glass panes are usually bonded together by an interlayer material such as polyvinyl butyral (PVB), ethylene vinyl acetate (EVA) or several other foils. The installation of the PV-modules to the substructure can easily be realized with point-type clamp fixings. These types of fixings may generate stress concentrations in the area of the supports especially if compared to the rather smooth stress distribution of linearly supported glass panes. The local stress peaks are crucial for the design of glass-to-glass thin-film PV-modules. In addition to this, the designer needs to consider the composite action between the plies, the type of glass as well as the geometry and positioning of the backside contact holes.

In absence of other codified references, the mechanical durability of the glass-to-glass modules can be tested and certified according to IEC 61646. The therein described test program is based on the application of quasi-static loads. The IEC standard, however, does not cover the mechanical durability of a frameless glass-to-glass module subjected to thousands of unequal load-cycles according to its expected lifespan. The need for a dynamic testing regime for PV-modules has been noted in previous scientific studies [1] and [2] yet.

2. Aspects of Mechanical Stability

2.1. Interlayer Material

The composite action between the individual plies of the glass-to-glass laminate contributes to a safe load transfer while keeping the glass thickness to a minimum. It should be noted, however, that the composite action depends on a variety of influencing factors which, until now, are not comprehensively examined. The effective composite action also influences the stress level of each individual glass ply and the durability of the PV-module.

The lack of understanding the composite action of coated glass panes makes the design of durable PV-modules more difficult. Some uncertainties regarding the composite action of coated glass panes led to a change in perception of glass-to-glass laminates with coating towards the interlayer material.

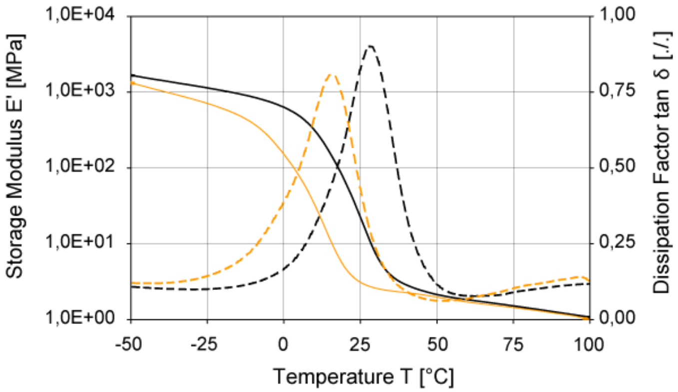

Figure 1: DMA thermogram for two different PVB-foils [3].

A comprehensive series of chemical and mechanical tests of equal interlayer materials from various manufacturers showed a wide range of differences in their characteristics like a high temperature and load-history dependent stiffness [3]. A sample diagram is shown in figure 1. The aspects mentioned above lead to the assumption that the interlayer material could also have an important influence on the long-term dynamic behavior of the whole module.

2.2. Glass panes

In order to ensure a profitable production process, the build-up of glass-to-glass PV-modules usually comprises very thin glass plies. A structurally adequate thickness of the panes is usually determined by calculation using FEM analysis or alternatively by experimental testing against quasi-static loads according the test regime of IEC 61646. Additional requirements, such as deformation limits or minimum glass thicknesses are not specified in this standard. In contrast to the structural use of glass in buildings, the deformations of PV-modules may significantly exceed the panel thickness if subjected to loads specified in IEC 61646. This can cause problems in areas of high bending, for instance at the clamp fixings or around point fixings.

The glass, which is used for the modules, has to go through several stages within the production process. Experimental studies indicated that coating processes can affect the mechanical strength of the glasses. The resulting tensile strength can be achieved by the coaxial double ring test and show which processes have a high level of influence. The achieved data was used to get statistically proofed values for the numerical simulation.

An important material characteristic of glass is known as stress corrosion. Authors of [4], [5] and [6] describe a phenomenon, which occurs under the presence of water on the glass surface in combination with tensile stresses within the material. This scenario may lead to crack propagation of surface flaws on the glass, which results in a decreasing tensile strength of the glass pane. Yet, the certification process after IEC does not contain any mechanical load tests under presence of water.

2.3. Support of the laminates

As the modules increase in size, it becomes necessary to introduce additional supports within the glass surface to achieve adequate system stability. It should be noted, however, that the thin-film is not to be disturbed by structural members or shading devices, in order to ensure its functionality. In order to comply with and be certified under IEC 61646, the PV-modules shall be loaded with equal loads from both sides. The support must therefore be designed to provide stiffness in both load directions while ensuring the performance of the PV-module, for instance keeping the top surface of the glass free of any shading elements. Simple contact supports without structural connection to the glass can only be applied on the backside of the module, so that they do not offer support for wind suction loads. To avoid disturbance of the PV active layer, the supporting member can be adhesively bonded to the backside of the module. The adhesive joint still provides support in both load directions. The curing time, durability and mechanical parameters of the adhesives are key aspects in the research of bonding techniques. Quick bonding technologies, such as bonding tapes for back rails of frameless PV-modules or light-curing bonds, are already in use in some areas and currently part of the institute’s research work [7].

3. Research and Results

3.1. Simulation

The use of the finite element method (FEM) for simulation provides far more opportunities of analysis of PV-systems compared to stand-alone mechanical tests. The influence of each component of the entire PV-system can be checked; bonded and reinforced modules can be analysed, in addition.

The experimental equipment of the institute's Friedrich-Siemens-laboratory allows for the set-up of several tests for determining input parameters for numerical simulations of the materials used. This approach ensures consistency among the various simulations done. Once a sub-model is calibrated and validated under various scenarios, it can be used to simulate more complex models and obtain reliable results. Figure 2 shows a test of a specimen in a tensile testing machine on the left hand and a stress plot of a FEM simulation on the right hand.

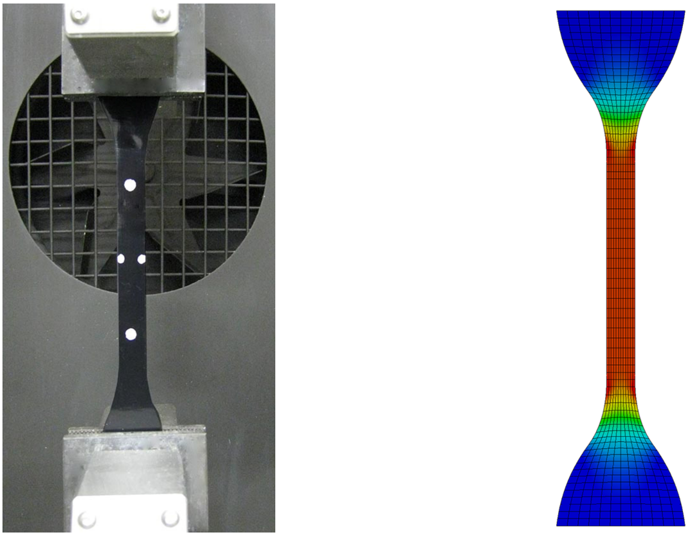

Figure 2: Specimen in tensile testing machine and simulation.

The use of FEM analysis always requires that realistic situations are represented in general terms. The analysis of smaller modules requires considerably less CPU-time and provides easier opportunities to obtain validated results at lower costs. The effect of assumptions regarding these reductions could be used to develop reliable approaches for studying larger-sized glass-to-glass PV-modules.

Prior to experimental tests numerical simulations are used to study the effects of various adhesives and their different material properties on the mechanical stability of PV-systems. Possible adhesives are polyurethane, epoxy resin, and silicone because of their durability and resistance to environmental influences. The use of silicones with their proven long-term stability would likely be favoured, but the cure time is too long to serve as a reliable solution for short cycle times in PV-module production. Quick light-curing acrylates are favourites for a short production cycle but can only be used with paying attention to durability.

Studies by numerical simulation of the institute showed that the use of stiff adhesives may generate stress concentrations immediately surrounding round point fixings. Given the deformation of the glass-to-glass PV-module is great and the thicknesses of the glass panes are small the bending radius around the edge of a point fixing of the module is very small when using a stiff bond. Special designed round point fixings with varying stiffness areas to avoid the named problems were developed and are currently tested at the Institute of Building Construction. Some prototypes are shown in figure 3. This new developed bonded fixings allow the glass to bend more smoothly around the fixing even with stiffer adhesives thus generating a much lower stress level.

Figure 3: Prototypes of point fixings.

An additional study by the institute comprises the simulation of linearly bonded, 2-sided support of a large-sized module. The bonded support width was very small thus the moments at the edges are very small too and the glass panes are securely held in place. The glass module can, therefore, achieve very large deformations - much greater than the thickness of the module - without cracking. The stress distribution is steady and the stress level low. In contrast to the solution of additional linear supports at the back pane like back rails, the amount of adhesive needed may be smaller.

Results of numerical simulations should always be validated. The Institute of Building Construction is able to use a pneumatic testing apparatus to check obtained results of the numerical simulations of PV-systems.

3.2. Experimental testing

The base of the pneumatic testing apparatus is a easily resizable stiff frame used for mounting the substructure of the module to be tested. The regulations of IEC 61646 require that the load direction be reversed every hour during testing. Furthermore, the entire system, including the frame, must be turned in order to comply with these requirements absent the use of a pneumatic system, a wind tunnel, or other sophisticated testing machinery. The suction phase must immediately follow the pressure phase to drive the tested specimens to the limits. This system is comprised of uncoupled suction cups with each suction cup has its own, individual, pressure cylinder. These suction cup units are mounted to bars which are stiffly connected to the base frame. All cylinders are part of one system in which pressure distribution is equally distributed among each cylinder.

The standard task of the pneumatic testing apparatus (Figure 4) is the testing according IEC 61646-10.16. Different sized PV-systems can be tested cause of the resizable frame like mentioned above. The testing apparatus is fully programmable, and the position of the suction cup units can be configured as desired. It is also possible to have several suction cups into a separate pressure system thus for instance a higher loading can be applied to chosen areas of the specimen, for instance to represent higher wind loads at the edges.

It is, therefore, possible to monitor strains and deformations at various positions throughout the specimen without interfering with the loading apparatus. Bonded systems can be tested without any problems during the suction phase unlike testing which utilizes sand bag or rubber mat mechanisms for testing.

Figure 4: Pneumatic testing apparatus.

Overall the most important and largest advantage to the use of a pneumatic system is the consistency of all mechanical load tests. Various types of PV-systems can be easily compared and the apparatus can be used to validate the results obtained from numerical simulations. Load steps can be defined as desired and be used for better validation of the numerically achieved results.

The pneumatic testing apparatus may also be used to conduct twist tests of PV-modules. This is a test to see what happens if the PV-module is not installed in plane or the substructure was built incorrectly or deformed. The suction cups can tilt freely at the end of the rods thus even dynamic tests in various scenarios are possible.

Thus the pneumatic testing apparatus is constructed modular it is easy to expand the system to far more suction units to provide possibilities of testing large-sized PV-modules with the same advantages of the apparatus like mentioned above.

Experimental tests with various load cycles can be used to simulate dynamic load scenarios in order to obtain information about the long term durability of the modules. A recently conducted study of an own developed durability test showed the risk of failure of PV-modules already after a several one-hundred load cycles. The cracks did appear without any forewarning like higher deformations or higher strain rates some cycles before cracking. The maximum and minimum values of deformation during the dynamic tests are evaluated for each load cycle and can be plotted against the number of load cycles.

The first test series were conducted with short cycles of about 5 seconds and low level loads of around 1200 Pa due to the lack of standards for dynamic tests of PV-modules.

A comparison of the deformations of the first cycle with these of the last cycle of a 100-load-cycle series showed no differences which are worth to mention. Samples of the same assembling and tested under equal conditions did not show any change in results even after increasing the load cycles up to a number of 20000. Recent test series with 500 cycles of 2400 Pa according to [1] showed a very slight trend to the increase of the deformations in the suction load which was introduced by the substructure and was not significant. In figure 5 the maximum and minimum values for the described 500 load cycle test series and a 10000 load cycle test series is plotted. To sum up, neither the low-load high-cycle-number tests nor the high-load low-cycle-number tests showed indications of an imminent module breakage yet. The conducted test series did not yield assumptions for a meaningful dynamic testing procedure so far. Further dynamic studies will be carried out to obtain statistically firm data of deformations while loaded and the number of cycles that are needed to cause a glass breakage of the modules. All dynamic tests have been done with of non weathered samples yet. Studies on the described effects of stress corrosion will be done soon.

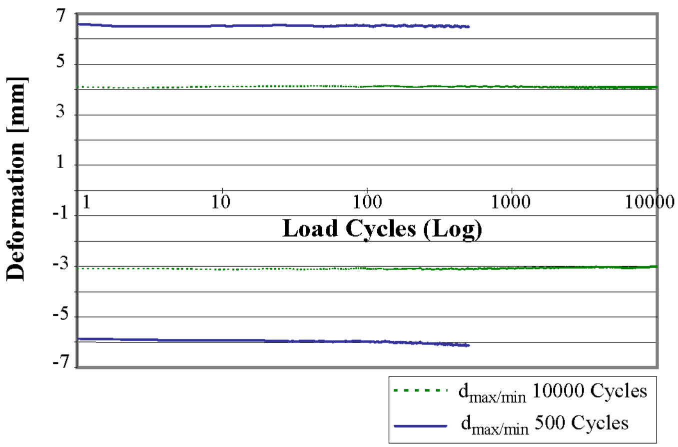

Figure 5: Deformation curves of PV-modules under different dynamic load conditions.

4. Summary and Conclusion

A number of influencing aspects on the mechanical stability of frameless glass-to-glass thin-film PV-modules are not studied comprehensively. This comprises the composite action and the mechanical strength of the weathered and aged glass panes under dynamic load situations in addition to other aspects. Since the glass strength also depends on the load history, there is a need for adequate standards for dynamic load scenarios. The design of PV-systems can be optimized by a combined approach based on simulations using FEM analysis and experimental tests to verify the results.

The new developments in bonded supports and reinforcement systems may help in the design of large-sized glass-to-glass modules in view of the expected lifespan of those systems.

Current studies at the Institute of Building Construction are aimed at the investigation of the breakage phenomena of the modules under dynamic load to provide a basis for designing durable frameless PV-modules.

5. References

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