Periodica Polytechnica
Civil Engineering

62(1), pp. 259–266, 2018
https://doi.org/10.3311/PPci.9988
Creative Commons Attribution

RESEARCH ARTICLE

Predicting Performance of Aluminum - Glass Composite Facade Systems Based on Mechanical Properties of the Connection

Maciej Cwyl[1*], Rafał Michalczyk[2],
Natalia Grzegorzewska[1], Andrzej Garbacz[1]

Received 07 September 2016; Revised 12 January 2017; Accepted 19 September 2017

Abstract
In this paper, an extensive Finite-Element (FE) numerical study is carried out on a glass framing with point mechanical connectors. The models have been calibrated based on literature studies and field research. The simulations have been performed in order to assess the mechanical behavior of the examined glass-aluminum panels. In frame-support glass structures, such as curtain walls, where glass plates are mounted onto a metal framework, the composite behavior between glass and the supporting aluminum elements is usually a problem. It has been showed that an application of elastomer gaskets decreases the stress concentration at the interface between aluminum and glass while does not significantly change the working scheme of the profile. Based on the proposed models, the failure mechanism for wider set of geometrical configurations can be analyzed.

Keywords
glazing-systems, aluminum-glass composite facade systems, glass damage prediction, curtain walls, gasket, elastic connection

1 Institute of Structural Engineering, Faculty of Civill Engineering,
Warsaw University of Technology,
16 Armii Ludowej Ave., 00-637 Warsaw, Poland
2 Institute of Roads and Bridges, Faculty of Civill Engineering,
Warsaw University of Technology,
16 Armii Ludowej Ave., 00-637 Warsaw, Poland
* Corresponding author, email: mc@il.pw.edu.pl

1 Introduction

Modern aluminium alloys are popular and widely used materials in civil engineering [13]. The main are of their application are glass-aluminium systems, particularly elements of facades of office buildings, exhibition halls and various kinds of public facilities (Fig. 1). Based on the current estimation, the world use of row material reaches 50.0 million ton per year.

The main reason for using aluminium in the construction of facades is the performance - it weight three times less preserving similar strength parameters in comparison to steel. Since most elements are manufactured by extrusion, casting and roll forming, this material allows the production of complex geometries of profiles for the proper mounting of glass panes, seals and insulators. It is a material easy for the surface treatment, non-flammable, non-toxic and resistant to corrosion. It has a flexural modulus similar to that of glass, this enables work with deformation and deflections facade elements.

Usually a glass-aluminium structure is designed as an independent part of a building construction. The metal skeleton of a curtain wall should not carry forces generated in a shaft of the building [8]. Its only purpose is to transfer dead loads, climate loads and technological loads, which occur on a surface of a glass-aluminium shell, to the main construction. Facades structures have to meet separate criteria of leak tightness, air and water infiltration, fire conditions and sound absorption [6] [11]. Furthermore, the structures are required to satisfy much stricter conditions of the ultimate limit state and the serviceability limit state.

Connections between glass panels and a metal skeleton of a mullion-transom structure of the facade play a special role in the overall building system. Currently, the two different solutions are being developed simultaneously [2]. The first one, a linear connection, supports the sheet of glass on two or four of its edges [3]. This is more traditional form of framing with a mechanical mean. The second way is a point connection which keeps the sheet only in its corners, usually by combination of removable and fixed stops on the inside or outside of the frame to hold the glass in place [4]. Due to significant development of materials engineering and constantly growing expectations of users, all connections are continually a subject of modifications and require subsequent research. The article follows from laboratory tests on wind pressure, water penetration, air infiltration, structural load tests and directives of the standards Eurocode 9.

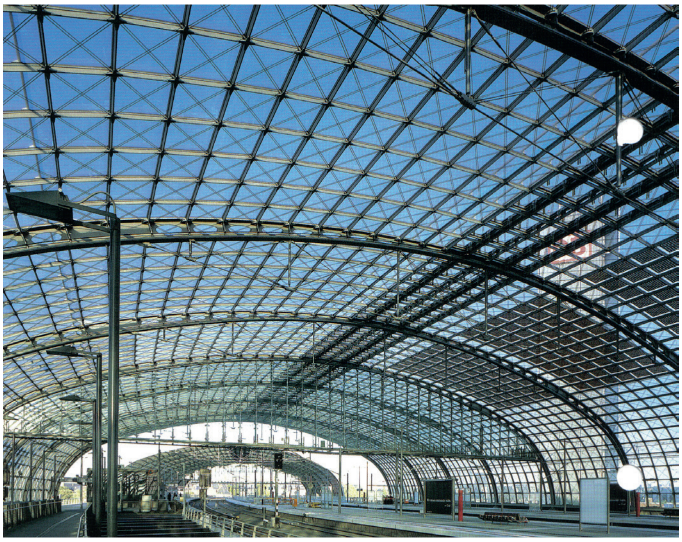

Fig. 1 The train station (Lehrter Station in Berlin), an example of the glass-aluminium shell structure

The point where a process of destruction is initialized often turns to be where a glass panel is connected with a metal frame. Therefore, the process of designing and then assembling the connections should be carefully reviewed [7]. A vast variety of new glass-aluminium systems appeared in Poland in the 90's. Due to economic reasons, the idea of fixing glass sheets directly into metal frames appeared and was eventually introduced into the market [5]. In this particular case there is a direct pressure put from a metal profile on a glass surface. Such a solution was justified by the fact, that both materials show similar values of the elastic modulus E (Young's modulus) what is: 70–75 GPa for glass and 69–80 GPa for aluminum alloys. Also in this method the fasteners were used to tighten aluminum strips to the glass surface, to bind the elements of the facade and the construction points.

These kinds of systems were easier and cheaper for an assembly since it was decided to abstain from using gaskets and spacers. Moreover, such a solution simplified production process and eventually gave a lower price of the final product. Particularly, the significant costs reduction was visible in element-wall solutions. The relevant issues often neglected in the analysis of the glass and the metal connections were: aging processes, imperfections obtained during assembling, an impact of insulation on glazing's performance. Thus, the following failures have been caused because of the omission of elastic spacers: cracking and breaking of glass panels, large shifting within the glazing frame, causing air infiltration and water leakage, and overstressing of the glass due to loss of support. Subsequent repair works also affect normal building functioning such as occupants' inconvenience, security. Glass cracking and falling down may immediately put the human life in danger so it should be considered a potential life-safety hazard, especially for multistory buildings.

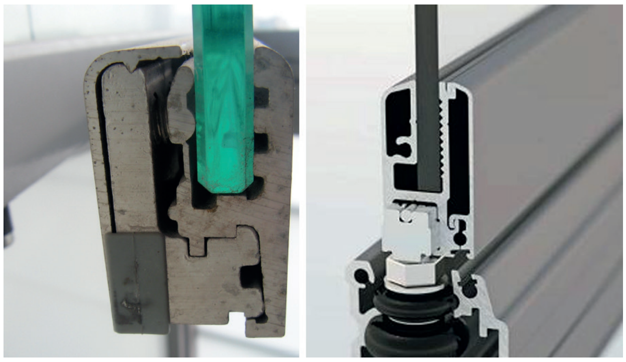

Fig. 2 Examples of system solutions of the connection of a glass panel and a metal profile without the use of flexible spacers

During field studies the authors noticed that not taking into account deformations between the joined materials when introducing the solution without flexible rubber spacers was the cause of most problems. More attention should have been payed to the difference between values of Poisson's ratio, which for glass ranges from 0.18 to 0.23 and is typically around 0.33 for aluminum. Resilience of glass and aluminum alloys also shows a significant difference. Another adverse phenomena is stress concentration in spot zones where point fasteners were used to tighten aluminum strips to the glass surface. These factors, both combined with influence of exterior forces like wind and thermal loads, caused a number of accidents, breakage and cracks.

The purpose of studies carried out by the authors was to characterize the performance of different types of glazing systems according to a type of the connection. These studies also help identify aspects of the design that can be modified for better performance. This article presents the analysis of how the application of the flexible glue layer provides an improvement in working conditions of the glass-aluminium connections, especially in facade panels. The research has been based on the authors' experiences and Finite Element Method numerical investigations. Model of the representative connection in the most often used facade systems has been presented. The next section provides more insight in field studies on performance of architectural glass as well as a discussion on the more recent studies.

2 Description of problem

The classic way of embedding glass in a metal profile using rubber spacers or glue layers, which separate the glass from the metal part, was a reference point to the direct glass-aluminium connection shown in Fig 2. The removable rubber inserts are 3.0 to 8.0 mm thick while flexible glue layer is usually 0.2 to 4.0 (6.0) mm thick. An example of that kind of connection with the rubber inserts is shown in Fig. 3.

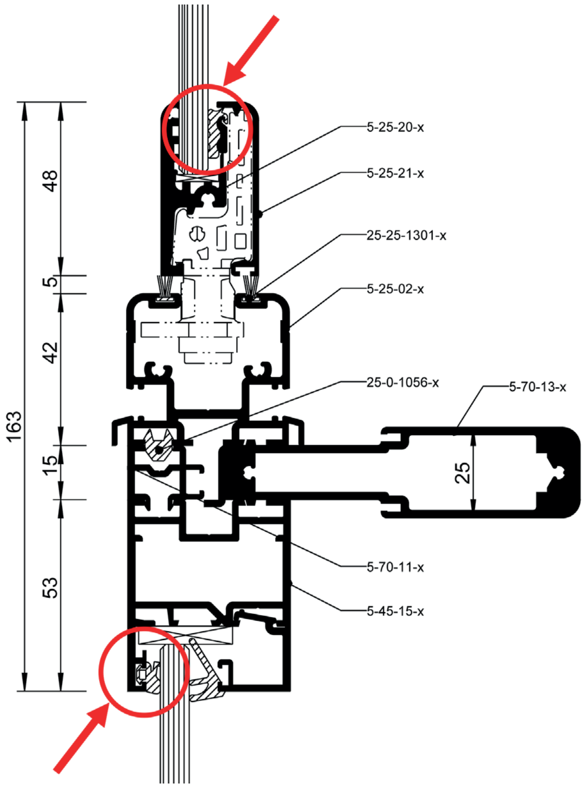

Fig. 3 One of the solutions of the connection between the glass panel and the metal profile with the elastic inserts – marked with arrows

Fig. 4 One of the damaged glass panel (ESG type) mounted without elastic inserts spacing glass and metal faces of transoms of the facade system. The neighbouring panels, properly assembled, exposed to the same load, work properly

Below an example of failure of glazing system in a building located in Warsaw area has been presented. After seven years of exploitation, the building inventory shown that 85% of the glass panels, in which rubber spacers or flexible adhesive glue hadn't been applied, were destroyed. In the course of the ongoing expert works, it was noticed that even if the glass panels were precisely embedded in the metal construction, but without compensation, they were destroyed. Damaged panels were exchanged to the elements of glazing with proper spacing between the glass sheet and the metal part. Fig. 4 shows the glass panels of the facade of the building. The middle one was destroyed because any kind of elastic inserts hadn't been assembled between glass and metal structure. Additionally, the broken panels did not have required spacing between a lower edge of a bolt's face which steady the glazing panel. On the both sides you can see the panels that work properly because they had been secured by the elastic spacers and the flexible glue layers.

Fig 5 shows the same destroyed window panel but magnifying the corner to illustrate the crack pattern that can also suggest the distribution of the stress in the glass panel. The image presents the selected panel mounted without the use of spacing flexible elements. The research has shown that high pressure had been generated on the frame-to-glass contact area. The region of predicted pressure application was also marked on Fig. 5. It is worth noting that the same color lines indicated the direction of main cracks, initialized by a "stress concentrator" or simply a "notch".

Fig. 5 Representation of the actual way of the propagation of the general stress in the glass panel, consistent with lines of cracks from the place of the initiation of the process of destruction (marked point) generated by excessive pressure of the glass panel to the metal without elastic spacers

The place of disorder called a "stress notch" is a point where, even if standard wind load is applied, the stress exceeds the bearing capacity of ESG tempered glass, which is 50 MPa. The destruction process of the glass panel is initialized in that stress notch and when the stress exceed the permissible value, the element falls apart into small pieces, approximately one square centimeter large. In the inventoried building, tested facades panels with inappropriately assembled glass sheets revealed that the level of generated local stress caucused by pressure of the metal framing to the glass surface ranges from 8.0 to 12.0 MPa. These are significant values in relation to of the most popular and most common types of produced glass. For ordinary float glass the maximum value of stress cannot exceed 18.0 MPa. For VSG glass which also is the variant of "safe glass", the stress level cannot reach 24.0 MPa. As already mentioned, the limit of stress for tempered glass type ESG is 50 MPa. From the given values, it appears that when using other type of glass than ESG, point load cause by the fastener can cause the emergence of local stress and finally led to the value of ultimate strength of glass panels. It happens even if no additional dynamic, wind or thermal loads are imposed.

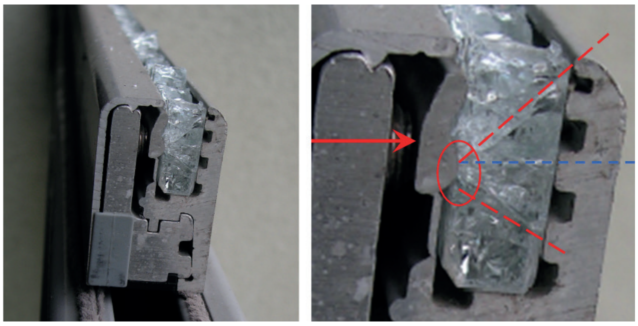

Fig. 6 Showed the nature of the destruction. The place of the initiation of the process of destruction caused by the local pressure between glass and metal (the description in the text).

Crack patterns presented in Fig. 5 help to understand the overall process of glass destruction. Most likely this failure mod has been caused by the pressure induced by the metal element to the glass surface. Better insight into this detail is shown in Figure 6. Picture has been taken after disassembling the tested glass panel and removing cullet appeared as a result of the glass destruction. The axis of point load application was marked with a blue line, while the red ones show approximate direction of the surface break. According to the theory of stress distribution in the panel these lines disperse at 45 degrees angle. It has to be noted that we observe smaller pieces and glass dust near metal fastener (marker with red ellipse). This has to be the place where the destruction process has been initiated. It lets conclude that it was a result of high pressure applied to the glass panel. This phenomenon called "quartz pulp" is characteristic for glass elements. One can see that farther from the load point, fading of the quartz pulp can be observed and broken glass transforms into regular pieces with dimensions up to one square centimeter.

To avoid a kind of situations presented above, the elastic spacers should be used. Also an elastic glue layers have the same purpose, as the flexible spacers. They compensate the state of deformation appearing locally in vicinity of the stress notch, align the local surface inaccuracies, which usually increase stress in the brittle glass sections. They provide spacing between the glass and the metal elements transferring all kind of dynamic loads. Moreover, the elastic masses improve tightness and durability of facade's elements.

Another type of glass failure has been reported during one of the buildings inventory while the damage to four glass panels has been found. The damage occurred despite the fact that panels on the tested facade were fitted correctly into the frame. The appropriate spacing, using flexible plastic inserts and assembly through the glue masses (silicone) has been provided. The destroyed glass sheets were around 1.4% of all correctly mounted. Analyzing the breakage attention was put to specifics of assembly of glazing, the duration of their use and the characteristics of glass as a material. The tested glazing was particularly exposed to the sun, heating during the day and then cooling during at night. They were only partially shaded as a result of the orientation of the building according to geographical directions. Occasionally, during the process of glass production, the nickel inclusions get into its structure and because the glass panel is exploited for several years, the inclusion acts as the "defect with delayed ignition". Under influence of solar radiation and heating, a molecule of nickel sulphide significantly expands which results in an increase of internal stress in the glass panel. If this phenomenon occurs in the tensile stress area there is a high probability that level of permissible stress will be exceeded and spontaneous breakage of glass can occur. This kind of cracks are more often observed in Spring. It is a result of changes in the time when glass is exposed to sunlight as well as a larger wind load and daily temperature amplitudes. This happens in case of 0.8-2.0% of all produced glass panels. During the ongoing researches, a mechanism of the spontaneous breakage effected 1.4% of the properly embedded glass panels. This is the reasonable number according to the period of observation and maintenance of glazing which took several years. Currently, knowing the course and scope of the phenomenon associated with the spontaneous breakage of properly mounted glass, the special technical treatments may be applied to limit the impact of this type of factory defects. The mechanism of spontaneous breakage of glass under the influence of nickel sulphide is reduced by eliminating panels in Heat Soak Test (HST). In tested elements of facades, it is recommended to use glass panels which are subjected to the additional heat treatment during manufacture and have the designation (HST) certifying passing the test. In this kind of glazing, alternatively, chemically strengthened glass may be used. In this case sodium ions are replaced with potassium ions. Additionally, this glass is hardened by a surface layer with thickness of 100μm, which causes a 25% increase in strength of float type glass.

3 Finite-Element numerical investigation

Several approaches can be used to understand and solve the problems discussed in the previous section. While analytical solution is hard to find or limited to only simple cases, the authors decided to use of numerical experiment instead. Numerical modelling was used to demonstrate the difference how the two mentioned type of glass framing work: the glass panel embedded directly in the metal profile's socket and with use of elastic gaskets. The results were presented as cross sections of the metal profile and the glass sheet, which illustrates the differences in stress distribution and deformations in both materials.

The numerical model was created in the well-known FEM system ABAQUS [1]. It was assumed that the behaviour of all materials is limited to elastic range. Glass can be characterized as a brittle material and once deformation state reaches its limit the material breaks. In this case stress level in aluminium is definitely below material strength and no ductile deformation occurs. For that reason using only theory of elasticity seems reasonable. Material parameters used in the simulation have been presented in Table 1.

Table 1 Material parameters used for simulations

Material	Density [kg/m^3]	Young's modulus [GPa]	Schear modulus [GPa]	Poison ratio [ ]
Aluminium EN AW-6060	2750	70	26,3	0.33
Glass	2500	80	32,5	0.23
Elastic spacer	1200	2	0.69	0.46

The Finite Element models presented in Fig. 7 consist of two main parts: the glass panel and aluminum profile that provides support and transfers loads. The surface of the glass panel was loaded by wind pressure. In the first case, with aluminum parts keeping the glass, the pressure was absorbed directly by the glass pane. In the second case pressure was absorbed though the 4.0mm thick elastic spacer.

In both variants the numerical model consists of about 2,000 finite elements, connected in 6400 nodes. Quadratic shape functions (second degree polynomial) were used as an approximation for displacement field, so eight-nodes finite elements with reduced integration were chosen [16]. The description of this type of element can be found in ABAQUS documentation and they are known as type CPE8R. The use of quadratic elements makes the task more computationally expensive per one solution, however, the overall expected accuracy can be achieved more likely. Because of the expected significant variations of stress fields in both metal and glass elements, it was decided to examine the growth of stress inside the cross section by higher level of approximating functions [17].

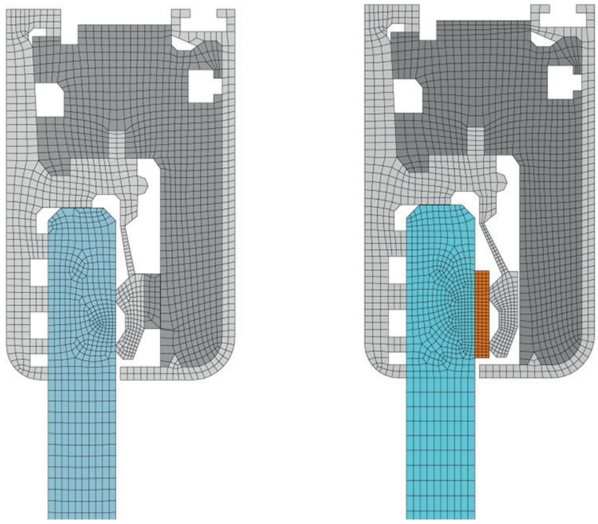

Fig. 7 Numerical models of the direct metal-glass panel connection (left) and connection with the use of rubber gaskets (right).

Boundary conditions were applied by restraining vertical and horizontal displacements of the nodes located in the lower and upper edge of the model (part of the metal profile). The glass panel and aluminum profile were connected by sharing the same nodes, so assuming the equal displacements of the nodes located at the interface between both materials. The picture of the connections was shown in Fig. 7. The glass elements were marked with blue color, the metal ones with grey and flexible inserts with brown.

The second finite elements model has been developed to examine deformation of monolithic glass panel. Although, the glass models is rather simple and consist of 4-node shell elements, the main advantage is the detailed elastic support used. It is possible to reproduce all kind of boundary condition that can be found in real glass framing. Aluminum profiles support glass panel at both edges. Overall view of the model is shown on Fig. 8. The panel dimensions and elastic support were presented in Table 2.

Table 2 Characteristic dimensions for model-2.

Name	Height [mm]	Width [mm]	Thickness [mm]
Glass Panel	2120	950	8
Aluminum support	57	950	44

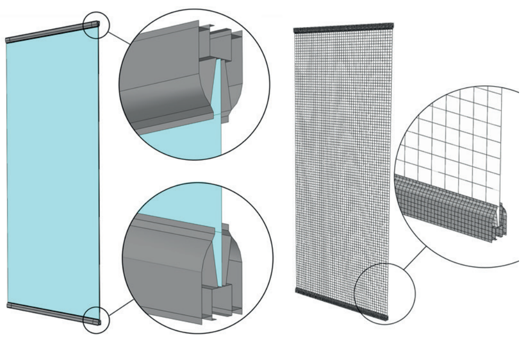

Fig. 8 Numerical models of single glass panel with elastic support. Finite elements mesh (right).

Standard wind load, normal to the surface, has been applied. Wind pressure has been determined based on Eurocode 1 and all the assumption were presented in Table 3.

Table 3 Determination of wind load pressure.

No.	Quantity	Value	Reasoning
1.	Wind zone	1	Typical 100 m a.s.l.
2.	Category	IV	Located in the city center
3.	Panel is built-in at the height	20 m	For residential building in Warsaw area
4.	Base wind velocity	22 [m/s]	Building located below 300 m a.s.l.
5.	Influence of terrain	$c_0(10m) = 1$	Neglected since average incline < 3°
6.	Characteristic wind pressure	q = 0.881 kPa	-
7.	Design wind pressure	q = 1.320 kPa	With safe factors

4 Results and discussion

4.1 Deformation of glass-aluminium connection

The simulation results confirm that the gasket greatly reduces adverse stress, which can exceed permissible values in the case of its non-use. The elastic insert reduces the possibility of the initiation of glass breakage and increases safety of glazing. In Fig. 9 distribution of general deformations (maximum compression strain) for profile cross section is shown.

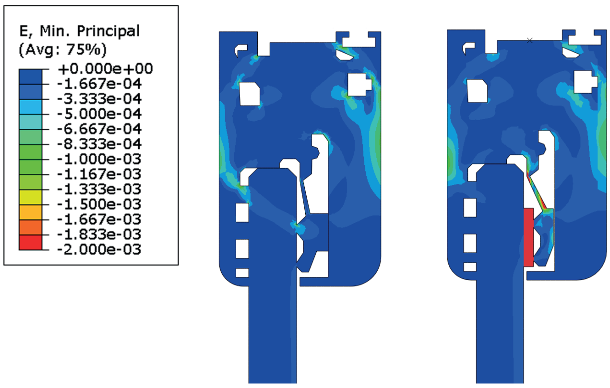

Fig. 9 Distribution of maximum compressive principal strain in the model using gasket (right) and without any elastic inserts (left). Standard wind load (see Table 3).

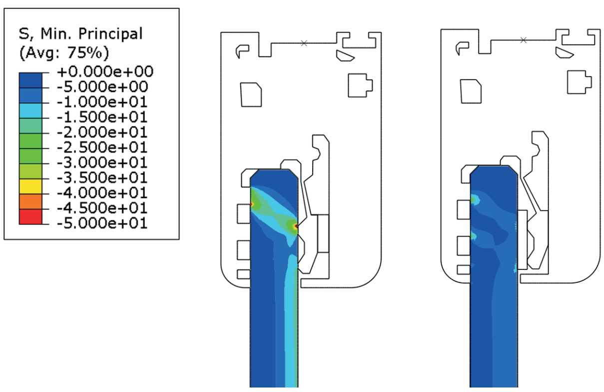

Fig. 10 Distribution of the general compressive stress in glass sheet (MPa). The model with the gasket (right) and without (left). Standard wind load (see Table 3).

An application of the elastomer gaskets does not significantly change the working scheme for metal profile but decreases the stress concentration at the interface between aluminum and glass. Distribution of maximum compression principal stress in the glass panel cross section depending on kind of the connection with the metal profile has been shown in Fig. 10. It is easy to see that the use of the gaskets makes stress field more uniform and stress points exceeding the acceptable state are not observed. Also, too stiff elastomer and bolts influence the results.

Parametric study has been carried out to determinate range of stiffness for elastomer gasket. Five types of gaskets (0.1 ÷ 5.0 GPa) in combination with two types of pressure applied to the bolts have been used. Additionally, the rigid connection (no gasket) has been simulated. Comparison of maximum stress in glass for all cases can be seen in Fig. 11. Any gasket used, even quite stiff, is much better than raw glass-aluminium connection and prevents stress concentration. Simulation shows that the use of higher bolt pressure leads to higher unnecessary stress and should be avoided.

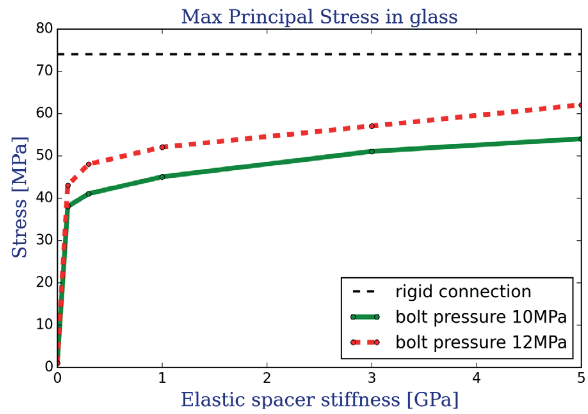

Fig. 11 Highest compressive stress in glass panel depends on the stiffness of elastic spacer and force applied through bolts.

4.2 Results for monolithic glass panel

Similar research has been done for a single panel with various connection properties. It was assumed that panel is built-in at the height of ~ 20 m above the ground level (e.g., residential building in Warsaw area). For standard wind load applied and a connection without the gaskets, stress concentrations in the glass panel were observed at the connection from the beginning, even if less than 30% of load was applied. Another numerical experiment simulating the use of flexible spacers (which 3.0 mm thickness and Poisson ratio is n = 0.46) shows that stress can be limited to the value of 38 MPa, and comes only from pure bending in the middle of the panel (see Fig. 12). The value of permissible stress for tempered glass should not exceed 50 MPa. This means that the use of the flexible rubber element compensates for the potential dangerous stress concentration, wherever a local notch might be created and breakage might be initialised (see Fig. 6).

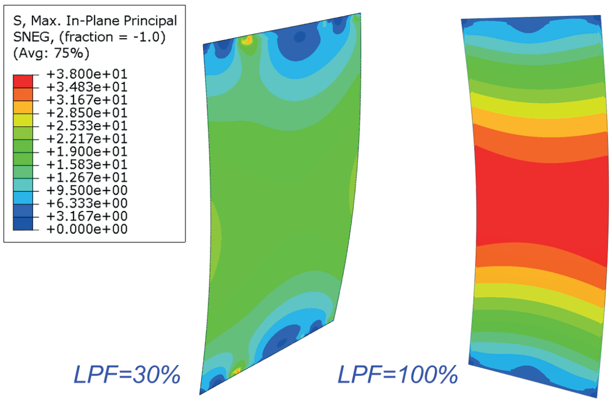

Fig. 12 Stress distribution in glass panels under the wind loads. Panel assembled without elastic spacers on its edges (left), with flexible inserts (right). LPF(Load proportionality factor) - % of loads applied.

Details of the connections, where the elastic inserts are not used, show the uneven growth of stress on the edges of the glass panel. This is because of the usage of point fasteners and high rigidity of glass-aluminium interface. The flexible spacers compensate inaccuracies in assembly, reducing the possibility of local stress notches formation, and distribute reaction forces on the edge of the glazing. The comparison of single overview of stress distribution in a single panel with and without spacers has been shown in Fig 12. Stress concentration zones, stress notches where possible cracking can be initialized, can be seen on left picture (Fig. 12). Compared with smooth stress redistribution (right picture) values can be twice or even three times higher. The result of this numerical analysis also confirms the research made on a high building's facade in Warsaw area (compare Fig. 5).

To understand the stress increase process in a single panel better, time analysis with incremental loading applied has been carried out. Pressure adequate to standard wind loading has been applied. Numerical model takes into account point fasteners for glass and inaccuracies in assembly which leads to bending and shearing deformation mods. This situation can happen if supports do not compensate displacement sufficiently. Directions of principal stresses, that help to understand propagation of glass panel destruction, can be seen in Fig. 13. Vector length of the general stress corresponds to its values.

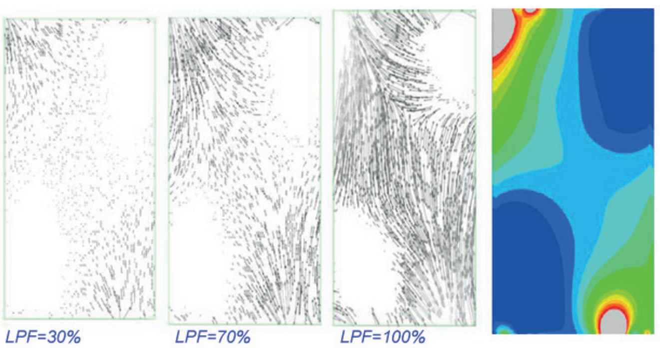

Fig. 13 Stages of single glass panel loading (left to right). Arrow indicates the direction of principal stress.

5 Conclusions

The main purpose of the studies carried out by the authors was to assess the performance of different types of glazing systems according to different type of connection. The paper is particularly focused on the problem how elastic layer provides improvement in working conditions of the glass-aluminium connections. The results of the research carried out confirm that using too stiff glass-aluminium connection for building facades can increase probability of glass failure during service. This is usually the result of removing elastic inserts at the design stage. Similar observations have been made during both field studies and numerical simulations.

Glazing system solutions, currently available on the market, without rubber or polymer spacer elements should be improved. Numerical studies clearly show, that any gaskets support glass panels much better than metal fasteners. If there is not enough space required for the gaskets, elastic structural masses (e.g. silicone) should be applied. Their thickness depends on the type of aluminium framing and glass dimensions and may vary between 0.5 to 3.0mm. The studies have shown that using the flexible spacers increases bearing capacity for 30% by reducing the probability of appearance of local stress concentration.

The study indicates that local faults and events (executive, technological) in the design of facades have great influence. Any changes in the stress distribution caused by badly fixed glass panels are crucial for safety of facade structure. The results meet the conditions contained in the Eurocode 9 standard. Based on the proposed models, the failure mechanism for wider set of geometrical configurations can be analysed in the future.

References

[1] "Abaqus Analysis User's Manual". Ver. 6.12. Dassault Systemes 2012. http://abaqus.software.polimi.it/v6.12/books/usb/default.htm

[2] Arnold, A., Neumann, L., Hochhauser, W. "Stability of glued and embedded glass panes: Dunkerley straight line as a conservative estimate of superimposed buckling coefficients". *IFAC Proceedings volumes*, 45(2), pp. 124–129. 2012. 10.3182/20120215-3-AT-3016.00022

[3] Bedon, C., Amadio, C. "Exploratory Finite-Element investigation and assessment of standardized design buckling criteria for two-side linear adhesively supported glass panels under in-plane shear loads". *Engineering Structures*, 106, pp. 273–287. 2016. 10.1016/j.engstruct.2015.10.033

[4] Bedon, C., Amadio, C. "Shear glass panels with point-fixed mechanical connections: Finite-Element numerical investigation and buckling design recommendations". *Engineering Structures*, 112, pp. 233–244. 2016. 10.1016/j.engstruct.2016.01.024

[5] Cwyl, M. "Rozwój konstrukcji powłokowych fasad metalowo-szklanych". Świat Szkła. 17(1), pp. 21–23. 2012.

[6] Cwyl, M. "Podstawowe wymagania normowe współczesnych ścian metalowo-szklanych". *Inżynieria i Budownictwo*, 69(6), pp. 305–307. 2013.

[7] Huveners, E. M. "Circumferentially adhesive bonded glass panes for bracing steel frames in façades". Technische Universiteit Eindhoven, Eindhoven. 2009.

[8] Horr, A. M., Kertz, R., Just, M. "Numerical Damage Modelling of Aluminium Alloys for Wide Range of Stress Triaxiality." *Materials Science Forum*, 794–796, pp. 646–651. 2014. 10.4028/www.scientific.net/MSF.794-796.646

[9] Memari, A. M., Schwartz, T. A. "Glazing and curtain wall systems to resist earthquakes". In: *Architectural Glass to Resist Seismic and Extreme Climatic Events. A volume in Woodhead Publishing Series in Civil and Structural Engineering.* (Behr, R. A. (Ed.)). *Woodhead Publishing Limited*, pp. 28–63. 2009. https://doi.org/10.1533/9781845696856.28

[10] Overend, M., Jin, Q., Watson, J. "The selection and performance of adhesives for a steel–glass connection". *International Journal of Adhesion and Adhesives*, 31(7), pp. 587–597. 2011. 10.1016/j.ijadhadh.2011.06.001

[11] PN-EN 13830:2005 Ściany osłonowe – Norma wyrobu. 2005.

[12] Richman, R. C., Pressnail, K. D. "A more sustainable curtain wall system: analytical modeling of the solar dynamic buffer zone (SDBZ) curtain wall". *Building and Environment*, 44(1), pp. 1–10. 10.1016/j.buildenv.2008.01.006

[13] Weller, B., Unnewehr, S., Tasche, S., Härth, K. "Glass in building: principles, applications, examples". Walter de Gruyter, 2009.

[14] Vaucorbeil, A., Poole, W. J., Sinclair, C. W., "The Effect of Obstacle Strength Distribution on the Critical Resolved Shear Stress of Engineering Alloys". *Materials Science Forum*, 794–796, pp. 449–454. 2014. 10.4028/www.scientific.net/MSF.794-796.449

[15] Vilamosa, V., Clausen, A. H., Bøervik, T., Skjervold, S. R., Hopperstad, O. S. "Behaviour of Al-Mg-Si alloys at a wide range of temperatures and strain rates". *International Journal of Impact Engineering*, 86, pp. 223–239. 2015. 10.1016/j.ijimpeng.2015.08.008

[16] Zienkiewicz, O. C., Taylor, R. L. "The finite element method: Solid mechanics". Vol. 2. Butterworth-heinemann, 2000.

[17] Żółtowski, W., Zbiciak, A., Król, P. A. "Modelowanie numeryczne pełzania połączeń klejowych w konstrukcjach metalowych". *Problemy Naukowo-Badawcze Budownictwa, Tom II Konstrukcje Budowlane i Inżynierskie*, pp. 555–562. Wydawnictwa Politechniki Białostockiej, Białystok 2007.