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Research paper

Laboratory tests and numerical analysis of aluminum helping hand brackets with polyamide thermal break

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Abstract: The developments in materials science and engineering, especially in the field of composites and polymers, have extended the scope of application of such materials in modern industrial construction. This article presents polyamide/ aluminium helping hand brackets, designed for use in rainscreens (a.k.a. ventilated façades) and metal and glass systems. The main purpose of this study was to assess the load-bearing capacity, safety and durability of these elements through laboratory tests and numerical analyses. The laboratory tests were carried out on a three-dimensional test stand. Boundary conditions and the applied loading represented real conditions on the façade (e.g. a typical wind pressure load acting on the façade was used). Next, the experimental results were used to build a representative numerical model. Finite Element analysis was utilised to obtain a true representation of the actual behaviour of the analysed brackets subjected to various loads, taking into account the aluminium/ polyamide interaction. Constitutive behaviour of both materials, polyamide and aluminium alloy, was represented by a linear elastic model. The proposed modelling methodology was validated through full-scale load tests up to failure. The numerical model can be further used to predict the stress and strain fields in newly designed brackets subjected to any type of loading.

Keywords: polyamide-aluminum brackets, helping hand brackets, thermally-broken brackets, helping hand brackets (a.k.a. L-brackets), numerical analysis of L- brackets, numerical models of L-brackets

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1. Introduction

Helping hand brackets (a.k.a. L-brackets) are structural fixings used to attach the structures of metal and glass or composite curtain walls to the backing wall. These parts withstand all permanent, variable and environmental loads acting on the curtain walling system and allow rectification of wall cladding. Helping hand brackets can be classified based on the materials used in their fabrication, the type of loads they are designed to withstand and their role in the external walling system. The materials from which L-brackets are made include aluminum, structural steel, stainless steel and plastics. Nowadays, in order to meet high requirements, L-brackets are fabricated from several materials used in combination. Based on the resisted loads [1] two types of brackets can be distinguished: support brackets and wind restraints. Support brackets resist both vertical and horizontal loads and are fixed by two anchors. Wind restraint brackets, in turn, resist only horizontal loads, which are transferred through one anchor. Based on the role played in the walling system, helping hand brackets can be divided into the following categories: structural (primary) brackets, geometrical (secondary) brackets and spacing brackets (used to ensure the desired physical parameters).

Helping hand brackets are used in all kinds of façade systems and also for fixing suspended ceilings and various sub-frame systems. They first came into use in the 1980s [2, 3]. Initially, brackets were of one simple design and were made from one material (steel or aluminum) [4]. From the building physics viewpoint such brackets should be considered low-performance construction products. These days researchers pay much more attention to building physics in their studies [5–7]. As a result, new cladding and curtain wall materials and technologies are being developed all the time [8]. This article deals with thermally-broken helping hand brackets, an example of cutting edge products used as cladding and façade supports and wind restraints in many modern buildings.

These innovative products combine the advantages of two different materials: aluminum and plastics. This combination allowed to obtain better building physics parameters, higher strength and increased durability under dynamic actions and fatigue loads. Fire resistance requirements specified for building envelopes can also be satisfied with these products. Specifically, this article presents the results of strength tests and numerical analysis of selected aluminum L-brackets with a polyamide thermal break.

2. Helping hand brackets

Curtain walls are part of the building envelope and consist of a framework, usually built of horizontal and vertical profiles, connected together and anchored to the backing wall of the building, and containing fixed and/or openable infills. While providing all the required functions of an internal or external wall or a part thereof, they do not contribute to the load bearing capacity or stability of the building structure. Curtain walling is designed as a self-supporting construction which transmits dead, imposed, environmental (wind, snow, etc.) and seismic loads to the main structure of the building [9]. The requirements to be met by curtain walls are given in the relevant construction codes. The rapid increase in thermal performance requirements for external walls of buildings resulted in a continuous search for new facade support systems. Fixings which eliminate thermal bridging while safely transmitting the reactions to the backing wall are an example of such new developments. Also growing demands of clients have motivated the development of new products and technologies which meet the fire resistance requirements of the relevant codes, do not transfer electric charges and enhance sound absorption of the curtain walling system as a whole.

Thermally-broken brackets are used mainly in rainscreen (a.k.a. ventilated facade) systems. Rainscreen infill panels are made of various materials, including HPL, concrete, ceramics, metal or glass. The advantage of using polyamide thermal break aluminium brackets is reduction of thermal bridges, otherwise unavoidable due to the method of fixing the cladding panels to the backing wall. Thermal bridges are formed where the brackets, most often made of aluminium (Fig. 1a) or perforated steel sheet (Fig. 1b), i.e. materials of a relatively high thermal conductivity penetrate through the thermal insulation layers.

So far, appropriate design and accurate assembly of the sub-structure were the most popular measures to reduce heat losses through curtain wall. In addition, washers are used to provide a thermal break between the bracket and backing wall and prevent galvanic corrosion. These isolators are made of plastics of a very low conductivity, such as PVC or special plastics. An example of such an assembly is shown in Fig. 1. It is composed of a few layers of sheet metal and epoxy laminate plate, which are held together by rivets. Still, aluminium brackets with a polyamide thermal break are the most efficient solution to reduce thermal bridging in any curtain wall systems. In the assembly described in this article the polyamide layer is fully bonded to the aluminium part. Polyamide has better strength properties and withstands high stress levels in the elastic region. In terms of mechanical properties it is similar to structural aluminium alloys.

2.1. Aluminium brackets with epoxy glass fibre thermal break

The bracket shown in Fig. 1a is composed of aluminium sheet and thermal break made of epoxy glass fibre laminate with thermal conductivity $\lambda = 0.36$ W/(m·K). This idea came up in the beginning of 21st century in response to the first extruded sheet metal brackets developed in the 1980s, an example of which is shown in Fig. 1b. The thermal break is attached to the aluminium parts by means of stainless steel rivets.

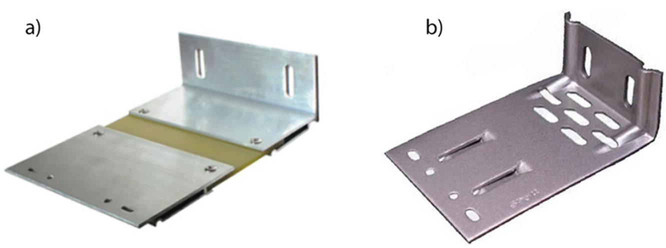

Fig. 1. a) Aluminium L-bracket with thermal break [10], b) stainless steel bracket [11]

2.2. Tables and figures

Thermal stainless steel brackets (Fig. 1b) have been used in construction since 1980s. Made entirely of a single material, i.e. extruded, perforated or punched, improved corrosion resistant steel, these brackets feature simple design and monolithic construction. Perforated and punched steel sheets have been used in this application since 1990s. This type of steel was preferred to aluminium because of a higher strength and lower thermal conductivity. Perforations are made to improve the thermal properties and isolators are fitted to separate the bracket from the surfaces of other materials. Proprietary reinforcing ribs are formed at the joint between horizontal and vertical parts to yet increase the high mechanical strength of the steel bracket.

2.3. Aluminium brackets with epoxy glass fibre thermal break

Aluminium brackets with polyamide thermal break (Fig. 2) came onto the construction market in the beginning of 21st century. This state-of-the-art technology ensures the required bearing capacity and stiffness of helping hand brackets, transmitting loads from the facade support system onto the backing wall of the building. These brackets combine the advantages of aluminium and plastic (glass fibre reinforced polyamide). Very good thermal insulation allowed almost 100% elimination of thermal bridges. Yet another advantage is a high level of stress at small strains in the elastic region. This is owing to the ribs provided in the sheet of plastic and addition of glass fibres. The ribbing pattern was designed with the use of numerical methods, based on appropriate material models and solid elements used in the numerical models of the composite. Two types of brackets of different widths are analysed in this study: narrow ones called BMP (Bracket Medium Passive [12]) and wide ones called BLP (Bracket Large Passive [12]). The above terminology is used by companies implementing products of this kind in the construction market. These brackets are 180–280 mm long and letters B (black) or R (red) respectively designate the type of plastic of the thermal break. Letter R (Red) designates specific performance under fire.

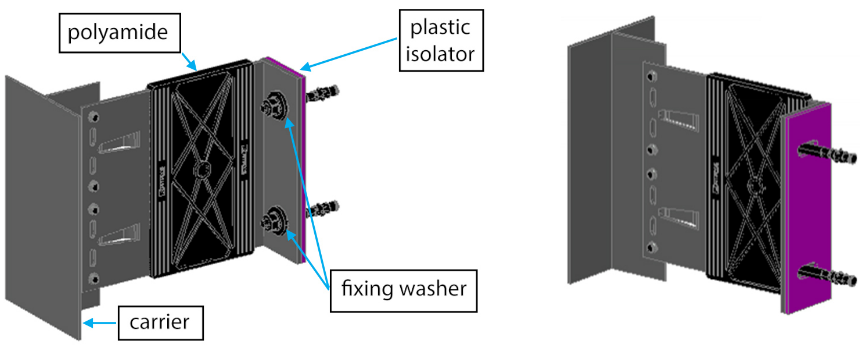

Fig. 2. Aluminium brackets with polyamide thermal break overview

The "red" bracket material is a non-combustible plastic with only a small (by max. 20%) decrease of strength up to ca. 150°C. With this performance it is comparable to structural alloys of aluminium and steel.

3. Numerical model of aluminium brackets with polyamide thermal break

Several approaches can be taken to understand and analyse the problems related to the use of aluminium and polyamide, as described in the previous section. Since in this case analytical solutions are difficult to find or, if found, are limited simple cases the authors opted for numerical experiments that better describe the polyamide/ aluminium interaction. Numerical modelling was used to represent the interaction of two types of aluminium sheet materials inserted directly in the pocket of the polyamide thermal break. The results obtained in these indirect numerical experiments were verified by laboratory tests. On the basis of the conducted tests and numerical calculations, it was found that aluminium/ polyamide connections were fully restrained (see Fig. 3). In addition, the aluminium sheets have a local thickening to additionally secure the connections with polyamide. The results are presented as cross-sections through the polyamide profile and aluminium sheet, which show similarity of stress and strain distribution patterns between these two materials.

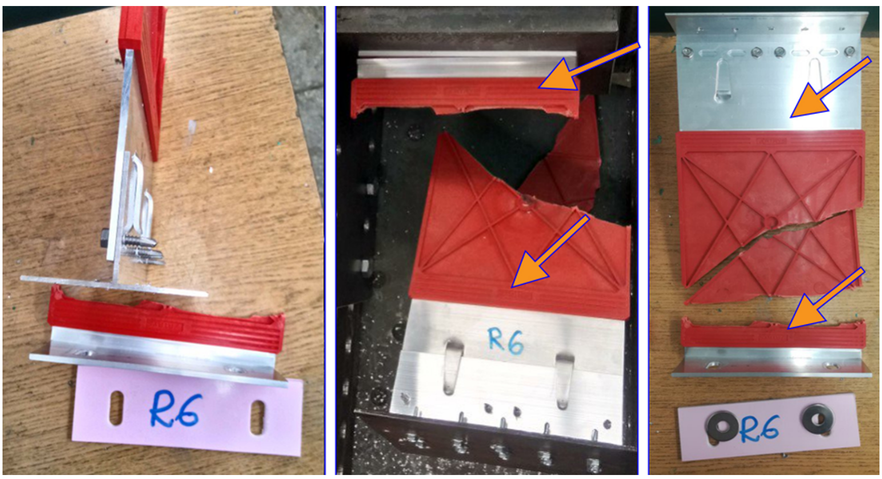

Fig. 3. Full integrity of the polyamide / aluminium joint

ABAQUS FEA software was used to develop the numerical model used in the analysis [13]. It was assumed that the behaviour of all materials is limited to the elastic region. Being a brittle material, polyamide fractures once it has reached the failure strain. In the case under analysis, the level of stress in aluminium is definitely below the ultimate stress of this material and, therefore, no ductile deformation occurs. Thus is seems justified to apply only the theory of elasticity. The properties of the materials applied in the simulation are given in Table 1.

Table 1. Properties of materials applied in the simulation

Material	Density [kg/m^3]	Young's modulus [MPa]	Shear modulus [MPa]	Poison's ratio [–]
Aluminium EN AW-6060	2750	70 000	26 300	0.33
Polyamide 66 GF 50	1350	30 000	12 500	0.18

The mechanical properties of the analysed materials were taken in accordance with the data sheet of Polyamide 66 GF30 in controlled conditions included in the documentation and for aluminium EN AW 6060 / T6 in accordance with EN 755-2: 2016, Table 2. Polyamide PA66 GF50 (Black), A3 GF50 (Red).

Table 2. Mechanical properties of the analysed materials

Polyamide 66 (PA 66 GF50)		
1.	Breaking stress	185 MPa
2.	Elongation at break	3%
3.	Modulus of elasticity in tension	30 000 MPa
Aluminium EN AW 6060/T6		
1.	Elongation at break	8%
2.	Relative elongation A50	6%
3.	Tensile strength Rm	190 MPa
4.	Yield strength Rp0.2	150 MPa

The numerical model of both materials contained about 2,000 finite elements and 6,400 nodes. Quadratic shape functions (second degree polynomial) were used as an approximation of displacement field, so eight-node finite elements with reduced integration were chosen [13]. The description of this type of element, referred to as CPE8R, can be found in the ABAQUS software documentation. While quadratic elements make the task more computationally expensive per one solution, it is more likely to achieve the desired overall accuracy. Because of the expected significant variations of stress fields in both metal and polyamide parts, it was decided to examine the growth of stress inside the cross-section with the use of higher-order approximation.

Boundary conditions were applied by restraining vertical and horizontal displacements of the nodes located at the lower and upper edges of the model (part of the metal profile). The polyamide plate and aluminium profile were connected by sharing the same nodes, this meaning equal displacements at the interface of the two materials. Also friction between the concrete backing wall and the bracket was taken into account (static friction coefficient $\mu = 0.65$). The load value was as typically applied for curtain wall connections of this kind. Standard wind load, normal to the surface, was applied. Wind pressure was taken on the basis Eurocode 1 and the assumed values are given in Table 3. The tests were performed on three types of helping hand brackets: BMP220, BMP240 and BLP280. BMP-X stands for Artrys bracket type (Bracket Medium Passive [12]) and X indicates element length in the direction perpendicular to the wall. In the case of BMP220 and BMP240 brackets gradually increasing horizontal tensile force, horizontal compressive force and vertical shear force distributed evenly over the surface of a tee connected by two bolts to the brackets were applied in each test. In the case of BLP280 bracket, the tensile and compressive loads were the same as for the other brackets and to investigate the effect of eccentricity on the load capacity of the element shear point load was applied to the tee piece.

Table 3. Determination of wind pressure

No.	Parameter	Value	Basis
1.	Wind zone	1	Typical for 100 m a.s.l.
2.	Category	IV	Downtown location
3.	Installation height	20 m	For a residential building in Warsaw area
4.	Base wind velocity	22 [m/s]	Building located below 300 m a.s.l.
5.	Influence of land surface	c_0 (10 m) = 1	Neglected due to mean inclination < 3°
6.	Characteristic wind pressure	$q = 0.881$ kPa	–
7.	Design wind pressure	$q = 1.320$ kPa	Including safety factors

4. Laboratory test

4.1. Test stand and scope of research

A special, multi-directional strength tester shown in Fig. 4 was used in the laboratory tests of the analysed brackets. The test stand is designed for multi-directional strength testing. The tested elements may be loaded by eight independent actuators, each acting at any pre-set angle. Each actuator is capable of producing a force of up to ca. 350 kN. Displacements may be controlled at the same time. Up to 360 mm displacement can be caused by each actuator. In this configuration, the value of force at threshold displacements is read for the pre-determined displacement. Both static and up to 15 Hz dynamic tests can be carried out on the machine. Each actuator may vibrate with a different frequency. The test stand may be used for long-term tests with alternate long-term loading of elements. These tests are used for analysing fatigue phenomena of materials.

Load was applied in three planes. The purpose was to represent the actual loading conditions of real brackets installed on the building wall. Static test was chosen for the

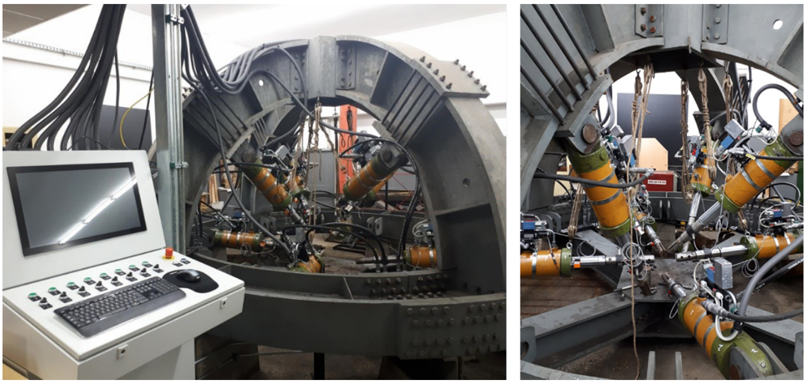

Fig. 4. Test stand for multi-directional strength testing

purposes of this study. A force acting in the plane of the curtain wall was applied to each bracket by the respective actuators. This force represents the dead load of the curtain wall acting on a single bracket. Installation density of one bracket per 1 m^2 of the curtain wall surface was assumed. The weights of the system components were calculated, including 44.2-16-6ESG glass infill panels (ESG – hardened, 44.2-safety glass, 16-width of the spacer, 6 glass thickness [mm]), support frame (stick system) and insulation layers (metal and mineral wool sandwich panels in opaque fields). This actuator generated a load acting along the bracket. Simultaneously, a second actuator was applied to the tested surface, generating a load representing pressure tangential to the wall surface. For a curtain wall this value is small (3–5% of the wind pressure perpendicular to the wall surface). However, it should not be neglected due to the small stiffness of brackets in this direction. This load was based on the maximum standard value for the wind speed zone of Warsaw, Poland. The third actuator generated a force acting along the main axis of brackets, thus representing the positive or negative wind load. The value determined in this case was the maximum wind load acting on the surface area of the curtain wall supported by one bracket (i.e. 1 m^2). The dead load and the load tangential to the wind direction were taken as a constant maximum value for the specific curtain wall. The negative/ positive wind pressure was taken as a time-dependent value, ranging from 0 to the value given in the standard. The displacement of the actuator representing wind load acting on the perpendicular plane was controlled in the test. With the assumed displacement rates, the obtained values of force representing the negative/ positive wind pressure were recorded. This procedures allowed determination of displacement at which the bracket was loaded with a force corresponding to the load imposed by wind, as given in the standard. The displacements were increased successively during the test. The subsequent phases gave the failure forces and displacements for the bracket concerned. The failure modes of different brackets were compared. As the next step, the forces obtained at known displacements were compared with the numerical model with equal strain rates. Next failure modes obtained in the tests were compared with the failure patterns obtained by numerical modelling. Having consistent failure modes, it is possible to accurately locate the stress concentration areas, both in the plastic panels and in the aluminium elements of the curtain wall system. By comparing the numerical and laboratory data it is possible to confirm the appropriateness of standard procedures used for determining the bearing capacity of these structural components.

Actuator 1 on Fig. 5a applied displacements at a rate of 1 mm/s. As the displacements increased, the control software recorded the applied forces. The role of actuator 2 was to impose and maintain a force corresponding to the standard wind load. This load, acting tangential to the curtain wall, was determined in accordance with Eurocode [14]. The load generated by actuator 3 represented the curtain walling dead load per support bracket. It is a constant force transmitted by the bracket onto the backing wall.

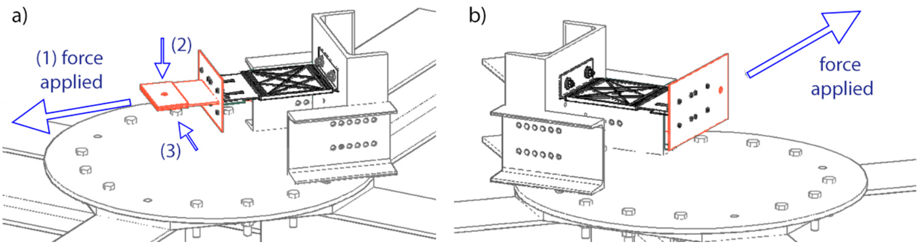

Fig. 5. Bracket mounting and loading setup on multi-directional strength test stand

4.2. Results of laboratory tests and numerical analyses

The results presented in this article were obtained by application of tensile and compressive forces representing the action of wind on the curtain wall surface and on the polyamide/aluminium helping hand brackets. This direction of load application caused axial tension and compression of brackets. In addition, the brackets are loaded by the dead weight of the curtain walling system, causing in-plane bending. These elements were subjected to bending also in the other plane, to represent the action of wind in the tangential direction. The ultimate purpose of this study was to determine resistance of the tested brackets to: axial tension/ compression (under static load), in-plane loading and out-of-plane loading (also under static load). Thus each bracket type was subjected to the action of vertical and horizontal forces, as per the guideline of ETAG 034 [15].

Comparative analysis of the laboratory test data and numerical results was also part of this research. The purpose of this comparison was check if the numerical model of an element composed of a few different materials, taking into account the complex analysis of the contact surface between the parts of the bracket and attachment to the backing provides a true representation of the actual situation, established on the basis of the laboratory test data. A very important element of this research was to describe the stress concentration areas and verify the consistency between failure modes obtained in the laboratory and theoretical numerical models. The approach presented in this article allowed to conduct analyses related to fatigue, impact and dynamic loads in the subsequent part of the project. This article is limited to static tests and thus the above-mentioned analyses will be described in the second article.

The conclusions are based on testing three series of specimens brackets: BMP220, BMP240 and BLP280. Five tests were done on each test series and the data were used to determine the average and minimum bearing capacities of connections F_c.

Force F_c is a characteristic value giving 75% confidence that it will be exceeded by 95% of all the test data. Its value is defined in European Assessment Document 0900034-00-0404 (June 2016): Kit composed by subframe and fixings for fastening cladding and external wall elements, Attachment D [16]., given by the following equation:

$$F_c = F_m - k_n \cdot S \tag{4.1}$$

where: k_n – distribution factor (for five specimens it is taken at 2.33), S – standard deviation, F_m – average force.

One of the test series is presented in Table 4 and the results are shown in Fig. 6. Simultaneously, numerical analyses were carried out for the presented laboratory data to determine the stress levels at selected, characteristic points on the brackets. The behaviour of the bracket for the obtained maximum tensile strength is depicted in Fig. 7 (negative wind pressure acting on the curtain wall).

Table 4. Results of loading of BMP 240 bracket with a horizontal tensile force

Specimen	Force [kN] required to cause displacement by										Max. load [kN]	Displacement at max. load [mm]
	0.5 [mm]	1 [mm]	1.5 [mm]	2 [mm]	3 [mm]	4 [mm]	5 [mm]	6 [mm]	7 [mm]	10 [mm]		
R1	0.9	1.3	1.8	2	2.5	3	3.4	3.7	4	4.5	9.6	32.6
R2	1.1	1.6	2.2	2.6	3.4	4.1	4.6	5	5.3	6.1	9.3	25.9
R3	0.8	1.3	1.7	2	2.6	3.1	3.5	3.9	4.2	5	9.9	32.7
R4	0.8	1.2	1.5	1.7	2.5	3	3.5	3.9	4.1	4.8	9	31
R5	0.6	1.2	2	2.7	3.4	4	4.6	5	5.3	6.1	8.8	22.1
F_m	0.84	1.32	1.84	2.20	2.88	3.44	3.92	4.30	4.58	5.30	9.32	–
S	0.18	0.16	0.27	0.43	0.48	0.56	0.62	0.64	0.66	0.75	0.44	–
F_c	0.42	0.95	1.21	1.20	1.76	2.14	2.48	2.81	3.04	3.55	8.29	–

The theoretical model of the bracket loaded in compression (representing positive wind pressure acting on the wall) is shown in Fig. 8 for comparison. The numerical models were based on the conducted laboratory tests. The specimens in which the greatest strains occurred also within the slotted holes were presented to allow comparison of the theoretical tensile deformation modes.

It is worth to compare Fig. 7 and Fig. 9 as it show the same parts of the bracket in which deformations occurred. Stress map (Fig. 7) helps to identify the places of the greatest deformations and failures at these points defines the load capacity of the bracket as a whole. The presented failure modes correspond to the recorded displacements of 12–15 mm. The force recorded at these strains exceeds 200% of the load capacity of the joint for the

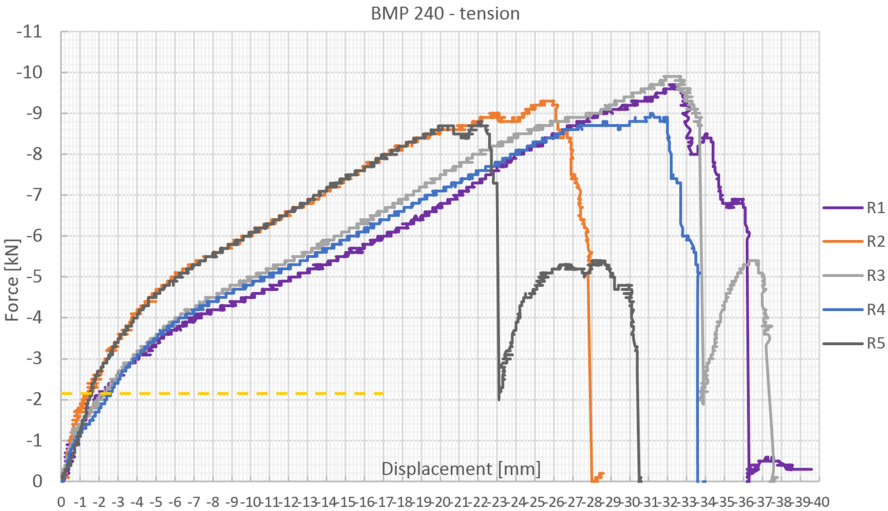

Fig. 6. Graphical representation of the results of testing the BMP 240 bracket under tensile force

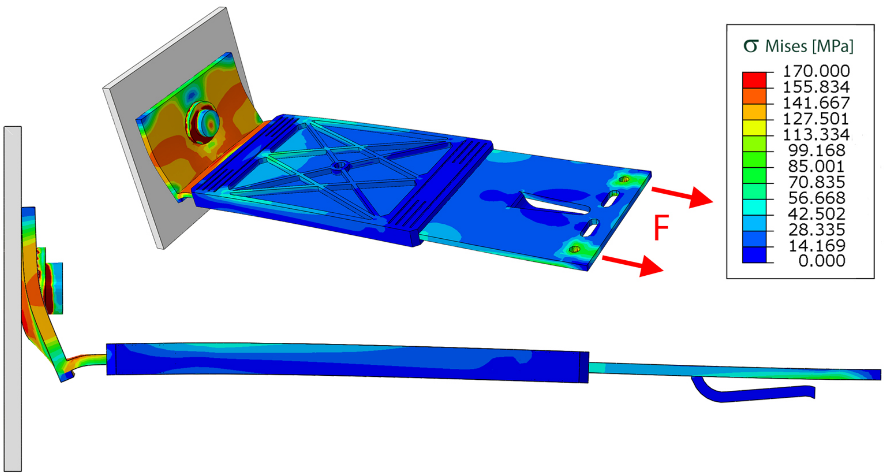

Fig. 7. The deformation mode and stress distribution pattern during the tension test

determined, standard wind load value. This value is represented by the yellow dashed line in Fig. 6 above.

Failure mechanisms were also analysed, as a separate part of the study. The examples are shown in Fig. 10 and Fig 12. It was established that all failure modes occurred after the load conditions caused exceeding the standard load capacity prescribed for the tested brackets by 400–500%. This value was determined on the basis of the relevant structural design standards and the support layout diagram (totalled actions from 1m2 of the wall surface) and is represented by the yellow dashed line in Fig. 6.

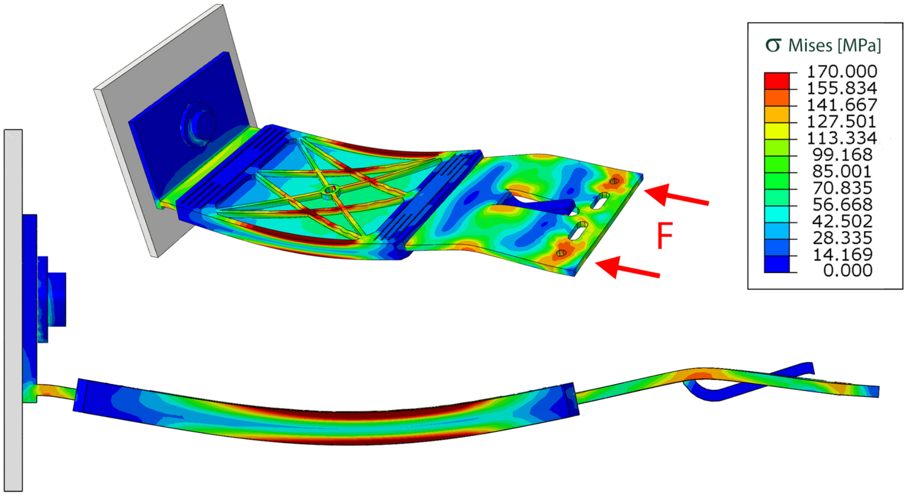

Fig. 8. Deformation mode and stress distribution pattern during the compression test

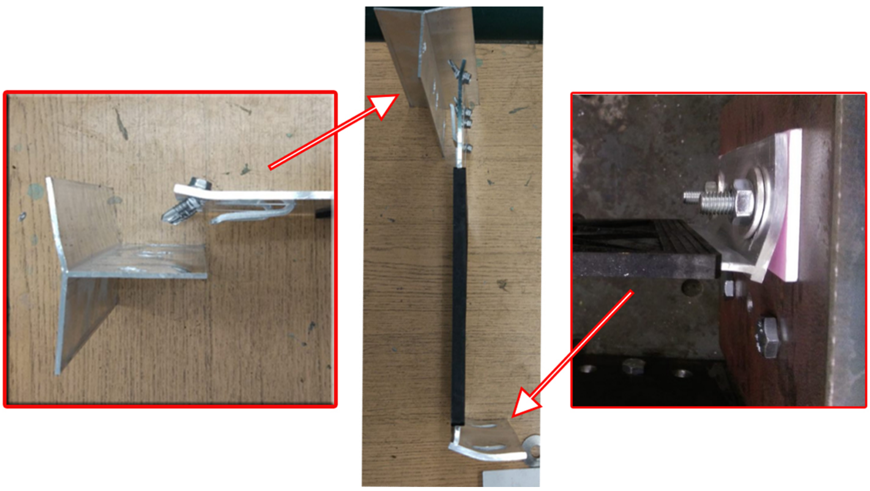

Fig. 9. Tested element during tension test

Two main bracket failure modes were described, based on the numerical analysis and the laboratory test data. In the first loading case prying effect takes place at fixings between the brackets and the backing wall, as shown in Fig. 7, Fig. 9 and Fig. 10. In this loading case, the places of stress concentration are the slotted holes for anchoring the brackets. Aluminium is a material that undergoes large strains. The final phase of the failure process is the characteristic standard condition of the screw head pulling through the metal plate or breaking of cross-section weakened at the fixing hole. These failures are depicted in Fig. 10 and represented by the model shown in Fig. 11 below.

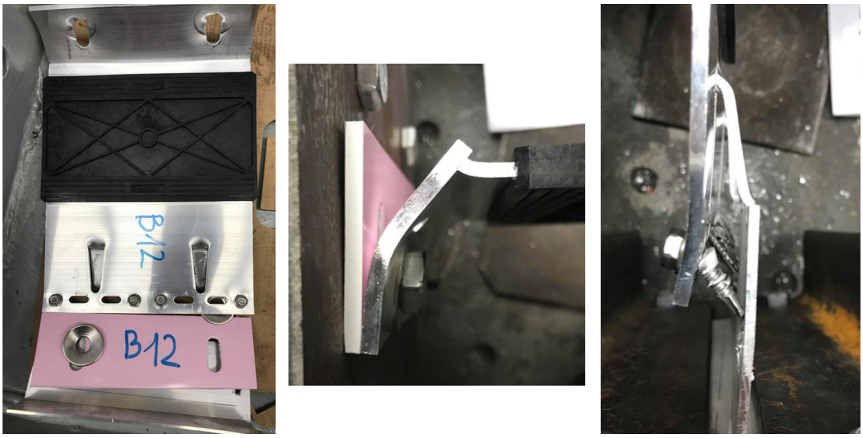

Fig. 10. Failure modes of helping hand brackets

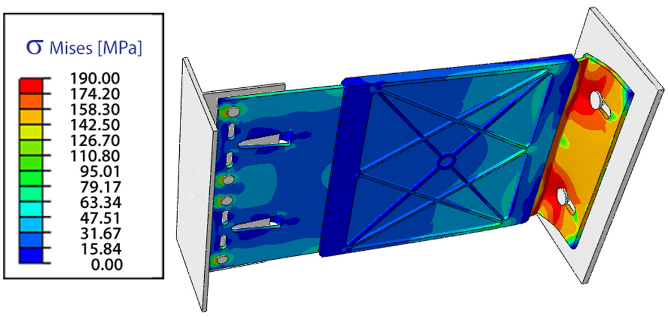

Fig. 11. Stress concentration points at the fixing holes, prying effect

Prying effect was followed by extension of the T-shape aluminium part of the bracket. For academic purposes, the specimen shown in Fig. 12 was tensioned to failure in order to depict the modes of failure at the holes. In first of the two failure modes the screw head passed through the fixing hole. In the standard it is referred to as the screw-head pull-through resistance criterion. Owing to the enlarged washers used in the tested elements this situation occurred very rarely. The other, more common failure mode at the fixing holes was by tearing away of the element at the weakened point. This failure mode is called block tearing. The process is very interesting itself, because once very large plastic deformations have taken place on the whole flange, brittle fracture, observed in Fig. 12, occurs over the circumference of the washer placed under the fixing hole.

The second important failure mechanism was by pulling out the screws which secure the curtain wall support structure to the analysed support brackets. The observed failure mechanism is shown in Fig. 13 below.

The curtain wall backup structure was secured to the tested brackets with two 4.5 mm screw fasteners. In the tests continued up to failure about 40% of final tearing cases occurred

Fig. 12. Final failure – bracket pulled apart at the weakened point of aluminium foot

Fig. 13. Failure of brackets by pulling out the screws securing the curtain wall backup structure

by failure of the screw fasteners. This failure mechanism was particularly dangerous. The yield point of the material was exceeded locally at the holes in the thin aluminium sheets. The holes have become conspicuously oval and next the screw fasteners were pulled through. This failure mechanism demonstrates that because of thin aluminium sheets and small screw diameters 3–4 fasteners should be used to make the bracket resistant to this particular type of failure. Failure of the bracket due to exceeded load capacity of the screwed joint gains in importance when the specimens are subjected to long-term loading (to test fatigue resistance) or to dynamic loads. These results will be presented in a subsequent paper. The amount of eccentricity at these screw fasteners exceeds the combined thickness of the joined sheets. The stress concentration points within the fixing holes are shown in Fig. 14 below.

Also worth noting is confirmation of the strength of joint between the aluminium plates and polyamide composite. The contact and interaction problems at the joint between these

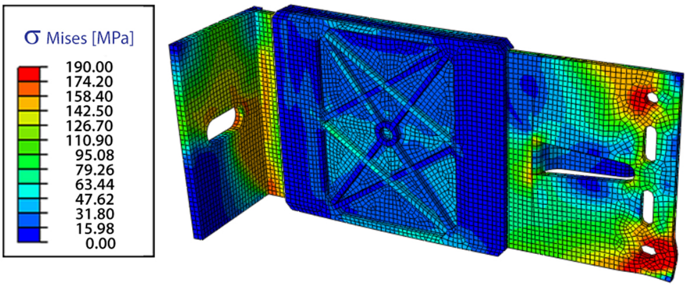

Fig. 14. Hanger failure model. Stress concentration points at the backup frame stud fixing holes

two materials make it a particularly difficult task to develop a model providing a true representation of such joints. A series of tests were performed to model a fully rigid joint on specimens with additionally stiffened fixing to the base and strengthened stud to hanger connections. In this way, failure could take place only within the aluminium or polyamide parts of the bracket or at their interface. The failed specimens are shown in Fig. 15.

Fig. 15. Testing the plastic/ aluminium joint strength

With additionally stiffened fixing of hangers, fracture occurred within the polyamide composite plate in all the tested specimens. This means that the integrity of the polyamide/ aluminium joint was maintained. In this way the possibility of finite-element modelling of the rigid joint under study was confirmed. This additional testing increased the confidence of the performed numerical analyses and confirmed the trueness of the mathematical modelling assumptions, which are subsequently used for analysing the load capacity, determination of the stress concentration locations and description of the failure models of the tested joints.

5. Conclusions

This article evaluates the mechanical performance of polyamide/ aluminium helping hand brackets, a structural fixings used to attach the structures of metal and glass or composite curtain walls to the backing wall. The evaluation included both laboratory tests and numerical analyses using Finite Element (FE) models. Refined FE models were developed for the purposes of this research, to obtain a true representation of the actual behaviour of the helping hand brackets subjected to various loads. The research and FE simulations discussed in this paper allow us to draw the following conclusions:

– The tests and numerical analyses performed as part of this study confirmed adequate interaction between aluminium sheets and polyamide (composite) plates combined in one structural component designed for securing the curtain wall structures.
– The load values prescribed by the relevant standard were achieved, causing small strains of the tested aluminium/ polyamide helping hand brackets. Residual capacity reached over 100%.
– The numerical models used in the study gave a higher value of transmitted force at a given, recorded strain. This was due to taking out the play in laboratory tested hangers. The numerical model ignores this phenomenon resulting from "settling" of screws in the fixing hole or taking out of play in the screwed lap joint between the bracket and the backup frame stud.
– The experiments revealed repeatability of failure patterns within a given type of bracket. Two failure mechanisms prevailed: failure of connection between hanger and backing caused by prying and failure of lap joint between the hanger and backup frame stud.
– All the tests followed the same pattern. The process started with yielding at slotted hole, followed by increased prying effect and failure within this part or, alternatively, after initial prying, the process of failure continued within the lap joint. Knowing the failure mechanism it can be easily counteracted by adding screw fasteners between the backup frame post and metal plate of hanger or, in the case of failure caused by prying, by increasing the thickness of aluminium flange.
– The tested polyamide/ aluminium composite hangers are an option of choice for curtain wall applications. Besides the high, experimentally demonstrated load capacity, they do not form local thermal bridges in the curtain wall system. In addition, these brackets do not transmit high-pitched sounds, thus improving the sound absorption of the curtain walling system as a whole. Moreover, they do not conduct electricity.
– The joint between polyamide and aluminium was found to be fully bonded.
– The experimental tests and comparative numerical analyses have confirmed validity of correlation between experimental and numerical results. Combination of numerical analyses and experimental tests ensures accurate determination of the standard load capacity of the tested elements. The numerical analyses allow accurate determination of stress concentration points and provide representation of failure mechanisms. When validated by experimental results, numerical analyses ensure accuracy of load capacity determination before implementation of the analysed elements before implementation in mass production.

– Curtain wall systems must be tested to ensure their structural safety. Therefore, it is recommended to implement long-term monitoring systems with automatic detection of any irregular behaviour of the structure.
– The obtained experimental results are repeatable as regards the load capacity and type of failure of the analysed elements.
– Additional studies are needed to investigate fatigue resistance under long-term loading and resistance to impact (dynamic) loads. These studies should confirm the durability of joints under long-term exposure to wind loading which due to the Benard-von Karman vortex street effect has the characteristics of dynamic actions on curtain walls of buildings.

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Badania laboratoryjne i analizy numeryczne konsoli poliamido-aluminiowych w konstrukcjach fasadowych

Słowa kluczowe: konsole poliamidowo-aluminiowe, konsole elewacyjne, konsole pasywne, wsporniki w elewacjach, analiza numeryczna konsol, modele numeryczne konsol

Streszczenie:

W artykule przedstawiono badania elementów konstrukcyjnych mocujących struktury elewacji metalowo-szklanych i kompozytowych do ustroju nośnego budynku. Elementy te przenoszą całość obciążeń stałych, zmiennych i klimatycznych, które są generowane na strukturach elewacyjnych oraz umożliwiają rektyfikację okładzin ściennych obiektów budowlanych. Rozwój nauki w dziedzinie inżynierii materiałowej, kompozytów, poliamidów i silikonów konstrukcyjnych daje wiele możliwości wykorzystania tych materiałów w nowoczesnym budownictwie przemysłowym. Wsporniki konstrukcyjne poliamidowo-aluminiowe znajdują zastosowanie w nowoczesnych elewacjach wentylowanych oraz metalowo-szklanych konstrukcjach powłokowych. W artykule skupiono się na badaniach laboratoryjnych konsol poliamidowo-aluminiowych oraz przeprowadzono analizy numeryczne w celu potwierdzenia nośności, bezpieczeństwa i trwałości tych elementów w budynku. Modele numeryczne konsol pozwoliły na uzupełnienie badań laboratoryjnych, prezentację wyników oraz wyjaśnienie zjawisk zachodzących w trakcie. Doświadczenia laboratoryjne przeprowadzono na trójwymiarowym stanowisku do badań elementów węzłowych. Przedstawione w artykule badania zawierają wyniki od działania siły rozciągającej i ściskającej oraz od działania wiatru na płaszczyznę elewacji i na wsporniki poliamidowo – aluminiowe. Zgodnie z kierunkiem tego obciążenia wsporniki są rozciągane i ściskanie osiowo. Jednocześnie wsporniki są obciążone ciężarem własnym konstrukcji elewacji, więc wieszaki są zginane w swej płaszczyźnie. Celem badań było określenie nośności w trzech kierunkach oddziaływań na konsole: osiowej wytrzymałości na rozciąganie/ściskanie (pod obciążeniem statycznym), wytrzymałości na zginanie w płaszczyźnie i z płaszczyzny konsoli (również pod obciążeniem statycznym). Celem badania była również analiza porównawcza otrzymywanych wyników z badań laboratoryjnych i analiz numerycznych. Tego rodzaju badania służą sprawdzeniu czy model numeryczny elementu składającego się z kilku materiałów, uwzględniający skomplikowaną analizę powierzchni kontaktu (zespolenia) i połączenia z podłożem jest zgodny ze stanem faktycznym, otrzymanymi wynikami laboratoryjnymi oraz otrzymanymi mechanizmami zniszczenia. Bardzo ważnym elementem badan był opis miejsc koncentracji naprężeń, zgodność form zniszczenia w rzeczywistym modelu laboratoryjnym i teoretycznym modelu numerycznym. Zaprezentowane w artykule podejście do badań pozwala także na przeprowadzenie analizy zmęczeniowej, analizy obciążeń udarowych i dynamicznych. Zostaną one opisane w drugiej publikacji, uzupełniającej przeprowadzone próby statyczne. Model numeryczny uwzględnia współpracę materiału z poliamidem i aluminium. Analizowano fazę sprężystą poliamidu i stopu aluminium. Na podstawie przeprowadzonych badań i obliczeń numerycznych stwierdzono, że zastosowane połączenia (grzebieniowe) pomiędzy tymi materiałami dają pełną sztywność scalenia tych materiałów na powierzchni kontaktu. Wyniki przedstawiono w postaci przekrojów kształtownika poliamidowego i płyty aluminiowej, co obrazuje podobieństwo rozkładu naprężeń i odkształceń w obu materiałach. Porównano wyniki odkształceń w modelu numerycznym oraz z badań laboratoryjnych. Wyniki uzyskane z modeli MES pozwoliły na wyznaczenie rzeczywistego poziomu naprężeń w badanych elementach konstrukcyjnych. Przeprowadzone testy i obliczenia numeryczne obrazują formy zniszczenia konsoli oraz pozwalają na detekcję punktów koncentracji naprężeń. Artykuł potwierdza potrzebę prowadzenia jednocześnie badań laboratoryjnych i obliczeń numerycznych przy ocenie takich rozwiązań w konstrukcjach elewacyjnych.

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