POLYMER ADHESIVES WITH ENHANCED PROPERTIES SUITABLE FOR ASSEMBLING OF STRUCTURAL GLASS

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ABSTRACT

Polymer adhesives designed for structural use is becoming more favourable and feasible for steel-glass load bearing connections since their properties were improved according to requirements of engineering point of view. Assembling of glass elements, or bonding of glass to steel members brings significant advantage in many factors like uniformly distributed stress contraction, low self-weight, absence of holes in glass etc. Every adhesive, given to be used in a joint with real load bearing role, has to be carefully tested and investigated before its practical use. Main interest of civil engineers is focused on strength and stiffness, particularly on possible elongation of tested polymer. Reputable adhesive producers are familiar with these required properties and their own research and development do the best to produce adhesives, with enhanced properties. In the past, material tests of many types of adhesives were performed at CTU Prague as well as instant shear connection tests. There is a new generation of acrylic adhesive on the market, which shows significantly better properties in comparison with previous types. The paper deals with the explanation of polymer adhesive behaviour, describes structural action of bonded joint between steel and glass, which shows real load bearing role between connected members.

1 INTRODUCTION

Civil engineers are forced to join still thinner and various structural members and bonding is becoming very important technology, which doesn't stay focused only for industry anymore. Adhesive connection minimizes visual impact of the joint and therefore the technology of bonding is growing up and going to be more common, especially nowadays, when requests for the design of modern transparent structures are still moving higher. Using structural adhesives, we are able to connect more materials together reaching their optimal structural interaction. Glue in addition to its ability to bond parts together with significantly uniform stress distribution can also act as crucial elastic element of the system, where stress peaks, impacts or vibrations are consumed. In general, by specific bonding technology we are able to assemble, seal, reinforce the structure or dampen the noise and vibrations. As there are thousands of polymer adhesives available on the market, their strict division is always very complex and can be sorted by several parameters. Choice of appropriate adhesive is the first step on the way to perform successful bonded connection. Most of the structural adhesives with real load bearing role are subjected to shear, therefore the most important characteristics are shear strength and shear stiffness of the connection, which depend on material properties of adhesive as well as on geometry of the joint - area and thickness [1]. But there are many more different properties of adhesives needed to be evaluated for each specific load bearing joint. Set of adhesives in terms of stiffness and strength starts with a very stiff epoxy resin, goes down via acrylics and polyurethanes to very flexible silicone, which is better to be used as filler than as a load bearing material (or shear contractor).

2 INVESTIGATION OF BONDED JOINTS

Load bearing adhesively bonded joints are mainly subjected to shear in most of the applications. Bonded joint has to be able to provide a structural interaction between connected elements – transfer the load by its stiffness and strength, but on the other hand, many times it has to be flexible enough to compensate different temperature elongation of connected materials or to redistribute stress peaks from the end of the joint inwards. Load carrying capacity of the area glued joint as well as its stiffness characteristics can’t be derived directly from experimentally assessed value of the material strength and stress-strain diagram from basic material tests, because of another state of stress under different way of load acting on volume adhesive layer by shear. Instant shear connection tests were carried out to obtain real behaviour of the joint. See simple set-up of these experiments in Figure 1.

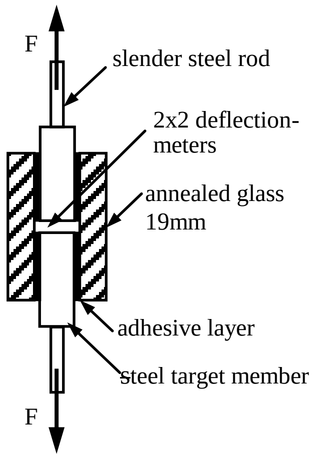

Figure 1. Set-up of the shear steel-glass connection tests

These experiments were performed to investigate the exact behaviour of adhesively bonded joint with specific thickness between steel and glass subjected to shear to find out its realistic shear load carrying capacity and also to calibrate volume finite-element numerical models of the glued joints with adhesive layer including the non-linear material properties of polymer adhesive.

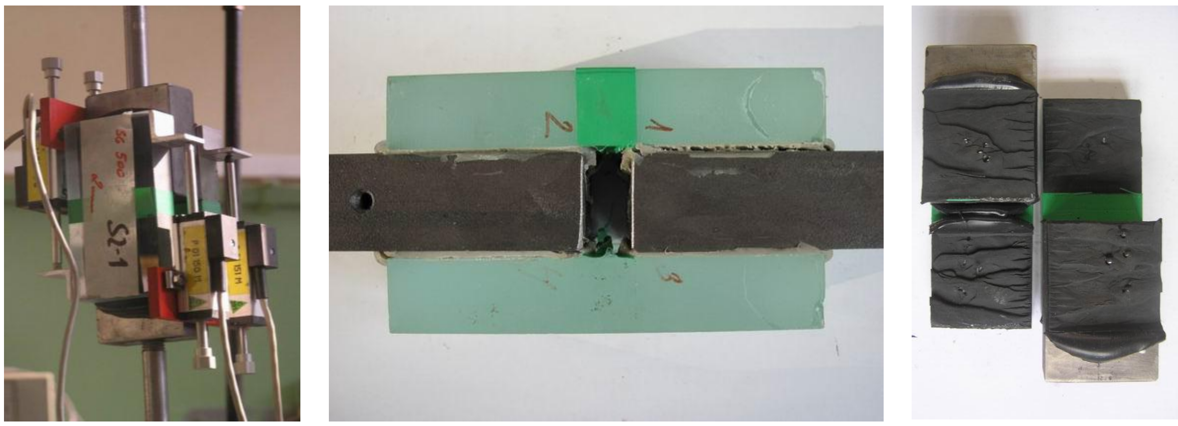

Figure 2. Shear steel-glass connection tests, on the left - measuring device, centre - cohesive failure of acrylic, on the right - cohesive failure of polyurethane

More than 50 specimens with different adhesives and thickness of the layer were prepared and tested. All applications of adhesives were made professionally by the bonding expert in the laboratory of SIKA CZ to ensure cohesive failure within the adhesive layer as a determinant of carrying capacity of the joint, see Figure 2 on the right. Generalized and summarized results of the shear connection tests are in the Fig. 3, where the representative curves of the shear stress-strain diagrams (where strain means longitudinal movement divided by thickness of the joint) of the joints are drawn for each of the tested adhesives and its specific thickness (except stiff epoxy resin).

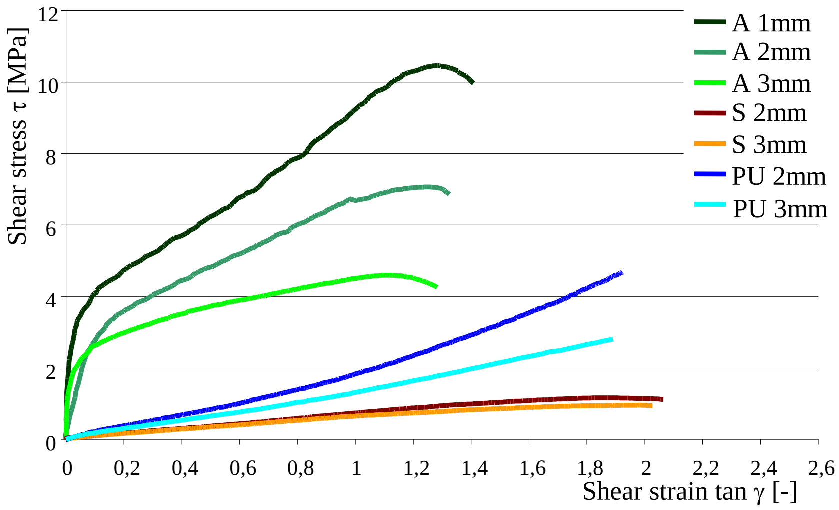

Figure 3. Shear stress – strain diagrams of different adhesives in connection (S- silicone, A- acrylic, PU- Polyurethane booster system)

According to achieved results, each adhesive shows different behaviour under increasing load regarding to the thickness of the joint. By increasing thickness of the joint over the ideal value, possible elongation (or slope) of the adhesive layer increases too, but the connection loses its load carrying capacity, which was proved experimentally for common types of adhesives by steel-glass connection tests. See Figure 3, where representative curves of the shear stress - strain diagrams are drawn for each of the tested adhesives (except stiff epoxy resin) and influence of the thickness of the joint is significant especially for acrylic and polyurethane. One of the main tasks of the connection design is to find the state of the adhesive thickness, where the glued joint can fulfil the requirements on load carrying capacity and stiffness, but still provides a necessary elongation (or shear slope). This kind of experiment can also bring many input parameters for basic hand calculation of the adhesive layer, where structural response of the adhesive is based on shear modulus of adhesive, [2].

3 ADHESIVES WITH ENHANCED PROPERTIES

3.1 New technology of acrylics

Representative sample of the new generation of acrylic adhesive SikaFast 5211 NT (new technology) shows the progress of the producer Sika in the field of research and improvement, which reflects the interest of civil engineers in high strength and semi-rigid stiffness, particularly also in possible elongation of polymers for structural use with glass. Main problems for modeling of the older version were the changeability of the stiffness during the range of load and relatively low elongation at break. New technology shows more or less bi-lingual stress-strain diagram with stiffer initial part (close to elastic behaviour), achieves higher strength as well as higher possible elongation at break. These characteristics bring save and economic design of adhesively bonded connection closer to civil engineers without advanced knowledge of finite element software.

3.2 Experiments – material tests

Testing procedure was chosen according to EN ISO 527 [3], [4]. Mechanically worked dumb-bell specimens were prepared according to this standard as a type 1B, see Figures 4, 5 and Table 1.

Three different velocities of applied load were tested to obtain the real behaviour of adhesive according to different load types - 5 test specimens were loaded by controlled deformation of 1 mm/min, 3 specimens by 2 mm/min and next 3 specimens faster by 8mm/min.

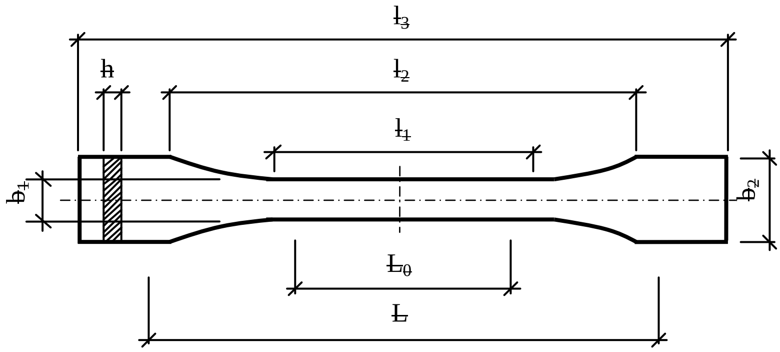

Figure 4. Test specimen according to EN ISO 527 – type 1B

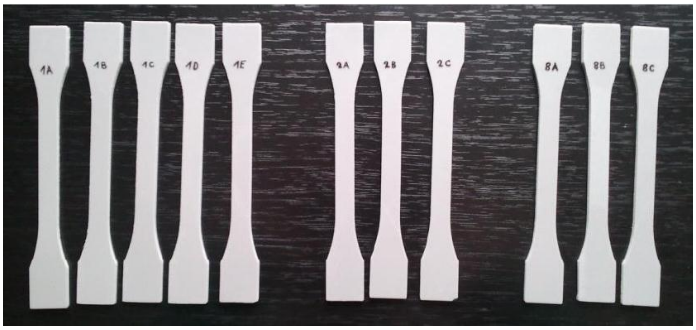

Figure 5. Test specimens according to EN ISO 527 – type 1B, ready for testing

Table 1. Dimensions of the specimens - type 1B

	Test specimen – type 1B	**Dimension [mm]**
l_3	Total length	≥ 150
l_1	Length of the narrowed parallel part	60 ± 0,5
r	Radius	≥ 60
l_2	Distance between the wide parallel parts	106 - 120
b_2	Width of the end	20,0 ± 0,2
b_1	Width of the narrowed parallel part	10,0 ± 0,2
h	Recommended thickness	4,0 ± 0,2
L_0	Initial measured length	50,0 ± 0,5
L	Initial distance of the clamping jaw	$l_2{}^{+50}$

Results of described experimental set can be found in Table 2, where statistically evaluated values are presented for chosen material properties.

Table 2. Experimental results - type 1B

SikaFast 5211 NT		**loading speed**		
	unit	**1 mm/min**	**2 mm/min**	**8 mm/min**
ultimate stress (5% quantile)	[MPa]	7,22	8,83	10,38
strain	[-]	2,19	2,36	2,30
yield stress (5% quantile)	[MPa]	5,06	5,23	6,56
E according to ISO 527	[MPa]	260,1	269,3	360,7
E_y	[MPa]	47,0	54,2	76,3

3.3 Evaluation of the experiments

Velocity of load introduction significantly influences adhesive behaviour mainly due to the visco-elastic behaviour of polymers. During the experiments, three different velocities of load introduction were used – 8 mm/min, 2 mm/min and 1mm/min (specimens were loaded by controlled deformation). High speed of loading means higher stiffness as well as higher ultimate strength of adhesive. For practical use, due to this effect, there are differences in response of composite structure with load bearing adhesively bonded joint as a shear contractor for specific types of dead or imposed load. Ratio of interaction and stress redistribution between assembled structural elements depends on contracting adhesive layer, which looses its stiffness by increasing time of loading. In case of dead load, next creeping effect can decrease the considerable stiffness even much more.

Initial modulus of adhesive determined by ISO 527 is not safe value for design because it is determined between values of $\varepsilon_1=0{,}0005$ and $\varepsilon_2=0{,}0025$ (*0,05%* and *0,25%*), which is very low for such a kind of material with high level of elasticity (visco-elasticity). More feasible as an input parameter should be the value E_y, which describes the modulus evaluated on the part of the stress-strain diagram between *(0,0)* and yield stress value, see Figures 6-7.

3.4 Comparison of two generations

Material tests of previous generation of the SikaFast 5211 adhesive were performed at CTU Prague in the past. Main problems for modeling of this older version were the changeability of the stiffness during the range of load and relatively low elongation at break, see Figure 6. Experiments were managed by controlled deformation 1mm/min according to ISO 527 on specimens type 1B, it means, that results are fully comparable with the set of experiments of the new generation described above. Experiments described in this paper proved significantly enhanced properties from the previous generation, see results in Figure 7 or compared values in Table 3.

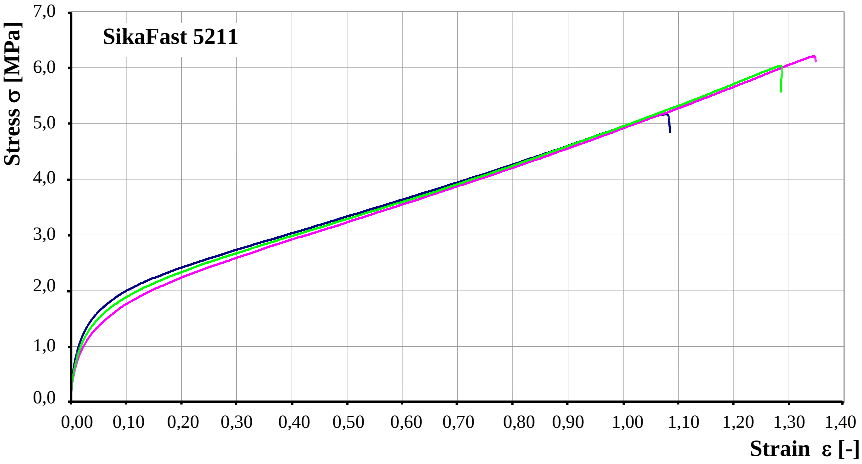

Figure 6. Stress-strain diagram of SikaFast 5211 (old generation), type 1B, 1mm/min

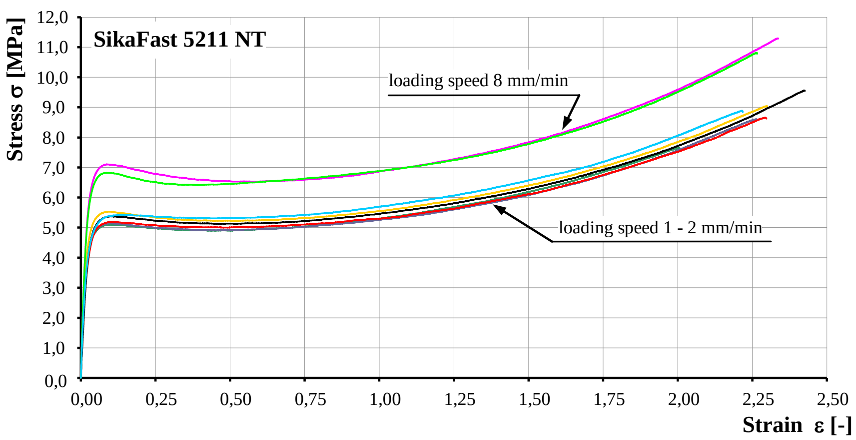

Figure 7. Stress-strain diagram of SikaFast 5211 NT (new generation), type 1B

Experimental results show higher stiffness and strength of the new generation of acrylic adhesive SikaFast 5211 NT especially in the first period of loading between 0 and yield stress, which is the most important part in terms of civil engineering point of view, because design value of the adhesive strength has to be in this range. Safety factors for adhesives are therefore relatively high. In this phase, adhesive has almost linear behaviour, which is very feasible for clear idea about stress transfer in the joint by increasing load. Next phase is characterized by decreasing of stiffness till the failure of the specimen. This yield phase is not so important for the determination of the safe design input values of stiffness, but it is very important for the behaviour of longer complex bonded joint due to the possibility of stress redistribution along the adhesive layer when it is locally overloaded or subjected by stress peak. High possible elongation at break is obvious also from Figure 8 captured during experiments. This phenomenon is very valuable especially in connection of glass structures, where stress peaks are more dangerous than ever. Comparison of selected values for both generations of SikaFast 5211 is presented in the Table 3.

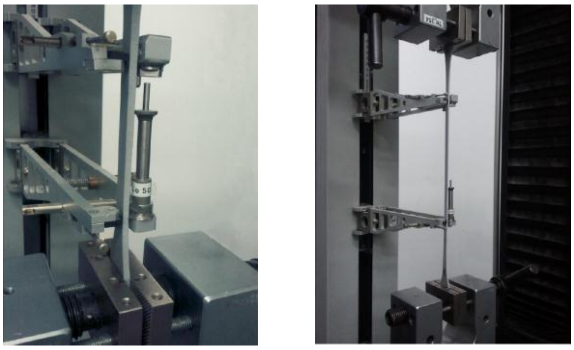

Figure 8. Material tests of SikaFast 5211 NT – possible elongation at break

Table 3. Comparison of two generations in values

Material properties of SikaFast 5211 and SikaFast 5211 NT			
value	unit	old technology	new technology
Strength σ_{ult}	[MPa]	6,1	7,22
Yield stress σ_y	[MPa]	1,8-2,0	5,06
Strain ε	[-]	1,24	2,19
E by ISO 527	[MPa]	96,94	260,1

Described significantly improved properties of polymer adhesive bring the save and economic design of adhesively bonded joints closer to civil engineers without advanced knowledge of finite element software and reflect on the requirements of "ideal" structural member called "semi-rigid adhesively bonded joint".

4 NUMERICAL STUDIES

Finite-element method was chosen as a device for numerical studies. Volume models of tested glued connections were created by software package Ansys 11. Steel and glass parts were modelled by a member SOLID45. This element type can be used also for adhesive, but only in case of stiff connection with small deformations and behaviour of adhesive close to linear elastic. Other element types, i.e. SOLID185, have to be used in case of compliant connection with significant non-linear behaviour and huge deformation in hundreds of %. Finite-element models of the adhesive layer were found and fine-tuned according to the thickness of the joint. There is a different stiffness of the adhesive in thin layer close to bonded surface from the rest of the thickness of the joint. This phenomenon affects more thin layer than thick one. Models of the adhesive layer were developed and calibrated for each tested adhesive to be in conformity with experimental results. Working numerical model is in the Figure 9.

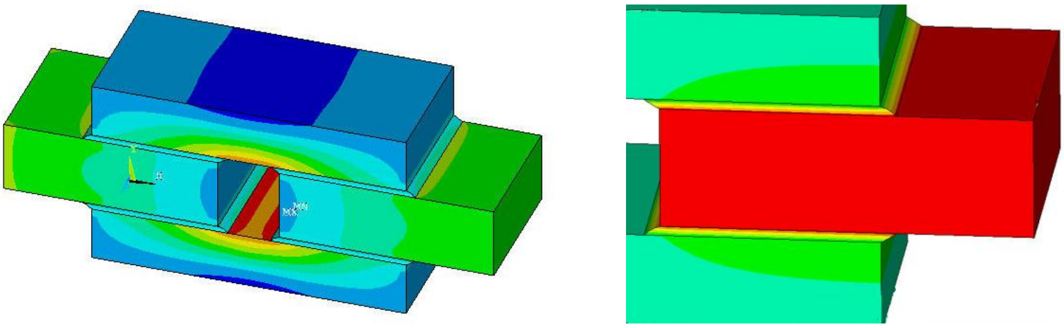

Figure 9. Numerical model of the shear steel-glass connection test

Adhesives, which are tougher, for example epoxy resins or acrylics could have been modelled as multi-linear elastic by using appropriate input material parameters. In the Figure 10, there is a comparison of FE calculation made on calibrated multi-linear model of acrylic adhesive SikaFast-5211(old generation) with the thickness of joint 3 mm subjected to shear and experimental obtained results for the same adhesive and thickness.

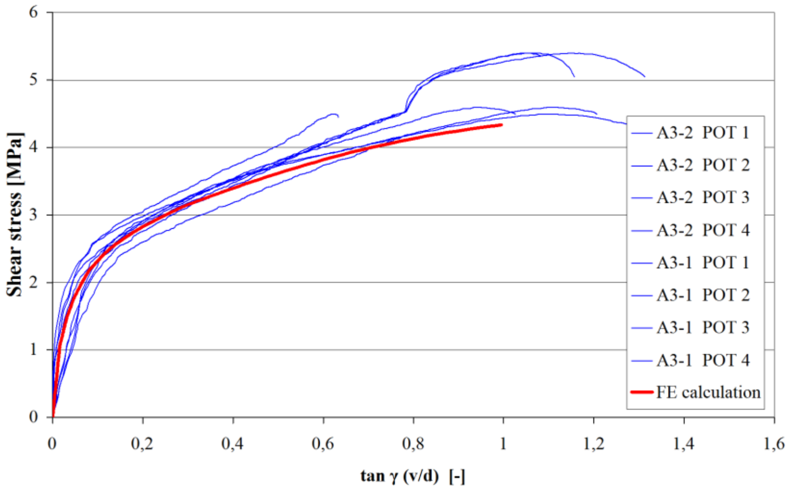

Figure 10. Comparison of FE calculation and experiments for acrylic adhesive modelled as a multi-linear elastic material

There is a possibility to use phenomenological material models, which are included in most of the common used finite element software. Hyper-elastic models, i.e. Mooney-Rivlin, Arruda-Boyce or Ogden, can very accurate predict the behaviour of compliant adhesives like silicones or tested polyurethanes. Their calibration isn't easy because a lot of input parameters are needed and longer calculation time is required. Whole process of calibration of the material model is more complex, but these models can withstand extensive deformations. Therefore they can be very useful for materials, which show high-elastic elongation.

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