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Steel-glass Structural Elements with a New Generation of Adhesives

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Intensive progress in the field of polymer adhesives opens up new opportunities in their usage. Glass is combined with steel in hybrid systems to improve its load-bearing capacity, stiffness, residual load-carrying capacity and to preserve a high degree of transparency at the same time. Adhesive connection between glass and other materials in hybrid structures is beneficial, because in dependence on geometry and stiffness, the glue in joints can provide uniform stress distribution along the contact area. The current paper deals with the research study of two generations of adhesives. The study begins with a description of tensile behavior of dumbbell test specimens made from a new type of adhesive and its predecessor. Because shear connection is used in hybrid steel-glass beams due to its suitable stress distribution and good feasibility, both glues were tested in shear joint specimens to compare their properties. Both adhesives were also applied in the linear connection of steel-glass beams with the span of 4 m and compared to each other as the last step of the study.

Keywords: Steel-glass element, adhesive, joint, beam, FE modelling

1. Introduction

Polymer materials of adhesives are no longer limited to the sealing function. They can fulfill real load-bearing purpose (Abeln et al 2014, Belis et al 2012, Weller et al 2009). In contrary to the traditional bolted connection, an adhesive joint provides many important advantages for brittle glass, such as uniform stress distribution along the larger connection area, the absence of drilling holes in the glass or possibility to join materials with different mechanical and thermal properties. The current article deals with the experimental analysis focused on the comparison of mechanical characteristics of two two-component acrylate adhesives (the older technology – SikaFast-5211 and the new SikaFast-5211 NT) produced by same manufacturer. The experimental research started by initial material tests by EN ISO 527, continued via small-scale steel-glass connection tests and graduated by full-scale testing of hybrid beams with the span of 4 m. A special part of the paper is focused on the numerical calculation of a shear bonded connection for both adhesives and their comparison in the glass-to-steel joint in a hybrid beam.

2. Material Tests

Material tests according to EN ISO 527 (Plastics - determination of tensile properties) were performed for both adhesives. Dump-bell test specimens were created by using a special form and the shape of the specimens is shown in Fig. 1(a). The specimen during the tensile test is shown in Fig. 1(b).

Fig. 1a) Shape of test specimens, b) Specimen during tensile test.

The specimens were subjected to uniaxial loading and the material properties (tension strength, stress-strain diagram, elongation at break) were determined. Comparison of adhesive behavior is shown in Fig. 2, where SF is adhesive SikaFast-5211, tested at displacement rate 1 mm/min, and SF NT is the new SikaFast-5211 NT. SikaFast-5211 NT specimens were tested at displacement rates 1, 2 and 8 mm/min. Experimental results show higher stiffness and strength of the new generation of the glue SikaFast-5211 NT. Adhesive has almost linear behavior up to the yield stress. After that there is phase characterized by decreasing of the stiffness and significant elongation. Comparison of the mechanical characteristics for both acrylates tested at displacement rate 1 mm/min is presented in Table 1.

Table 1: Comparison of the adhesive characteristics (acc. EN ISO 527), displacement rate 1mm/min.

	SikaFast-5211	SikaFast-5211 NT
Tension strength [MPa]	6.1	7.22
Strain [-]	1.24	2.19
Modulus of elasticity [MPa]	96.94	260.1

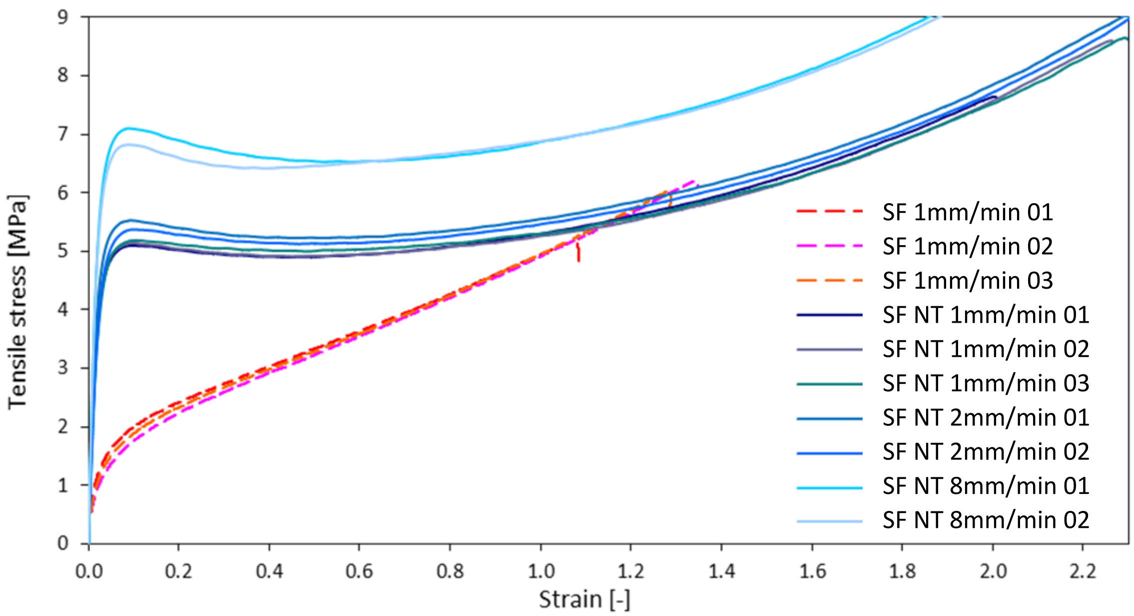

Fig. 2 Stress-strain relationship for both adhesives.

3. Small-scale steel-glass connection test

The important information about the glue is not only the ultimate strength but also the behavior in the particular joint under loading and mode of failure. A properly designed and manufactured joint should not break by adhesive failure mode. Adhesive failure mode means improper surface preparation or insufficient adhesive forces to substrate. It leads to a significantly lower ultimate strength and unsafe behavior of joint during loading (sudden collapse). On the contrary, cohesive mode of failure is a suitable type of joint breakage. Therefore as the next step of the research, shear connection tests were carried out. Test specimens were prepared in the laboratory of Sika CZ. Specimens consist of two steel plates with thickness 25 mm and dimensions 75x50 mm connected to two 19 mm thick float glass pieces with dimensions 110x50 mm, bonded area was four times 50x50 mm with bond line thickness 3 mm. Steel plates were cleaned by Scotch Brite abrasive pads and all bonded surfaces were activated by agent Sika ADPrep. Small-scale shear tests were performed according to test setup which is shown in Fig. 3. Shear stress in the adhesive layer was reached by tensile force applied to the specimen. Tensile load was introduced to the setup by long steel rods with displacement rate 1mm/min.

The shear stress-strain diagram, see Fig. 4, shows a comparison of adhesive SikaFast-5211 and SikaFast-5211 NT in the connections glass-to-steel. The representative curves were chosen according to their approaching to the average values of results. It is noticeable that the new type of the adhesive shows different behavior than its predecessor. SikaFast-5211 NT reached significantly higher shear strength (SikaFast-5211 NT reached 7.5 MPa, while SikaFast-5211 reached 4 MPa for same joint and arrangement) and larger shear strain at break. The large initial stiffness in the joints of the new adhesive was not changed up to 3.5 MPa, although the older type of the adhesive had the initial stiffness limited around 2 MPa.

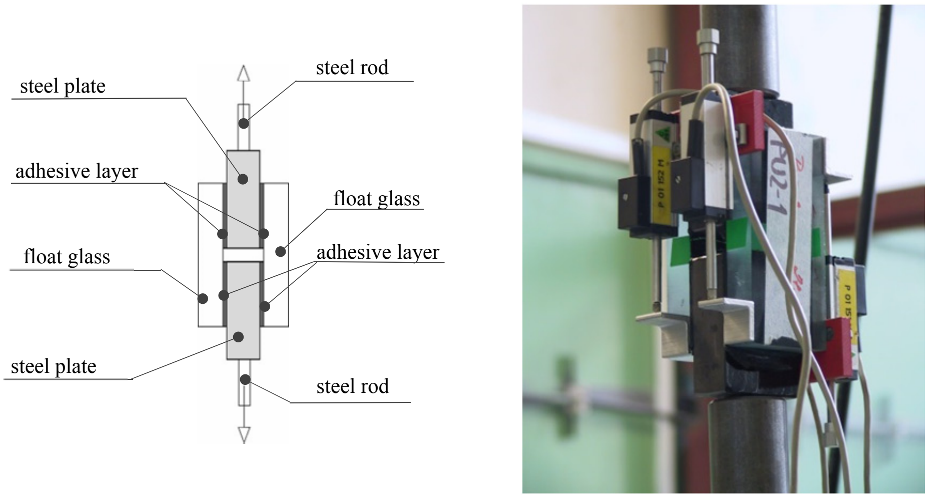

Fig. 3 Setup of the shear steel-glass connection tests.

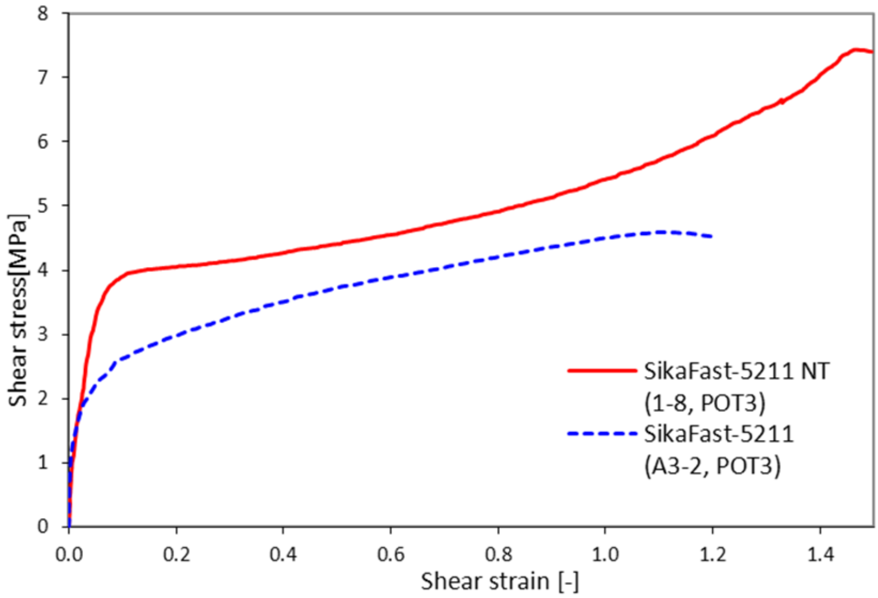

Fig. 4 Comparison of acrylate SikaFast-5211 a SikaFast-5211 NT in glass-to-steel connection.

No significant difference was observed at both glue failure modes, compare Fig. 5 and 6. Specimen failure starts predominantly in the adhesion manner at glass to adhesive interface. But rest of adhesive layer still behaved cohesively, so the joint was finally broken by combined adhesive-cohesive failure.

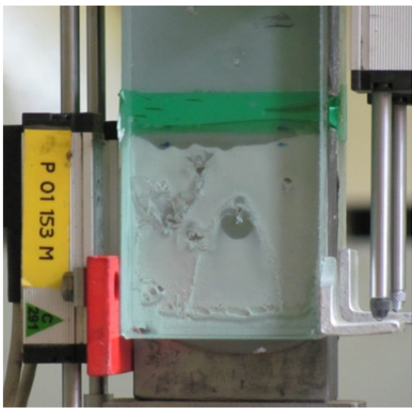

Fig. 5 SikaFast-5211 failure mode.

Fig. 6 SikaFast-5211 NT failure mode.

4. Numerical Analysis of Bonded Connection

The finite-element method was chosen as the tool for numerical studies. Volume models of tested specimens with SikaFast-5211 were created in two different software programs based on FEM – ANSYS v.11 and RFEM 5.05, see Fig. 7. The description of both models is in the following paragraphs.

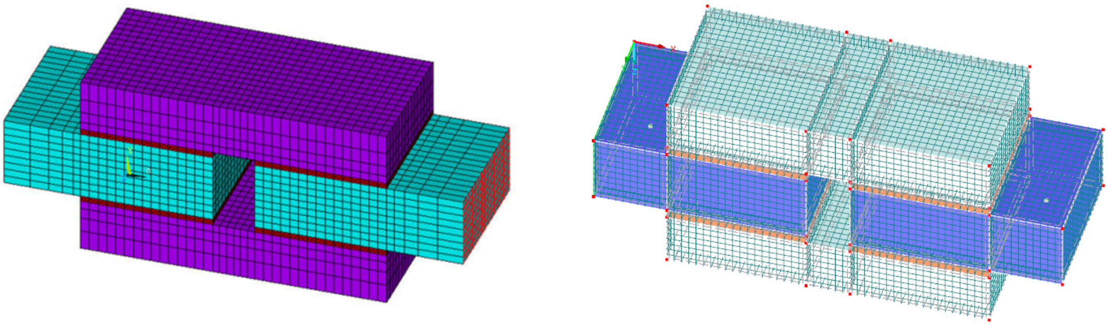

Fig. 7 Numerical model of the shear-glass connection test specimen,
on the left – ANSYS 11, on the right – RFEM 5.05.

4.1. Ansys 11

A volume model was created in 3D by an element SOLID45. The element is defined by eight nodes having three degrees of freedom at each node (translations in the x, y, and z directions). The material model of the glass was linear isotropic with modulus of elasticity E = 70 000 MPa and Poisson´s ratio 0.23. The material model of the steel was linear isotropic with modulus of elasticity E = 210 000 MPa and Poisson´s ratio 0.3. Adhesive layer was modelled as a multi-linear elastic material with initial values E = 186.5 MPa and ν = 0.4. Material characteristics of adhesive were defined on the basis of results from material tests described in Chapter 2.

4.2. RFEM 5.05

A model of the specimen was created by solids in the software RFEM 5.05. A solid element in RFEM has eight nodes having six degrees of freedom at each node. The material model of the glass and steel was defined as isotropic linear elastic with the same characteristics as in the Ansys model. The material model for the adhesive was chosen as isotropic plastic 2D/3D with the same material characteristics as in the previous model.

4.3. Results from both models

Fig. 8 illustrates a comparison of experimental results for test specimens with acrylate adhesive SikaFast-5211 and both numerical models. The shear stress-strain diagrams shows that both models are able to predict the behavior of the joint properly.

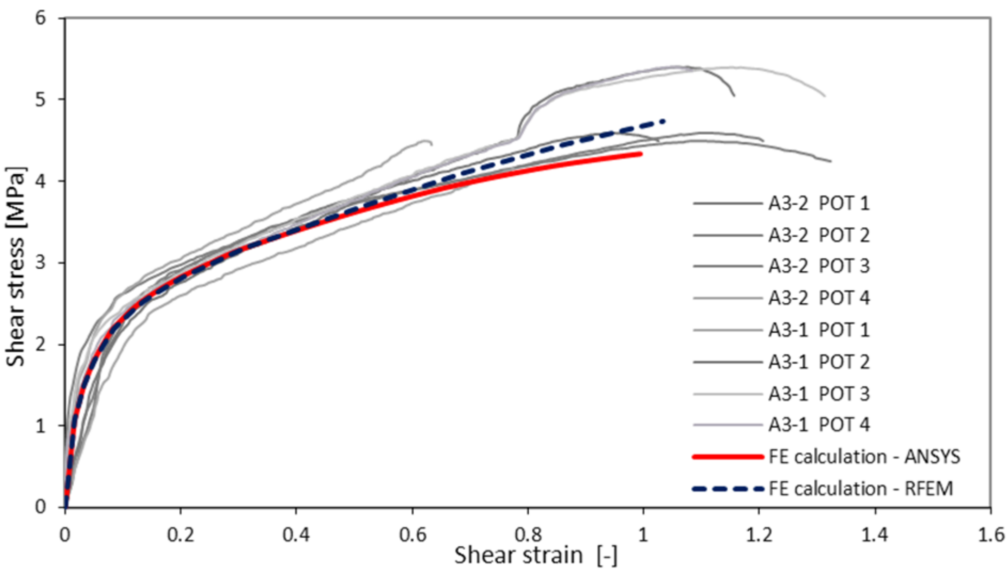

Fig. 8 Comparison of Ansys and RFEM calculations with experiments for SikaFast-5211.

5. Hybrid Steel-Glass Beam

Both adhesives were applied in the linear connection of hybrid steel-glass beams. Beams were 4.25 m long and consisted of glass web and steel flanges. For all beams a single layered 19 mm thermally toughened glass with the height of 290 mm and steel grade S235 was used. Direct connection between steel and glass was realized by a 3 mm thick adhesive layer. The dimensions of steel flanges and the test set-up differ for various adhesives, therefore detailed descriptions for both variants are provided in the following chapters.

5.1. Hybrid Steel-Glass Beam with SikaFast-5211

Three hybrid steel-glass beams were produced with the 2-component acrylate adhesive SikaFast-5211. The steel flanges had cross-sectional dimensions 100x10 mm. The beams were simply supported with a 4000 mm span and subjected to a 4-point bending test until the glass failure. Load introducing points were distant 1000 mm from each other. Lateral supports were placed at midspan and at the ends of beam to avoid lateral and torsional buckling. Schematic test setup is shown in Fig. 9 (Netusil and Eliasova, 2012).

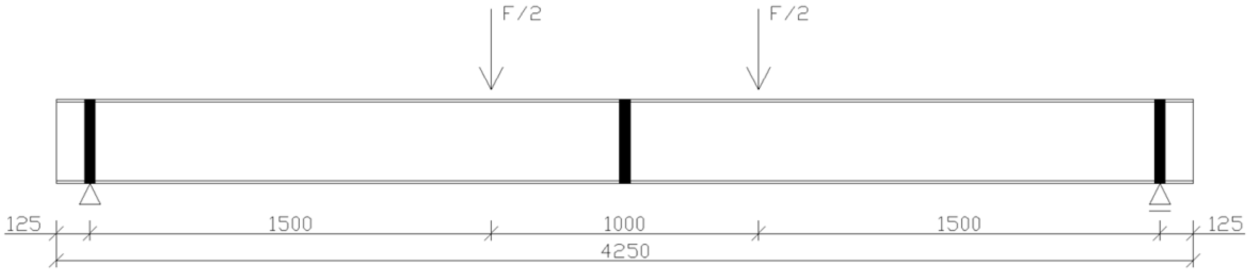

Fig. 9 Four-point bending test set-up of the of hybrid steel-glass beams with SikaFast-5211.

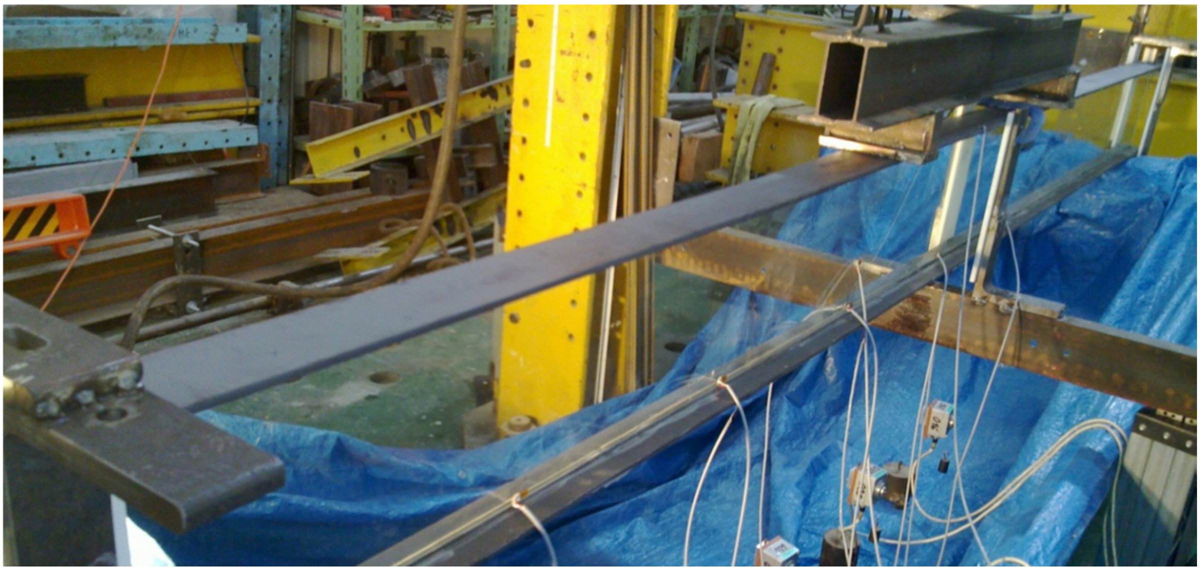

Fig. 10 Hybrid steel-glass beam.

5.2. Hybrid Steel-Glass Beam with SikaFast-5211 NT

Two experiments of the hybrid steel-glass beams with the new glue SikaFast-5211 NT were performed to describe the new adhesive behavior in a real structural element. The steel flanges had cross-sectional dimensions 60x8 mm. The beams were simply supported with a 4000 mm span and subjected to a four-point bending test. The load introducing points were distant 2400 mm from each other. Lateral supports were arranged at the load introducing points. The test specimens were loaded at rate 50 N/s and loading continued until the total collapse of the beam. Schematic test setup is shown in Fig. 11 and Fig. 12.

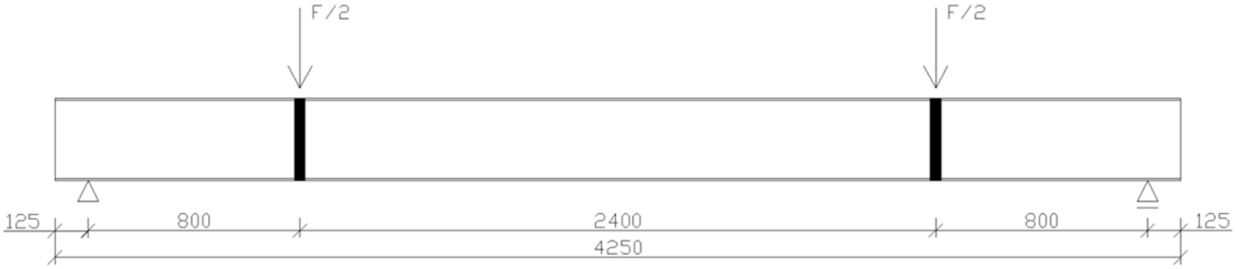

Fig. 11 Four-point bending test set-up of hybrid steel-glass beams with SikaFast-5211 NT.

Fig. 12 Hybrid steel-glass beam with SikaFast-5211 NT.

5.3. Numerical Model of Hybrid Steel-Glass Beam with SikaFast-5211 and SikaFast-5211 NT

Numerical models of the both types of beams were created in RFEM 5.05 software. Both test setups and beams with different adhesives were validated in the separate numerical models according to experiments firstly. Subsequently it was possible to compare the results for different adhesives on one setup and cross-section of the beam. The comparison of the results was performed for the steel-glass beam with flanges dimensions 100x10 mm. Beams were simply supported (4.0 m span) and subjected to four-point bending, see Fig. 13. Lateral restrictions were arranged at supports and midspan.

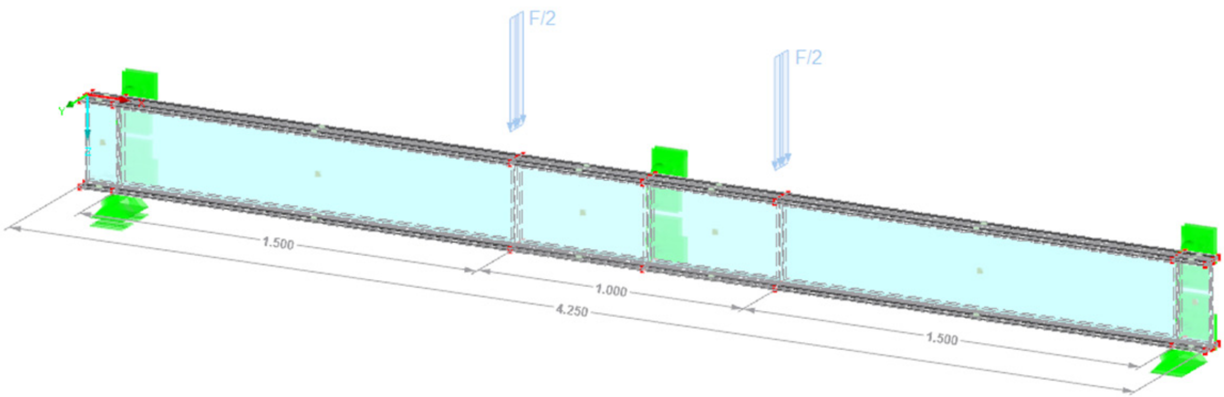

Fig. 13 Numerical model of hybrid beam created in RFEM used for numerical comparison of both adhesives in the real structural element.

Fig. 14 illustrates a comparison of experimental results with numerical calculations for the beam subjected to bending moment 18.9 kNm. The graph shows normal stress in the cross-section of the beam, where conversion to new adhesives SikaFast-5211 NT to older test set-up and cross-section arrangement is shown. It is noticeable that the full-scale bending tests of hybrid steel-glass beams confirm the knowledge obtained from the small-scale steel-glass connection specimens. New acrylate adhesive SikaFast-5211 NT is stiffer, therefore higher degree of shear interaction between steel and glass can be observed. It leads to lower normal stresses on the edges of the glass pane and subsequently to the higher normal stress in the steel flanges. Due to the high yield stress of steel (f_y = 235 MPa) still the collapse occurs in the glass web. It means that the hybrid beam with SikaFast-5211 NT reached a higher load bearing resistance.

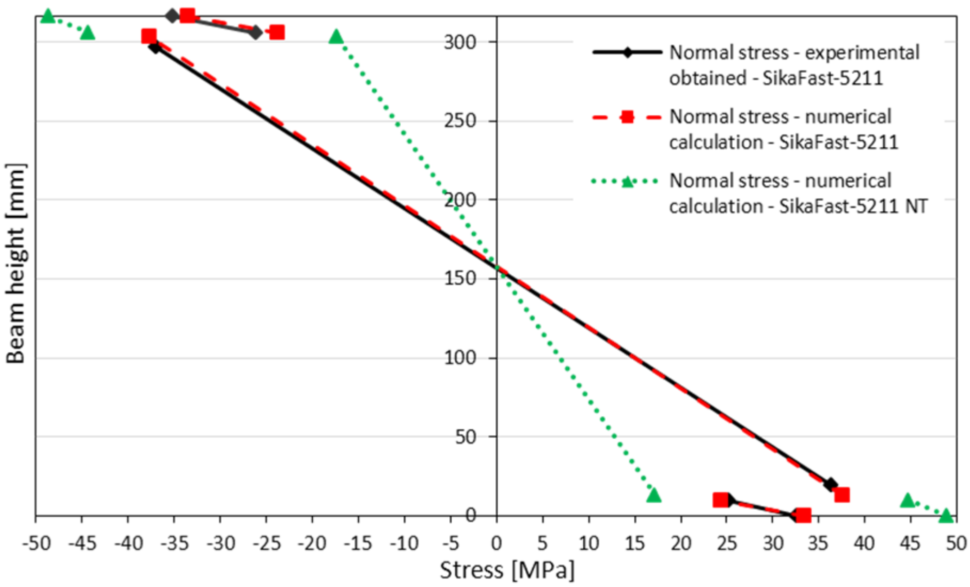

Fig. 14 Normal stress in cross-section of the hybrid beam under bending moment 18.9 kNm, comparison of experiment and numerical models.

6. Conclusion

Important differences were proven for the behavior of 2-component acrylate adhesives. The new type of acrylate glue (SikaFast-5211 NT) in glass-to-steel connections showed completely different behavior under shear loading with significant almost linear part of stress-strain diagram with high stiffness up to stress level of 3.5 MPa. Numerical models for original adhesive in connection were prepared in Ansys v.11 and RFEM 5.05 and calculations were compered. Part of the numerical study was focused on the modelling of both adhesives in 4 m long hybrid steel-glass beams. Models were validated with performed experiments for both adhesives with different loading set-ups and cross-sections in RFEM. Then conversion of the new type of adhesive into the first used loading set-up and cross-section was made and the results were compared. The new adhesive SikaFast-5211 NT showed also stiffer behavior in the beam connection, thus lower normal stresses on the edge of glass pane were produced.

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