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EXPERIMENTAL VERIFICATION OF THE RESISTANCE OF GLASS BEAMS

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ABSTRACT

Experimental research at the Department of Steel and Timber Structures at SUT in Bratislava focused on the verification of the behavior of modern glass structures. Four types of glass beams were tested - laminated beams made of annealed (ANG) and fully tempered glass (FTG) in interactions with or without steel elements (as reinforcement). The results of the experimental research were also compared with theoretical models using FEM calculations.

KEY WORDS

- *structural glass,*
- *laminated glass,*
- *beams*
- *reinforcement,*
- *post – breakage structural capacity.*

1. INTRODUCTION

The nature of unpredictable and brittle failures is the crucial disadvantage of the use of glass as a structural material. Improving the resistance of glass elements has often been realized by multi-layering glass sheets with PVB foil in the past, and it was essential to overdimension the glass structure. The load-bearing capacity of the partly damaged laminated glass element at a reduced level of stress was considered. Fully tempered glass was usually used, because as a result of heat treatment, it demostrates a higher tensile strength [8], [2].

The concept of reinforced glass beams focuses on ways to ensure the plastic (ductile) failure behaviour of the element. This ductile failure behaviour is obtained by bonding a reinforcement profile in the tensile zone along the edge of the glass beam. Exceeding the tensile strength of glass causes the initial formation of tensile cracks, but the growth of the cracks is limited. The fracture's energy is partly used for deformation of the reinforcement, which transfers the tensile forces at the point of the crack. Together with the compression forces in the uncracked glass, an internal coupling of the forces is created, and the reinforced beam is still able to carry the load.

There have been several research projects realized abroad dedicated to reinforced or composite glass beams. Except for steel reinforcement

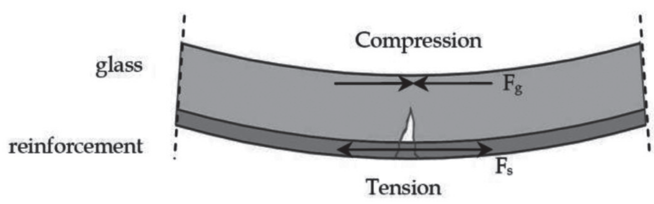

Fig. 1.1 *Schematic overview of the distribution of the force after the failure of glass [8].*

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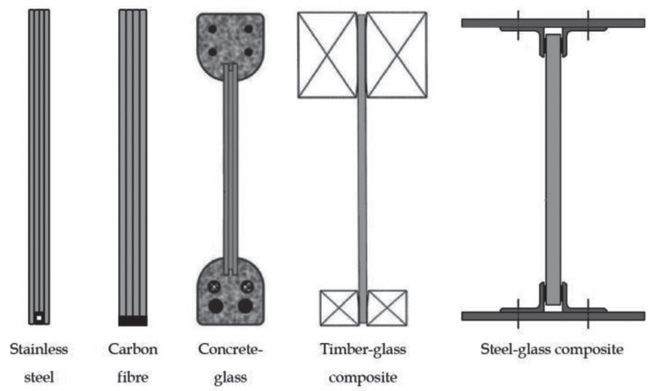

Fig. 1.2 *Similar structural glass composite beam concepts [8].*

profiles, a combination of glass with other materials has also been used. A brief overview of the most recent works is given in Fig. 1.2. These works examined glass beams reinforced with steel straps or profiles [8], [9], carbon-fiber reinforced glass beams [10], glass-concrete composite beams [4], glass-timber composite beams [7], [6], and also glass beams with steel flanges [11], [3], [5].

2. TYPES OF BEAMS, MATERIAL AND GEOMETRY

The first part of the experimental research focused on the basic mechanical properties of glass as a structural material. The effect of the heat treatment of glass (tempering) on its strength in tension and the improvement of the bending resistance of the glass beams were examined.
In the second part of the experimental research the behavior of glass beams reinforced with stainless steel profiles (as strips) was examined. Reinforcing profiles were attached to the bottom edge on both surfaces of the glass by means of an epoxid glue. The experimental results were evaluated in terms of the nature of the collapse at different stress levels and the different states of the operation of the reinforced glass beam.

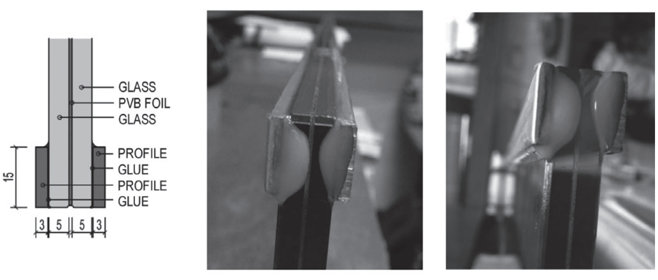

Fig. 2.1 *Glued reinforcing profile (detail), scheme and actual performance.*

The glass beam specimens had dimensions of 1500 x 130 mm, and laminated glass (annealed or fully tempered) was used for their production with a sheet thickness of 5mm and PVB foil with a thickness of 0.76 mm. The theoretical thickness of the laminated glass pane was therefore 10.76 mm. A stainless steel profile of the EN 1.4301 material‘s quality, respectively STN 17240, was used as a reinforcing profile. A profile of 15 x 3 mm was attached to both surfaces of the glass pane along the tension edge. Details of the reinforced glass beam with a stainless steel profile are shown in Fig. 2.1. The two-component Loctite Hysol 9466 epoxy adhesive was used for bonding the reinforcing profile.

2.1 Preparation of the experiment

All the types of glass beams were tested using a 4-point bending test. The theoretical distance between the supports (span) was 1400 mm with 1500 mm as the total length of the beams. The specimens were loaded symmetrically at two points at a distance of 200 mm from the middle of their spans. The total distance between the supports of the loading girder was therefore 400 mm. The loading girder and the test samples were fitted together in a ZDMU 30 stationary hydraulic testing machine with a maximum loading force of 100 kN (Fig. 2.2).
The course of the loading test was recorded using a HBM Spider8 measuring station, and the data were stored in a PC (notebook) via the Catman utility software. The measured data were exported to a Microsoft Excel file format after the loading test had finished. The following data were measured:

- vertical deformation of the glass specimen 5x
- horizontal deformation of the glass specimen 1x
- trajectory of the testing machine jack 1x
- loading force 1x
- strain measurement of the glass specimen 4x

3. EVALUATION OF THE MEASUREMENTS

Sixteen glass beam samples were tested in the laboratory of the Department of Steel and Timber Structures at SUT in Bratislava. The specimens were sorted according to the type of glass (ANG float glass or FTG fully tempered glass) and the beam type (unreinforced or reinforced = Reinforced) into 4 basic groups.

3.1 Testing of the unreinforced beams

The brittle breaking behavior of the glass elements for both types of beams (ANG and FTG) occurred through their total collapse, which had not been preceded by any noticeable formation of cracks,

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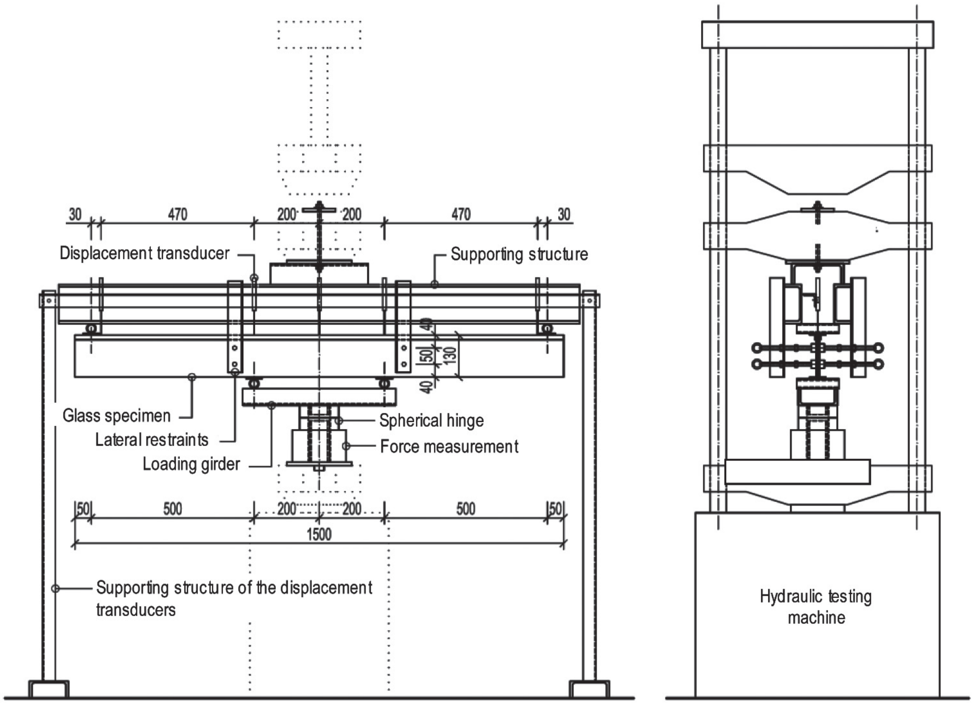

Fig. 2.2 *Loading girder, scheme and installation of the hydraulic testing machine.*

so the beams suddenly failed. For the beams made of float glass the final damage was strictly of a local character (one crack and intact compact parts); the beams made of fully tempered glass were broken into many small pieces due to the heat treatment, and some of the fragments were ejected for quite a distance. The broken specimens showed no residual resistance, despite the fact that the broken parts were connected by PVB foil.

3.2 Testing the reinforced beams of float glass

The main objective of the experimental research prepared was testing the reinforced beams made of float glass. The measurement results proved the relationship between the load and vertical deflection until the crack forms is almost perfectly linear. The extension of the size and number of cracks results in a decrease in the bending stiffness and an increase in the vertical beam's deflection. The typical brittle breaking behavior of the glass elements was transformed to a ductile (plastic) behavior, which showed a gradual decline in the bending stiffness of the beam. The decrease in the bending stiffness of the reinforced beam is caused by two crucial factors – the formation and progress of tensile cracks in the glass and the plastic deformation of the reinforcement in the crack.

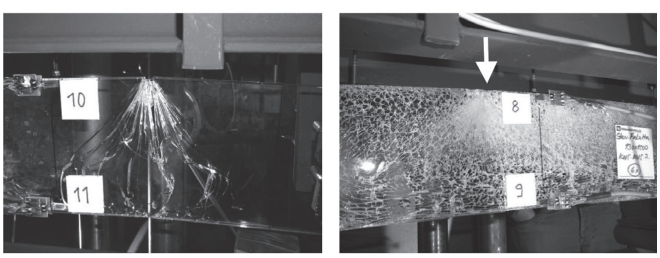

Fig. 3.1 *Typical breaking behavior of ANG (left) and FTG specimens (right).*

All of the reinforced beams made of float glass were able to carry the increasing load, and none of them collapsed after the first crack had occurred. The initial crack was formed on the tension edge of the beams. The cracks had a slightly branched shape and were oriented perpendicularly to the edge of the beam. They formed in both layers of the laminated glass almost simultaneously; in most cases they were in the area of the maximum bending moment. The initial crack's length was limited to a maximum 3/5s of the total height of the beam's cross-section. New cracks were formed under the increasing load, and the existing initial cracks grew.

The mechanism of the final collapse differed according to whether the beams with or without a secondary lateral restraint (stabilisation of the compression edge) were tested. For beams without any

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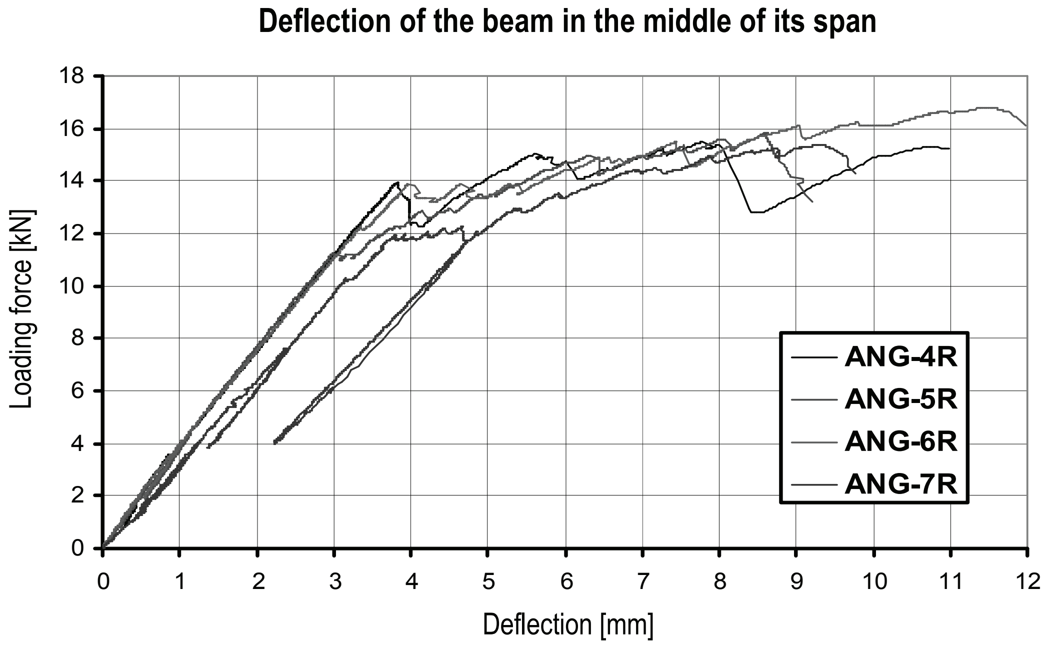

Fig. 3.2 *Graphs of the P - w relationship for the ANG-R beams.*

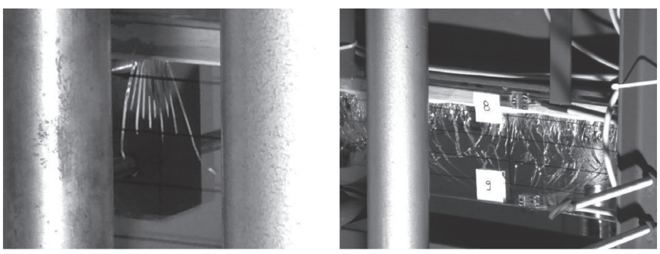

Fig. 3.3 *The initial cracks and their growth before the final collapse of the specimen.*

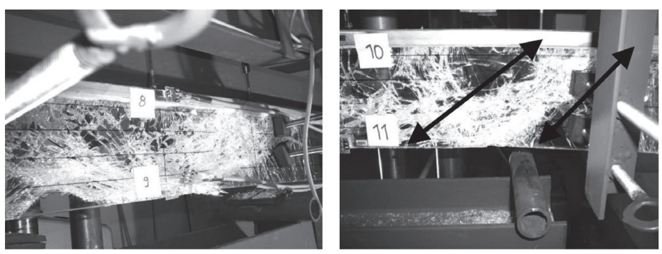

Fig. 3.4 *Total collapse of the beam caused by the buckling (left) and a collapse caused by the formation of a diagonal crack (right).*

stabilization most of the cracks had a diagonal direction. The cracks were linked to each other, and they reached the compression edge progressively. The total collapse of the beam was caused by the buckling and explosion of the compression edge, which was corrupted by a large number of cracks. For the beams with a secondary lateral stabilization, the cracks had a mostly irregular layout. There were two different forms of the final collapse - the buckling and explosion of the compression edge between the secondary lateral restraints or the formation of a significant diagonal crack near the supports of the loading girder. A diagonal crack with a slope of about 45° to 60° damaged both layers of the laminated glass through the total height of the beam‘s cross-section. The total resistance of the beam was probably affected by the transverse forces according to the character and location of the diagonal cracks. In both cases, the damaged beams were unable to carry any loads or forces. The ending parts of the beam (out of the area with the maximum bending moment) remained compact with a very small number of cracks. Due to the final collapse, the plastic deformation and delamination of the reinforcement profile occured in several cases of the specimens tested. The total values of the bending resistance of the reinforced beams made of float glass (ANG-R) had a relatively small variance, despite the fact there was a final collapse caused by the buckling or by the formation of a significant diagonal crack.

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3.3 Testing the reinforced beams of fully tempered glass

The reinforced beams made of fully tempered glass behaved identically as the beams made of float glass until an initial crack was formed. The fully tempered glass broke immediately into many small pieces or fragments; thus, there was no redistribution of the stress between the compressed glass and tensioned reinforcement. The collapse of the beams was not preceded by any noticeable formation of cracks, and the total failure was sudden, which was the same as for the unreinforced beams made of fully tempered glass.

4. OWERVIEW OF THE EXPERIMENTAL RESULTS OBTAINED

From the results of the experimental research, the following conclusions can be formulated:

- the extremly brittle failure behavior of the glass elements;
- a positive effect of heat treatment (tempering) on the tensile strength of glass; the fully tempered glass beams achieved a higher bending resistance from 2.5 to 4.5, compared to the beams made of float glass;
- the measured values of Young‘s modulus corresponded to a value of 70GPa;
- a positive effect of the lateral restraint of the compression edge on the stability and total resistance of the glass beams,
- the interaction of the glass with the reinforcing profile by means of the epoxy adhesive showed sufficient results;
- the aesthetics of the glued bond was satisfactory and not contradictory to the appearence of the glass element;
- the technological process of preparing the reinforced beams is relatively inexpensive and simple;
- the total bending resistance of the reinforced beams made of float glass was from 2.5 to 4 times higher compared to the resistance of the unreinforced beams made of float glass;
- the initial bending resistance (until the first crack was formed) of the reinforced beams made of float glass was from 1.7 to 3.3 times higher compared to the resistance of the unreinforced beams made of float glass, but only 50 to 100% of the total bending resistance of the unreinforced beams made of fully tempered glass;
- all of the reinforced beams made of float glass did not collapse after the first crack had occurred; thus 100% of the post-breakage load-bearing capacity was reached;
- the redistribution of the stress between the compressed glass and tensioned reinforcement developed after the crack‘s formation; a more significant increase in the normal stress was measured in the reinforcement (stainless steel profile);
- the typical brittle breaking behavior of the glass elements transformed into ductile (plastic) behavior, which showed a gradual decline in the bending stiffness of the beam;
- a decrease in the bending stiffness of a reinforced beam is caused by two crucial factors - the formation and extension of tensile cracks in the glass and the plastic deformation of the reinforcement at the point of the crack;

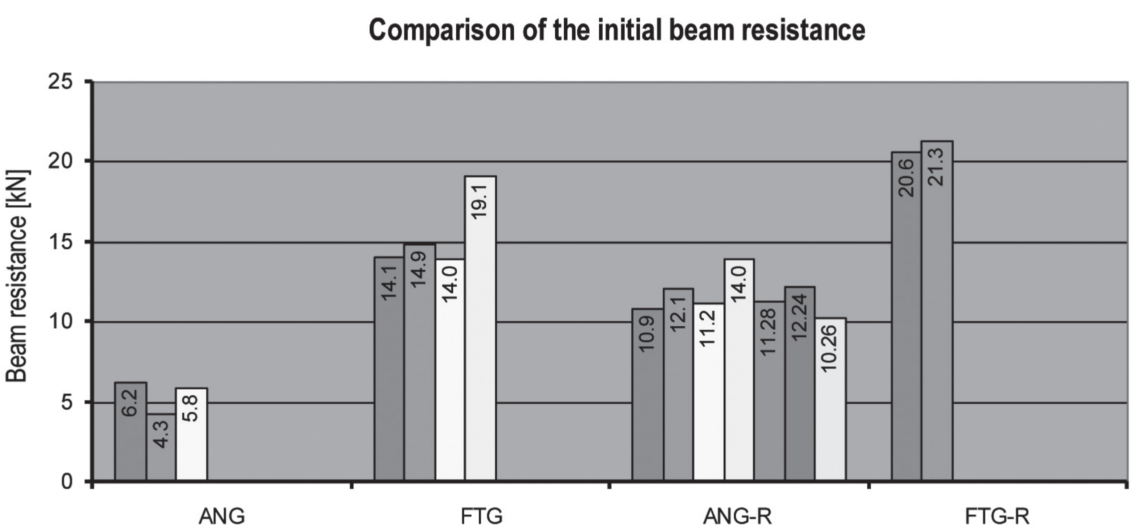

Fig. 4.1 *Total loading of the beams by the initial crack formation (initial resistance).*

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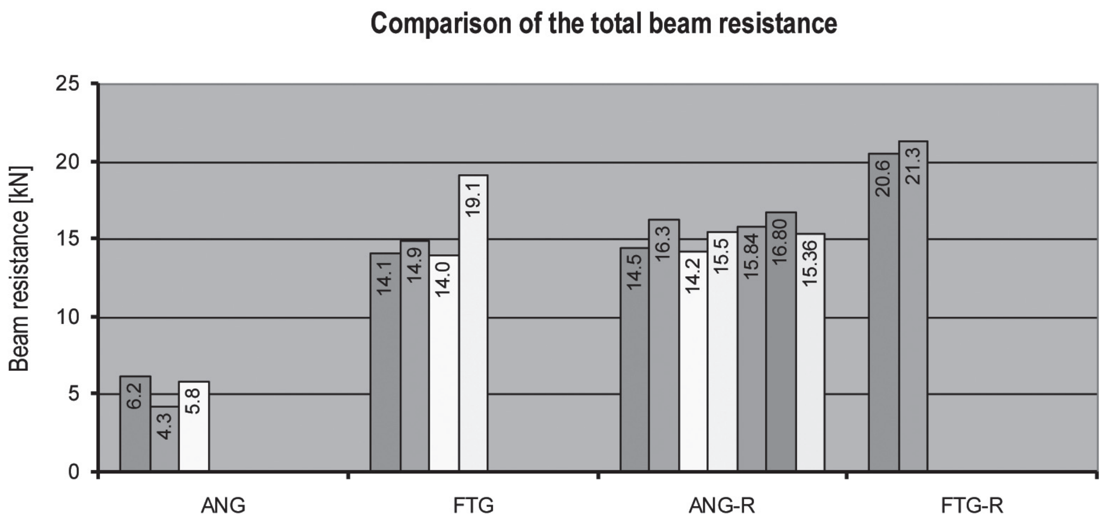

Fig. 4.2 *Maximal loading of the beams by total collapse (total resistance).*

- none of the specimens failed due to the delamination or rupture of the reinforcement profile; all of them collapsed after the failure of the glass part, which was corrupted by a large number of cracks;
- the application of the reinforcement in combination with the fully tempered glass was ineffective and had no practical importance;
- the increase in the total bending resistance of the reinforced beams compared to the unreinforced beams made of fully tempered glass was negligible in the tests (maximum 10%);
- the total bending resistance of the reinforced beams made of fully tempered glass compared to the reinforced beams of the float glass was approximately 30% higher (the positive effect of tempering on the tensile strength of the glass).

5. THEORETICAL ANALYSIS

5.1 FEM models

A total of 16 models was analysed in the FEM calculations using the Dlubal RFEM 4 software. The behavior of a beam was analysed both in terms of the extent of a beam‘s damage (without a crack, one crack, a number of cracks) and in terms of the working diagram of the reinforcement material (the linear and non-linear relationship of σ - ε).
The non-linear material model of the EN 1.4301 stainless steel used a simplified working diagram according to EC 1993-1-4: 2006 (E). The original continuous dependence of σ - ε was replaced in the FEM calculations by a polygonal.

The layered nature of the laminated glass was ignored in the FEM models; the laminated glass and also the reinforcing profiles were replaced by a shell element. Both the glass and reinforcement lay together on one common plane.
In the case of the cracked glass beams, the tensile crack/cracks were defined as FEM elements with the non-linear working diagram of

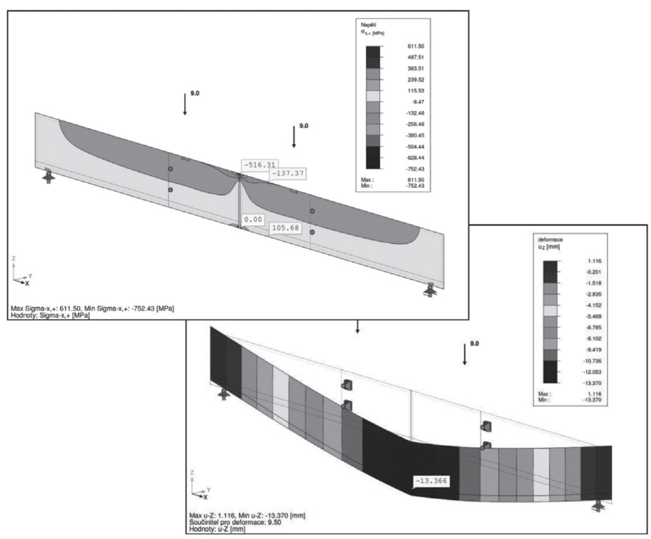

Fig. 5.1 - *Normal stress Sigma$_x$ in the glass and vertical deflection U$_z$ for loading force P = 18kN (one crack, non-linear material model of the reinforcement).*

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the glass of a width of 5 mm. Exceeding the normal stress in tension over 1MPa caused a rupture of the material, and these elements were no longer capable of carrying any tension forces. In the case of normal stress in compression, the unlimited linear behavior of the material was defined.

5.2 Overview of the theoretical results

The evaluation of the FEM calculations focused primarily on a comparison of the vertical deflection U_z, the normal stress $Sigma_x$ and the distance between the compression edge and the neutral axis x. Several of the graphic outputs from the RFEM 4 software are shown in Fig. 5.1 to illustrate the theoretical results of the FEM models.

5.3 Comparison of the results

The results of the FEM calculations proved that the number and extension of cracks do not affect the bending stiffness of a reinforced glass beam significantly in the case of the unlimited linear behavior of the reinforcement material (the dashed traces show a slight variance, Fig. 5.2). On the other hand, the effect of the number and extension of the cracks in glass is strongly manifested for a non-linear material model of the reinforcement (continuous traces). A glass beam has a very small bending stiffness, and the vertical deflection increases because of the plastic deformation of the reinforcement in the crack.

The comparison of the theoretical (FEM analysis) and experimental results indicates a plastic deformation of the reinforcement during the experiment after the cracks were formed; otherwise, the ductile (plastic) $P – w$ relationship of the real diagram (with an almost horizontal secondary partition) is not possible (Figs. 3.2 and 5.2). In most cases the reinforcement works elastically before the initial crack formation; therefore, the results of the theoretical and experimental research on the reinforced glass beams without cracks are similar.

5. CONCLUSION

The issue of glass beams is a relatively novel field for load-bearing structures. Experimental research at the Department of Steel and Timber Structures has shown that the reliability of glass structures can be significantly improved by means of combinations with metallic materials. Reinforcing glass with a glued stainless steel profile increases its total resistance and supplies a very important residual resistance to the damaged glass structure (post-breakage load-bearing capacity). The application of the reinforcing profile by means of epoxy adhesives is technologically a very simple and relatively inexpensive process, which is not contradictionary to the appearance of a glass element. The unpredictable and dangerous brittle breaking behavior of the glass elements is modified towards the ductile (plastic) behavior. The significant damage of the glass and large deformations is noticeable before the final collapse of the reinforced glass element occurs. The application of the reinforcement in combination with fully tempered glass has no practical importance, because it immediately breaks into many small pieces; thus, there is no possible redistribution of the internal forces, which leads to a sudden failure of the beam without any post-breakage load-bearing capacity.

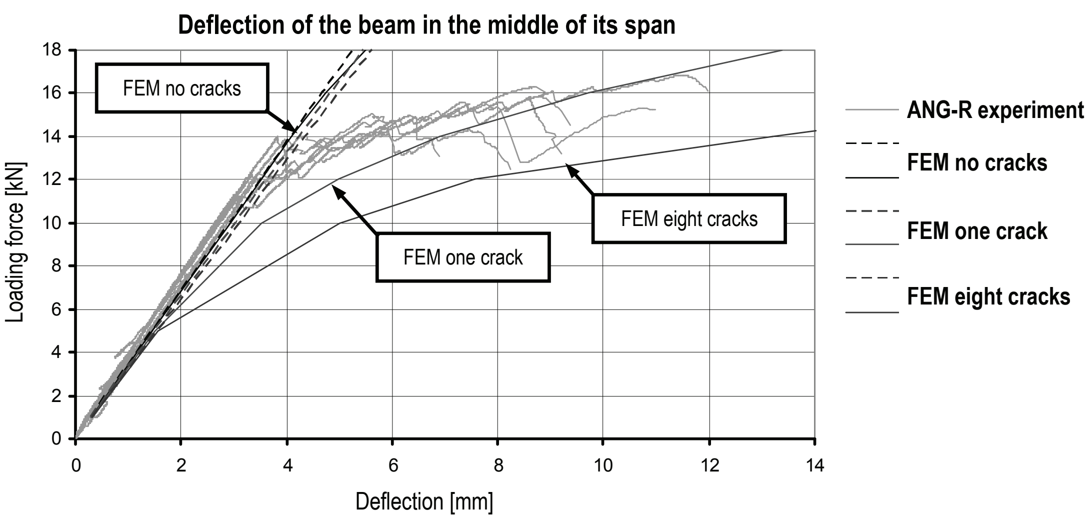

Fig. 5.2 *Diagrams of the P – w relationship of the reinforced glass beams, a comparison of the theoretical and experimental results.*

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The theoretical analysis provided helps in understanding the operation of reinforced glass beams in a general way. The deviations between the results of the FEM calculations and the experimental data mainly occur because the mechanical material properties of the stainless steel were considered according to the theoretical EC values, and the real working diagram of the reinforcement was not experimentally tested. The results of the experimental testing of the reinforced glass beams showed that the real elastic working interval of the EN 1.4301 stainless steel used was probably higher than the theoretical nominal value of the yield strength f_y = 210MPa, according to the EC.

The computational FEM models used are generally applicable in the design of reinforced glass beams despite the deviations listed above. Using the nominal material properties, the theoretical results (total bending resistance, vertical deflection, normal stress) represent safe values.

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