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LOAD-BEARING CAPACITY OF HYBRID TIMBER-GLASS BEAMS

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Abstract

The conservative approach to design timber-glass structural elements assumes that a glass pane only fills a load-bearing frame and does not contribute in the total load-bearing behavior of the component. This study is based on a different assumption – that timber and glass components work together to carry external loads. The objectives were to develop the knowledge about mechanical co-operation, mechanism of failure and post-breakage strength of adhesively bonded hybrid timber-glass beams. A sample of nine 300 mm high and 1800 mm long hybrid beams bonded with three types of adhesives: acrylate, silicone sealant and polymer based on polyurethane resin were built and tested in four-point bending test. To simulate the behaviour of the hybrid beams numerical models which include a simplified method of modelling cracks in the glass web were made. Additionally, a modified γ-method included in PN-EN 1995-1-1 was proposed to estimate the load at which the glass fails. The results show that the hybrid timber-glass beams are able to withstand a much higher load than the load that causes initial failure of the glass web. This solution provides ductility and a warning signal relatively long before the total collapse. The highest post-breakage residual strength is presented by the beams bonded with acrylate adhesive. Despite the lower load-bearing capacity, the beams bonded with silicone sealant and polymer allow for much greater deformations. The modified γ-method and numerical models simulate correctly the linear-elastic behaviour of the beams and estimate the load at initial failure of glass with good accuracy.

Streszczenie

Tradycyjne podejście do projektowania elementów szklano-drewnianych bazuje na założeniu, że szklana tafla jedynie wypełnia nośną, drewnianą ramę, a tym samym nie uczestniczy w aktywnym przenoszeniu obciążeń zewnętrznych. Przedstawiony w artykule projekt badawczy zakłada, że komponenty wykonane ze szkła i drewna współpracują ze sobą, tworząc synergiczną hybrydę. Głównym celem projektu jest rozwinięcie wiedzy na temat mechanicznej współpracy komponentów belki, w tym opisanie przebiegu zniszczenia i określenie nośności poawaryjnej hybrydowych belek drewniano-szklanych z połączeniami klejowymi. W artykule przedstawiono wyniki badań modelowych dziewięciu hybrydowych belek drewniano-szklanych o wysokości 300 mm i długości 1800 mm klejonych przy wykorzystaniu klejów konstrukcyjnych o różnej sztywności (klej akrylowy, poliuretanowy i silikon strukturalny) w próbie czteropunktowego zginania. Dodatkowo, przestawiono wyniki analiz numerycznych oraz propozycję rozwiązania analitycznego w postaci zmodyfikowanej metody gamma zawartej w normie PN-EN 1995-1-1. Wyniki badań modelowych potwierdzają wysoką nośność poawaryjną hybrydowych belek drewniano-szklanych; siła przy całkowitym zniszczeniu belek jest kilkakrotnie wyższa od tej, która powoduje powstanie pierwszej rysy w szklanym środniku. Połączenie szklanego środnika i drewnianych pasów sprawia, że hybrydowe belki niszczą się w sposób ciągliwy, a tym samym belka dostarcza sygnał ostrzegawczy na długo przed całkowitym zniszczeniem. Najwyższą sztywność i nośną poawaryjną osiągają belki łączone przy wykorzystaniu kleju akrylowego. Belki z klejem poliuretanowym i silikonem strukturalnym, pomimo niższej nośności i sztywności, ulegają zniszczeniu przy znacznie większych wartościach ugięć. Zmodyfikowana metoda gamma, jak i modele numeryczne poprawnie symulują zachowanie belek w fazie sprężystej oraz pozwalają na określenie z dużą dokładnością siły rysującej szklany środnik.

Keywords: **Glass; Hybrid glass beams; Adhesives; Post-breakage strength; Ductility.**

1. INTRODUCTION

Nowadays, timber and glass are widely used in many architectural applications. Solutions such as glass panes bonded to timber frames were known for a long time. However, traditional solutions assume that glass only fills the frame – does not contribute in the total load-bearing behaviour, only transfers wind load to the structural frame. Thus the glass pane needs a secondary structure to resist external loading. The research project on hybrid timber-glass beams is based on a different assumption – namely, that timber and glass work together to carry external loads – glass no longer acts as a filling but actively participates in load transfer and becomes, equivalent to timber, a structural element.

Timber is a natural material, environmentally friendly and perfectly in line with principles of sustainable development. Its high strength-to-weight ratio in combination with its low thermal conductivity makes timber a strong alternative to other constructional materials. In addition, an increased use of timber as a material for structural purposes will allow the European countries to reduce CO_2 emissions, mitigating climate change in accordance with international agreements such as The Kyoto Protocol.

It is well known that natural sunlight has positive impact on health and quality of life of people living or working in buildings. For this reason, the possibility of increasing the translucent surfaces through the use of glass structural components is desirable. Besides, modern trends in architecture are oriented towards the high quality of life and low energy consumption, in which modern glass products fit perfectly. Double glazed façades or large glass walls allow a significant reduction of energy demand and costs for air conditioning during summer and heating during winter. However, the material glass itself poses many difficulties in structural considerations. Firstly, it is a brittle material, when overloaded glass breaks immediately into shards with no warning. Secondly, glass is much weaker in tension than in compression and therefore it becomes a problem to exploit fully its strength in bending. Lastly, glass is extremely susceptible to stress concentrations so there is a big challenge to design structural connections between glass and other materials. A traditional approach to design glass elements takes into account the above issues and involves the use of tempered glass. Tempered glass has a considerably higher strength than annealed float glass, and laminating panes together to minimise the probability of total glass failure. However, structural design is today performed using very high safety factors and applying sacrificial sheets to the laminate to protect the load-bearing core. Such extremely conservative design approaches seem to be uneconomical and do not fully take advantage of the material glass.

The research project is based on another concept. It involves a single pane made of annealed float glass and timber to synergetic co-operation. This concept provides ductility and prevents brittle failure of the glass. The glass web cracks into shards which are held in place by the timber flanges. Therefore it offers a high post-breakage strength after possible glass failure. The post-breakage strength relates to an increased value of a load at a total collapse of a beam in relation to the load at which first crack in the web occurs.

2. PREVIOUS WORK AND APPLICATIONS

The current knowledge about synergetic features of timber-glass composites relates to a few previously conducted research projects in European research centres within last fifteen years. Early examples of timber-glass composites were presented in the mid and late 1990s and early 2000s [1, 2, 3, 4]. These research projects related to the basic studies on hybrid structural panels consisting of glass panes and frames made of timber, aluminium and glass fibre reinforced plastic (GRP), bonded with elastic connections.

More detailed technical research on timber-glass composites was made by Hamm in 2000 [5, 6]. He investigated the influence of combining timber and glass based on I-shaped beam and plate elements using polyurethane adhesive. Eight 4000 mm long and 250 mm high beams were tested. The flanges consisted of two solid timber blocks bonded on both sides of the glass web. The dimensions of flanges varied from 30x50 mm^2 to 50x60 mm^2. For all beams a 10 mm thick glass pane was used. Hamm observed an increase of around 250% of a load after first crack has appeared.

Some research on I-shaped timber-glass composite beams including float, heat-strengthened and fully tempered glass was performed by Kreher in 2004 [7, 8]. Design of the beams was similar to Hamm's specimens but he used thinner pane thicknesses: 4 and 6 mm, also the length was reduced to 2000 mm likewise the height of beam to 150 mm. The dimensions of flanges varied from 30x30 mm^2 to 50x50 mm^2. Kreher remarked an increase of 150% of a load after first crack has appeared before the total collapse of the beam. Moreover, Kreher presented an analytical approach to determine the stiffness of a hybrid timber-glass beam in a non-cracked stage and after failure of glass web. The concept developed by Kreher was tested on a full-scale model and applied in the roof structure of the conference room in The Palafitte Hotel in Switzerland [9]. The beams support a light roof and are supposed to transfer snow and wind load to steel posts hidden inside external walls. Each 6000 mm long and 580 mm high I-shaped beam composes of a single glass pane and timber flanges bonded on both sides of the glass web. The upper flange consists of two solid timber blocks 100x160 mm^2 whereas the lower flange involves two timber blocks 65x65 mm^2. For the web a 12 mm thick glass pane made of fully tempered glass was used. Due to lack of post-breakage strength of toughened glass the upper flanges were designed to resist external loads even in case of total failure of a glass web. This solution ensured the structural safety of the supporting roof structure.

Timber-glass composite beams were also researched by Cruz and Pequeno in 2008 [10]. Twenty beams were tested – 15 composite beams, including I-shaped and rectangular section, four timber beams and one glass beam. All composite beams were 550 mm high and consisted of a glass web and timber flanges 70x100 mm^2. The span of the beams varied from 650 to 3200 mm. The web was a laminate glass consisting of two 6 mm thick annealed float glass panes with PVB interlayer. For the composite beams three adhesives were used: polymer, silicone and polyurethane. Cruz and Pequeno observed post initial crack strength of almost 185%. The increase of load was observed for the 3200 mm long composite beam with polymer adhesive. However, Cruz and Pequeno state that silicone adhesive due to its great flexibility seems to be the most advisable for this application [10].

Research on I-shaped timber-glass composite beams was also performed by Blyberg and Serrano in 2011 [11]. All beams were 240 mm high and 3850 mm long. The section consisted of 10 mm thick glass pane 200x3850 mm^2 made of annealed float glass and solid timber flanges 45x60 mm^2. Two types of glass edges were tested: roughly polished and non-treated after the traditional cutting. For the flanges laminated veneer lumber (LVL) was used. The glass web was bonded with adhesive in a groove milled in timber flanges. In the set, fourteen beams were tested: seven with non-treated edges, five with polished edges – both bonded with acrylic adhesive, and one bonded with silicone sealant with polished edges. Blyberg and Serrano observed an increase of load of 140% after formation of the first crack in the glass web before maximum load was reached.

3. MATERIALS AND METHODS

3.1. Materials and preparation of specimens

Figure 1 presents a cross-section of the hybrid timber-glass beam. It consisted of a glass web and timber flanges combined together with a line bond adhesive connection. The total height of all beams was 300 mm.

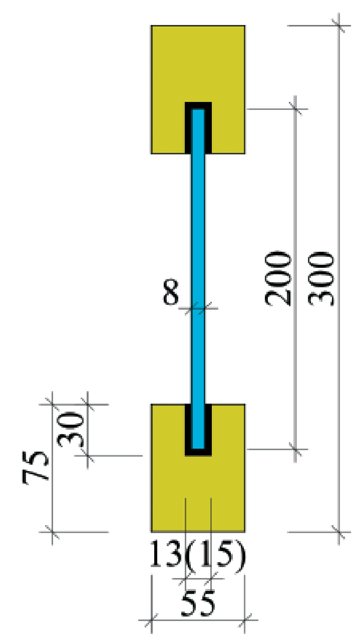

Figure 1.
Cross-section of hybrid timber-glass beam

The glass for all webs was made of annealed float glass according to European standard PN-EN-572 [12]. All webs were 200x1800 mm^2 with a thickness of 8 mm. To minimize the influence of edge quality on the glass strength, widely described in [13], after the traditional cutting to desired dimensions all edges were polished.

For the wooden flanges glue laminated pine beams with finger joints were used. All flanges were 1800 mm long with a rectangular cross-section of 55x75 mm^2. Since the glass web was planned to be bonded to the flanges, 30 mm deep machined grooves were milled in the beams. Three different groove widths were used: 12, 13 and 15 mm.

For the elastic connection a silicone sealant, acrylic adhesive and polymer grout based on polyurethane resin were used. Each adhesive has different stiffness. Sikasil® SG-20 is a high-strength, one-component structural silicone adhesive, designed for structural glazing and other high-demanding industrial applications [14]. It is a neutral, moisture-curing material, UV and weathering resistant. According to the product data sheet [14] the tensile strength is approximately 2.2 MPa, the elongation at break 450% and Shore A-hardness 39. SikaFast® 5221 is a fast-curing, flexible two-component acrylic adhesive with a nine minutes open time [15]. It cures by polymerisation and is designed for mechanical fastening techniques. Further, the product data sheet gives the approximate values of tensile strength of 10 MPa, the elastic modulus of 80 MPa and Shore A-hardness 90. Icosit® KC 640/7 is a flexible two-component polymer grout based on polyurethane resin. It is designed for embedding of monolithic or laminated glass panels in U-profiles or concrete joints [16]. It is suitable for indoor and outdoor application. According to the product data sheet [16] the tensile strength is approximately 3.5 MPa, the elongation at break 95% and Shore A-hardness approximately 75. Unlike SikaFast® 5221, Icosit® KC 640/7 is prepared (dosed and mixed) manually before application.

All specimens were manufactured manually. After filling the groove with adhesive the pane was placed in the groove and stabilised. When the adhesives cured the half-beam was reversed and the same procedure was conducted.

Table 1.
Notation system for the beams

Beam type	Adhesive	Groove width [mm]
BA1	Acrylate adhesive (SikaFast® 5221)	12.0
BA2		13.0
BA3		
BS1	Silicone sealant (Sikasil® SG-20)	13.0
BS2		15.0
BS3		
BI1	Polyurethane adhesive (Icosit® KC 640/7)	13.0
BI2		
BI3		15.0
TB1	-	13.0
TB2		
TB3		

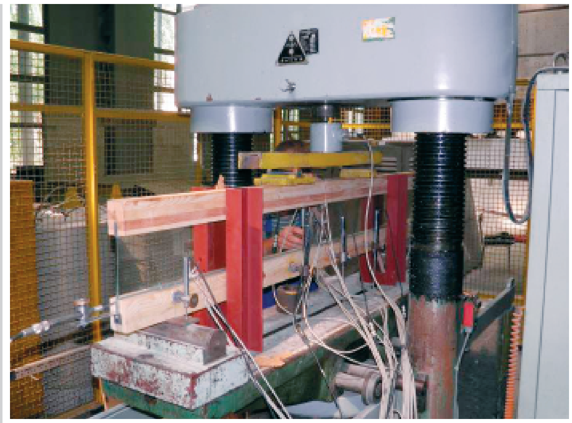

Figure 2.
Experimental set-up of the four-point bending test

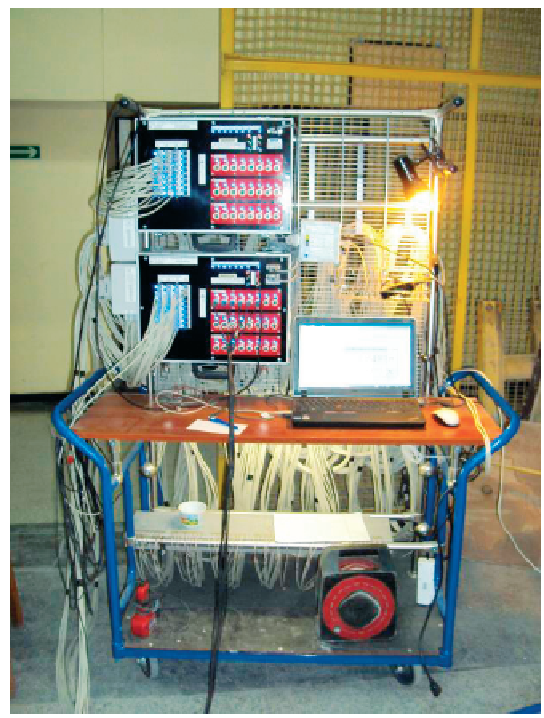

Figure 3.
128-channel signal converter with MLAB 32 software

3.2. Test specimens and test set-up

In this set, nine hybrid beams and three timber flanges were produced and tested. Table 1 presents the notation system of the produced specimens.

All hybrid timber-glass beams were 300 mm high and 1800 mm long. The test set-up was a four-point bending test. The theoretical distance between the supports was 1500 mm when the total beam length was 1800 mm. The forces were introduced symmetrically at 1/3 span through a transitional steel beam. Due to great slenderness of the beam two additional lateral supports were provided at the ends to protect the beam against sloping out of the plane. The tests were performed in a hydraulic testing machine (Fig. 2).

The beams were loaded at constant displacement rate of 2 mm/min. To read the response of the beam to loading a number of detectors were applied to the specimens. To measure deformations six inductive displacement sensors were installed at the mid-span, load introduction points, supports and at half-height of the glass web. Also a set of strain gauges was attached to the substrates.

The readings from all sensors were processed by 128-channel signal converter and the MLAB 32 software (Fig. 3). Subsequently, the data, recorded at every half second, were stored in a PC in a file that could be imported into Microsoft Excel.

In order to check the behaviour under loading and a load-bearing capacity of a timber flange separately a four-point bending tests were performed with three sample beams with the same cross-section and length as used to build hybrid beams. The beams were tested in the same set-up and with identical displacement rate as for hybrid beams, which was described before. To measure deformations an inductive displacement sensor was installed at the mid-span of the timber beam.

3.3. Analytical considerations

Parallel to experimental studies an analytical investigation was carried out. In order to determine the stiffness of the composite beam and stress distribution in components a method known as γ-method, presented in the Annex B of the Eurocode 5 for the design of timber structures, was used [17]. A γ-factor reduces the second component of Huygens-Steiner theorem depending on the connection stiffness. According to [17] the effective bending stiffness is described as:

$$(EI)_{eff} = \sum_{i=1}^{3} \left[E_i I_i n_i + \gamma_i E_i A_i (a_i)^2 n_i \right] \tag{1}$$

According to [17] the γ-factor is expressed as:

$$\gamma_i = \left[1 + \frac{\pi^2 \cdot E_i \cdot A_i \cdot s_i}{K_i \cdot l^2} \right]^{-1} \tag{2}$$

The γ-factor ranges from 0 for non-composite action to 1 for fully composite action (in a case of a rigid connection). According to [17] the γ-factor depends mainly on slip modulus (K_i) and spacing of mechanical connectors (s_i). For continuous adhesive joint the factor was modified by the author to the form:

$$\gamma_i = \left[1 + \frac{\pi^2 \cdot E_i \cdot A_i}{\left(\frac{2 \cdot G \cdot h_{adh}}{t_1} + \frac{G \cdot w_{adh}}{t_2} \right) \cdot l^2} \right]^{-1} \tag{3}$$

E_i, I_i and A_i indicate a modulus of elasticity, moment of inertia and a cross-section area of each component. a_i indicates the distance between the centroid of each component and the centroid of the total I-shaped section. G is a shear modulus of an adhesive and remaining variables are related to dimensions of a bond line. The similar approach was presented by Kreher [7]. Figure 4 shows the notation system for the bond line.

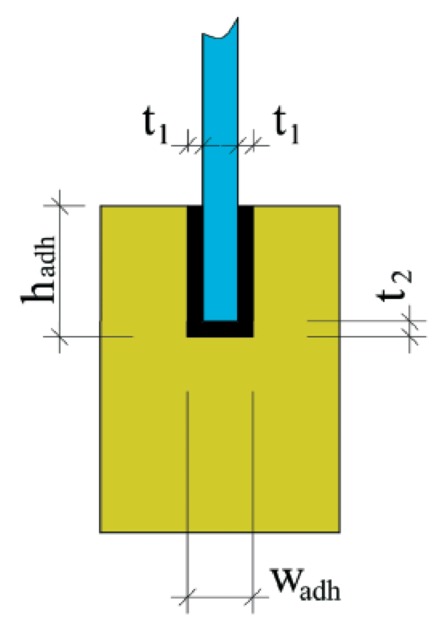

Figure 4.
Notation system for the bond line

3.4. Numerical modelling

Numerical calculations were performed using the ABAQUS Finite Element Analysis software [18]. All components were modeled using solid eight-node block elements (C3D8). In order to reduce the number of elements the symmetry of the model was used, as shown in Figure 5.

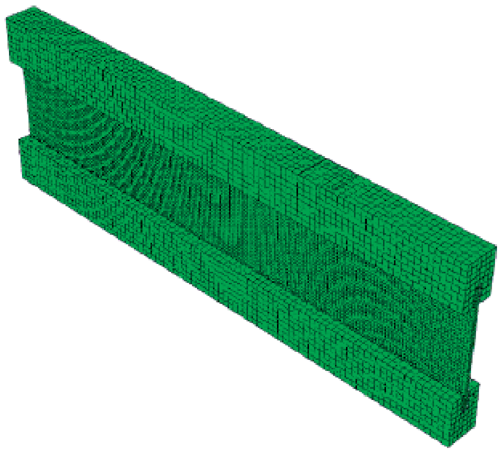

Figure 5.
3D model in the Abaqus Finite Element Analysis software

Calculations were run in displacement control including the nonlinear effects of large deformations. The glass was modeled with linear elastic material properties with E = 70 GPa and ν = 0.23 according to [19]. Modulus of elasticity along the timber fibers was determined based on a four-point bending test of timber beams used for flanges. Other parameters were determined proportionally based on [20] and taken from the literature [21]. The timber was modeled as a linear anisotropic material with the following parameters: $E_1 = 10.5 \cdot 10^9$ N/m^2, $E_2 = E_3 = 0.35 \cdot 10^9$ N/m^2, $G_{12} = G_{13} = 0.66 \cdot 10^9$ N/m^2, $G_{23} = 0.005 \cdot 10^9$ N/m^2, $\nu_{12} = \nu_{13} = 0.54$, $\nu_{23} = 0.027$. The SikaFast® 5221 was modeled with linear elastic material properties with E = 80 MPa and ν = 0.4 according to [15], alike the Sikasil® SG-20 was modeled as a linear elastic incompressible material with properties E = 1.0 MPa and ν = 0.5, according to [14]. Due to lack of knowledge about physical properties of Icosit® KC 640/7 it was not included in numerical modelling investigation.

To model the mechanism of failure of hybrid beams a simplified method of modeling cracks in the glass web was used. The method was used by Blyberg and Serrano [11]. The procedure was to increase a load until the tensile stress in the glass web reached the tensile strength of glass and introduce a vertical crack seam with a length of 150 mm at the point of maximum stress and continue loading until the tensile stress reaches the tensile strength of glass in the next point. The procedure was repeated several times. According to [19], the tensile strength of glass was assumed to be 45 MPa.

4. RESULTS AND DISCUSSION

Figures 6-9 present selected frames from a video in which a four-point bending test of the beam BA2 was recorded. A multistage mechanism of failure was observed. The initial crack formed under the load introduction point, the second crack formed symmetrically in relation to the first crack. Right after the third crack occurred the total failure of the beam was observed. It was caused by a timber flange failure. Unlike the beams bonded with acrylic adhesive the beams bonded with silicone sealant and polymer grout based on polyurethane resin presented a different mechanism of failure. The initial crack formed between the load introduction points.

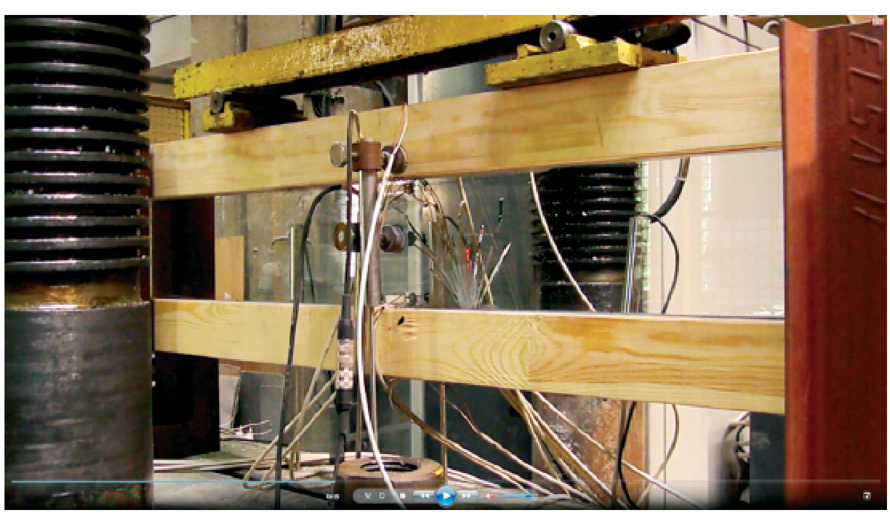

Figure 6.
Initial failure (first crack) of the glass web under the load introduction point

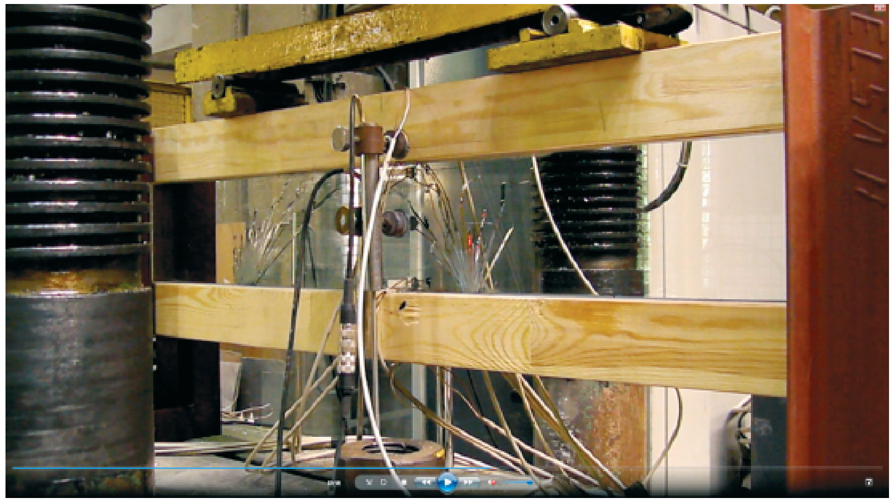

Figure 7.
Second crack was formed symmetrically to the first crack

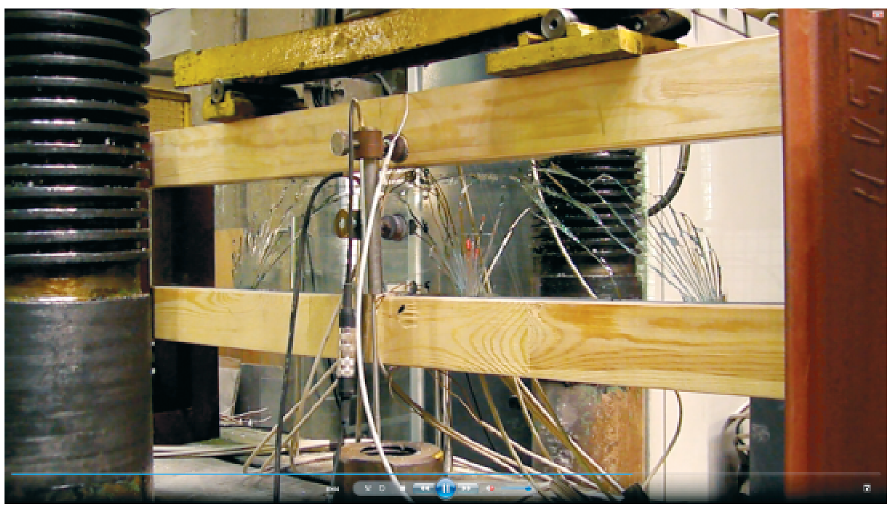

Figure 8.
Successive failure of the glass web

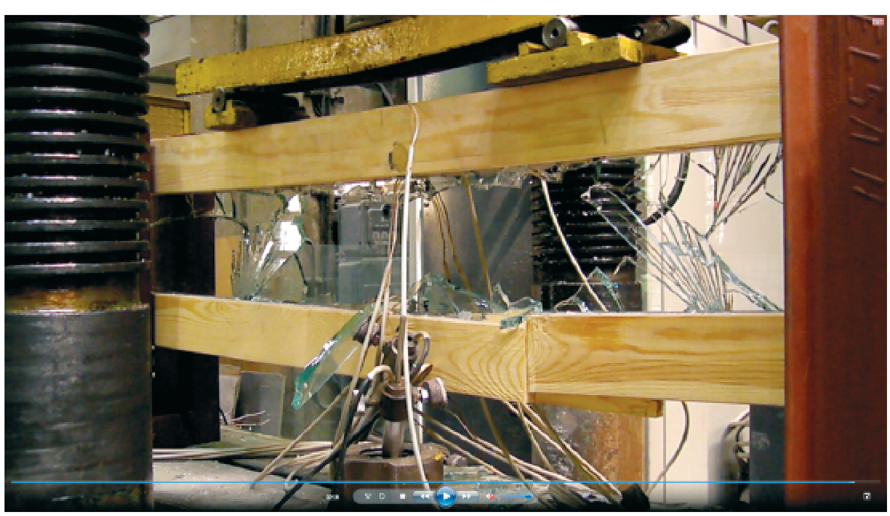

Figure 9.
Total failure of the beam BA2 caused by explosion of compressive zone and failure of bottom flange

For most beams, the load at which initial crack formed was much lower than the maximum load. Before the total failure of the beam several cracks were observed. Table 2 presents the loads at initial crack, maximum load and the increase of value of the load at initial crack for tested hybrid beams.

Table 2.
Values of loads for the tested hybrid beams

Beam	Load at first crack [kN]	Maximum load [kN]	Increase [%]
BA1	26.4	66.2	150
BA2	29.3	43.6	50
BA3	26.4	46.7	75
BS1	12.7	25.1	100
BS2	12.6	34.1	170
BS3	9.6	15.1	60
BI1	11.1	18.7	65
BI2	12.5	18.1	45
BI3	10.3	12.0	20

The highest load-bearing capacity, with respect to the initial crack, was achieved by the beam BA1-3 bonded with a stiff adhesive. The beams BS1-3 and BI1-2 bonded with softer adhesive reached almost the half of the value. A load at first crack for the beam BS3 differed from values for beam BS1-2. Detailed studies of the readings from strain gauges revealed a difference of 50% in the strains on the right and left side of the web of the beam BS3. Probably geometrical imperfections during production process or a fact that the force was introduced to the beam with an eccentricity caused the lateral buckling failure of the beam BS3.

Table 3.
Values of maximum loads for the tested timber flanges

Beam	Maximum load [kN]
TB1	7.98
TB2	8.21
TB3	8.16
–	$F_{average}$ = 8.12

Table 3 presents the maximum loads for three tested timber beams. All the beams behaved almost linearly elastic under loading until collapse. The sudden failure was caused by the failure of finger joints placed on tensile side of the beams. The average value of the modulus of elasticity along the fibers was determined as 10.5 GPa.

Figure 10 illustrates force versus mid-span displacement curves of the beams BA1-3, BS1-3 and BI1-3. The beams under the load presented a multi-stage mechanism of failure. In the first stage the relationship between the load and vertical mid-span displacement is almost perfectly linear until the initial crack formation. This is followed by a sudden drop of bending stiffness and an increase of vertical displacement. After an initial failure of glass a bottom flange acts as a crack bridge which together with a non-cracked compression zone of the web and top flange allows the beam to still carry the load. In the next stage the existing crack grows and next cracks form in another part of the web. Despite the failure of the glass web the beam can still carry load until the total collapse which is usually caused by an explosion of the compression zone of the glass web and a failure of the bottom flange, what can be seen in Figures 6-9.

Figure 10 shows also an average force versus mid-span displacement curve of timber flanges TB1-3 and derived analytically load bearing strength of a pure glass beam with the same cross-section and length as used for webs of hybrid beams. The average curve for three beams was shown to keep the clarity of the figure. All the timber beams failed suddenly at the average load of 8.12 kN and at the average displacement of 29.1 mm. In all cases the rapid collapse was caused by a finger joint failure. Likewise the timber flanges the pure glass beam failed suddenly at a load of 4.8 kN and at displacement of 1.44 mm.

As shown in Figure 10 beams BA1-3 bonded with an acrylic adhesive present significant stiffness and load-bearing capacity. Beams bonded with more soft adhesives (BS1-3 and BI1-3) present lower stiffness, but they allow for much greater deformations. The results for the beams bonded with polymer grout based on polyurethane resin (BI1-3) are unreliable since great spread of behaviour was observed. Additionally, the Icosit® KC 640/7 resin, in contrast to the other two adhesives, was prepared and mixed manually, which probably resulted in a variety of mechanical properties. Therefore, the resin was excluded from further analysis.

Figures 11 and 12 present a comparison between the results from testing and obtained from FEM analysis for beams BA1-3 and BS1-3. The results from FEM analysis slightly overestimate the results from experiments until the initial crack. To this point an elastic behavior can be observed. Subsequent occurrence of cracks decreases the stiffness but the slopes of the

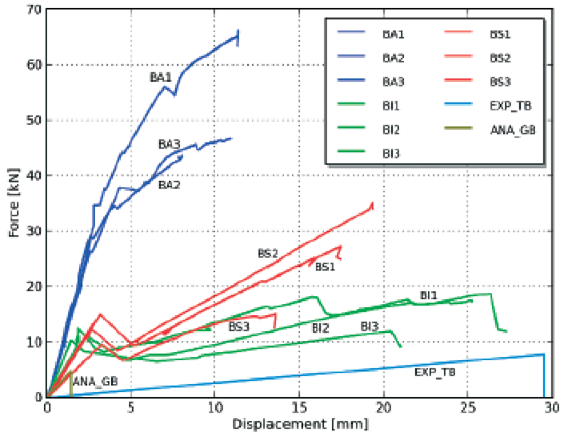

Figure 10.
Force versus mid-span displacement curves of tested hybrid beams, timber flanges and a pure glass web determined analytically

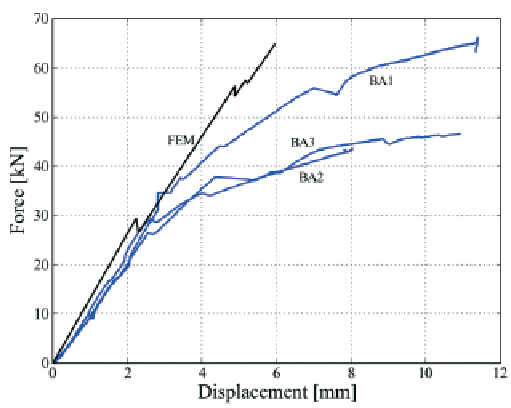

Figure 11.
Force versus mid-span displacement curves of beams BA1-3 in comparison to results obtained from FEM analysis

curves considerably differ from these observed in four-point bending tests. However, the slope of the FEM curve in Figure 12, in the phase when the glass web is cracked, is similar to that observed in the experimental study.

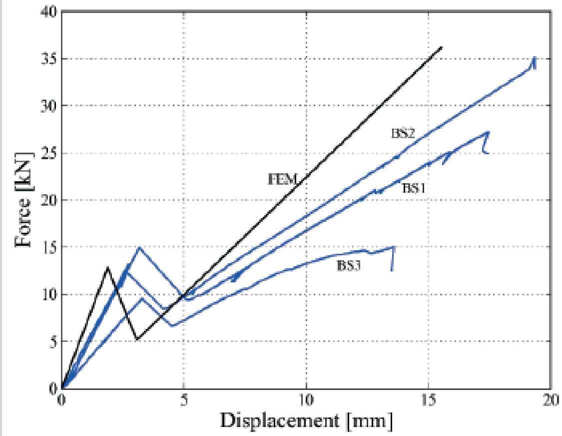

Figure 12.
Force versus midspan displacement curves of beams BS1-3 in comparison to results obtained from FEM analysis

Table 4 presents the comparison of the loads at initial crack obtained from experiments, numerical analysis and analytical considerations for beams BA and BS.

In general, the numerical and analytical analysis overestimates the experimental results. It can be noticed that the load at the initial crack obtained from numerical models do not differ more than 8% for beams BA and 3% for beams BS in comparison to experiments. It is probably caused by the assumptions for mechanical properties of glass and adhesives. It can also be seen that analytical approximation for the load at which the glass web fails is 8% for beams BA and 16% for beams BS if compared with the load based on experiments. In the Table 4 the γ-factors can be found. The beams with the bond line based on acrylate adhesive acts as almost fully composite (γ = 0.95), unlike the beams bonded with silicone sealant whose behaviour is closer to non-composite action (γ = 0.22). This result points out the applicability of the modified γ-method for estimation a load causing an initial failure of the glass web.

Table 4.
Values of loads at initial (first) crack for beams bonded with acrylic adhesive and silicone sealant (linear elastic range)

Beam	Experimental (average value)	Numerical		Analytical	
	F_{exp} [kN]	F_{num} [kN]	Δ_{num} [%]	F_{anal} [kN]	Δ_{anal} [%]
BA (acrylic adhesive)	27.37	29.4	7.4	29.6 (γ = 0.95)	8.1
BS* (silicone sealant)	12.65	13.0	2.7	14.7 (γ = 0.22)	16.2

* The experimental result for the beam BS3 was excluded (explanation in the text)

5. CONCLUSIONS

This paper presents the results of experimental and numerical investigation on hybrid I-shaped beams made of ordinary annealed glass and timber flanges, bonded with three types of adhesives with different stiffness. Based on a qualitative research with a limited number of specimens the following main conclusions are drawn:

1. Experimental studies on hybrid timber-glass beams show that the beams are able to withstand a much higher load than the load that causes initial failure of a glass web. The post-breakage strength relates to an increased value of a load at a total collapse of a beam in relation to a load at which first crack in the web occurs. The combination of a single pane web, made of ordinary annealed float glass, and timber flanges provides ductility and a warning signal relatively long before the total collapse. It gives time to temporarily support the element before the replacement and ensures the safety of users. The idea of the post-breakage strength and the ductility ratio is shown in Figure 13.

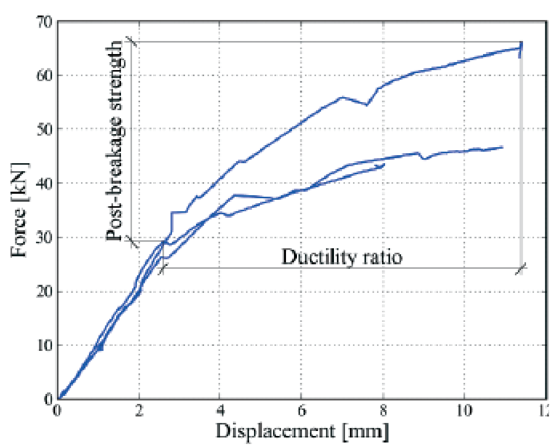

Figure 13.
The idea of post-breakage strength and ductility ratio based on experimental test of beams BA1-3

2. The results from experiments of hybrid timber-glass beams compared with testing of the timber flanges and pure glass beam proves the synergistic feature of the hybrid beams. The maximal load obtained by beams bonded with acrylate adhesive is much higher than a sum of maximum loads taken by two timber flanges and the glass beam. In the case of hybrid timber-glass beams the timber provides the ductility and the glass resistance and stiffness. Regarding hybrid beams bonded with silicone sealant and polymer based on polyurethane resin the synergistic feature was not observed. However, these beams allowed for much greater deformations before the total collapse.
3. Regarding the initial stiffness, post-breakage residual strength and maximal load hybrid beams bonded with stiff adhesive presented much better behaviour than corresponding beams bonded with softer adhesives. Beams BA1-3, bonded with acrylate adhesive, were much stiffer in the elastic phase and reached almost double load before total failure (high post-breakage, relatively low ductility ratio). However, beams BS1-3, bonded with silicone sealant, although characterised with lower stiffness and post-breakage strength, allowed for much greater deformations (high ductility ratio, relatively low post-breakage strength). The ratio of the force at the total collapse to the force at the first crack can be identified with a global safety factor (GSF) for hybrid timber-glass beams. The mean GSF for beams BA1-3 was 1.91 and for beams BS1-3 was 2.12.
4. The comparison of loads causing an initial failure in glass web from experiments to the loads obtained from analytical consideration based on the modified γ-method shows that it can be adapted to estimate the force at which the first crack in the glass web occurs. However, it requires more detailed investigation and improvement regarding accurate determination the level of co-operation between the web and flanges bonded with elastic line connections.
5. The numerical models, presented in this article, correctly simulate only the linear elastic behaviour of the hybrid timber-glass beams. The simplified method of modelling cracks in the glass web involving introduction of vertical crack seems not to work for simulating the post-breakage behaviour; it must be modelled with other methods. Therefore, the Extended Finite Element Method (XFEM) and other approaches, for which the fracture mechanics of glass will have to be considered, would be of interest.

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