Challenging Glass 5 – Conference on Architectural and Structural Applications of Glass
Belis, Bos & Louter (Eds.), Ghent University, June 2016.
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ISBN 978-90-825-2680-6

The Effect of Adhesive Joints on the Performance of Hybrid Steel-Glass Beams – An Analytical and Experimental Study

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The aim of the present paper is a preliminary assessment and critical discussion of full-scale experimental test results recently obtained for hybrid steel-glass beams composed of a laminated glass web and steel flanges, based on the analytical Möhler method. As known, the structural response of this typology of hybrid solutions markedly depends on the stiffness and resistance of all its components, and specifically the connection, which act as a flexible shear bonding layer between the glass web and the steel flanges. Therefore, the appropriate mechanical calibration of the component materials is mandatory for accurate calculations. In order to fully characterize the used adhesive, push-out shear tests and simple shear tests were performed on small specimens. The results obtained from these small specimens are then implemented as main input mechanical parameters for the analytical model, so that this latter could be applied to the full-scale tests in view of comparative analyses. As shown, due to accurate estimation of the main mechanical properties of the adhesive layers, the presented analytical method provides rather accurate results for the examined full-scale hybrid beams, hence suggesting its application for practical calculations and pre-design considerations.

Keywords: Hybrid Steel-Glass beams, Adhesive, Push-Out shear test, Simple shear test, Möhler method

1. Introduction

The recent demand for transparency has drastically increased the use of glass as a structural material due to its synergistic and aesthetic potentialities. Nevertheless, it is still regarded as an unsafe structural material because of its brittle nature and limited tensile resistance. This is being slowly overcome with significant technological developments like the tempering and lamination process and by combining glass with other ductile materials in order to achieve an extra level of structural redundancy. Glass has now an unavoidable presence in most of the architectural reference buildings, having made an enormous leap to a material that combines structural and cladding roles.

The structural capacity of glass elements can be enhanced by means of several typologies of reinforcing techniques. Among these possibilities, the novel concept of hybrid steel-glass beams consists in using an adhesive bonding layer to assemble a traditional glass web and steel flanges. The final result is a composite cross section in which the steel flanges allow to increase the load carrying capacity, lateral stability, ductility, as well as to achieve a certain level of redundancy, compared to the original glass section only. The research study presented in this paper is within the framework of *S-Glass* project (Jordão et al (2015)), aiming at characterizing the behaviour of hybrid I-shaped steel-glass beams. An assessment of four-point bending experiments carried out on two series of simple hybrid steel-glass beams is proposed, based on the Möhler analytical method. In doing so, the accurate mechanical calibration of its input parameters is carried out on the based of small-scale tests performed to assess the main properties of the adhesive. All the tasks were developed at the Civil Engineering Department, University of Coimbra.

2. State of the art

The structural behaviour of a hybrid beam depends to a large extent on the effectiveness of the connection between its components. In fact, it is well-known that when the section components are rigidly connected, no relative displacements can occur between steel and glass and normal forces at the flange have a high contribution on the load transmission. When the section components are bonded by means of a flexible joint, conversely, the web and the flanges behave individually, resulting in large relative displacements and a small global resistance of the assembled resisting section. The behaviour of hybrid beams lays between these two limit configurations. The adhesive allows in fact the applied external moment to be distributed into internal moments, both in the steel flanges and in the glass web, and normal forces on the flanges. In terms of deformability of the so assembled section, relative displacements between the glass web and the steel flange can also occur, see Fig. 1.

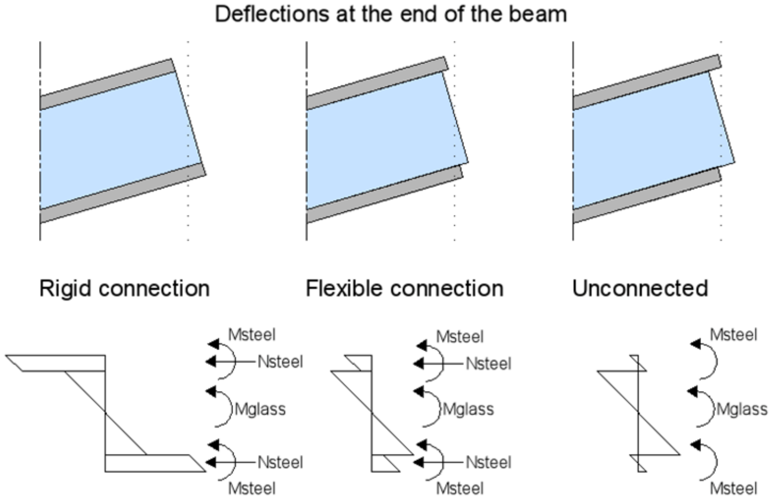


Fig. 1 Load bearing behaviour depending on joint flexibility (adapted from Feldmann et al (2010)).

From a practical point of view, the steel flanges could never achieve a major influence on the load bearing capacity of a fully hybrid assembly, since the normal forces are transmitted through the bonded joints. The stiffness of these joints can be described in the form of an "effective stiffness", which directly depends on the shear modulus of the adhesive (*G*), the bonding thickness (*d*) and its width (*b*). **Error! Reference source not found.** illustrates the geometry of different types of bonded connections of practical use. In the current research project, hybrid beams with a simple joint usually known as butt splice bonding were considered (Figure 2a)).

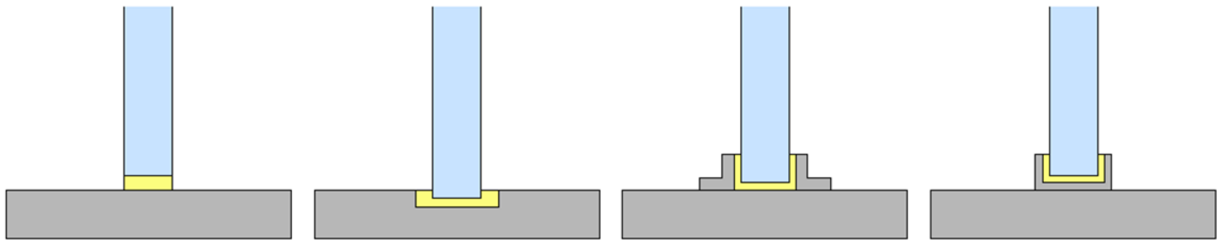


Fig. 2 Join details for different typologies of bonded connections, in accordance with Feldmann et al (2010) a) Butt splice bonding b) Channel bonding in a groove c) Bonding with "U" profiles d) Bonding with "L" profiles

As long as the connection between the assembled components can be considered fully rigid, the calculation of stress and displacements is rather ordinary, having an exact analytical solution established within the basic theories of strength of materials. This is not the case of hybrid steel-glass beams, typically representative of flexible composite assemblies, in which the effect of the adhesive layers on the structural behaviour of the systems should be properly incorporated, and specific formulations should be taken into account.

2.1. Available analytical models for composite beams

Different analytical models for composite beams are available in literature and can be used for the design of hybrid beams. The most usual is the method developed by Karl Möhler, the so called γ-method (Möhler (1956)). The Möhler method, although originally proposed for timber structures, can be applied to hybrid beams in general, once the mechanical properties of the structural components (e.g. steel, glass and adhesives, in this specific project) are known. The main advantage of this method is that the flexibility of the interposed joints can be rationally taken into account by means of an effective moment of inertia with reduced contribution of the flanges. The analytical solution of this approach is exact only for a sinusoidal load, due to the working assumptions of the method (e.g. congruence between the distribution of external moments, internal moments and displacements).

Despite that, several analytical and experimental comparative studies already highlighted that the Möhler method is suitable for the pre-design of flexible composite beams, even under different load distributions. In Feldmann et al (2010), for example, a maximum difference of -4% was found, in terms of load carrying capacity, between the predictions given by the Möhler method and the experimental values for hybrid beams with a small glass-to-steel ratio area.

On the other hand, the use of this analytical model requires accurate estimation of its input parameters. The main limit is represented by the mechanical behaviour the method assumes for the bonding adhesive (e.g. linear elastic constitutive law), while the majority of adhesives behave nonlinearly. To overcome this drawback, a linear stiffness of best fit should be used for analytical calculations.

Assuming a direct connection between the steel flanges and the glass web, the average elastic stiffness of the connection, *K,* can be rationally calculated by means of Eq.(1), where *G* is the shear modulus of the used adhesive, *b* is the width and *t* is the thickness of the layer, see Fig. 3:

$$K = G * \frac{b}{d} \tag{1}$$

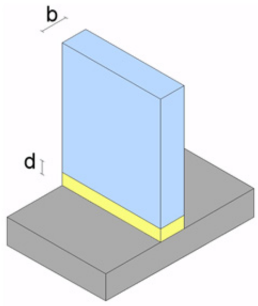


Fig. 3 Details of direct bonded connection between a web and a flange (Feldmann et al (2010)).

The efficiency factor γ and the effective moment of inertia $I_{y,eff}$ of the double symmetric cross section are given by:

$$\gamma = \frac{1}{1+k} \tag{2}$$

$$I_{y,eff} = 2I_{y,steel} + nI_{y,glass} + 2\gamma A_s z_{c,s}^2, \tag{3}$$

where

$$k = \frac{\pi^2 * E_S * A_S}{l^2 * K} \tag{4}$$

$$n = \frac{E_g}{E_s} \tag{5}$$

In Eqs. (3) to (5), E_s and E_g are the Young's modulus of steel and glass respectively, A_s is the area of the steel flange, *l* is the span of the beam; $I_{y,steel}$ and $I_{y,glass}$ denote the moment of inertia of the steel flange and the glass web; finally, z_s, is the distance between the middle axis of the steel flange and composite cross section.

The values of the normal stress distribution along the cross section depicted in Fig. 4 can be obtained from the following expressions:

$$\sigma_{e,steel} = \pm \frac{M_{y,Ed}}{I_{y,eff}} * (\gamma * z_{c,s} + \frac{t_s}{2}) \tag{6}$$

$$\sigma_{c,steel} = \pm \frac{M_{y,Ed}}{I_{y,eff}} * \gamma * z_{c,s} \tag{7}$$

$$\sigma_{e,glass} = \pm \frac{M_{y,Ed}}{I_{y,eff}} * \frac{h_g}{2} * n, \tag{8}$$

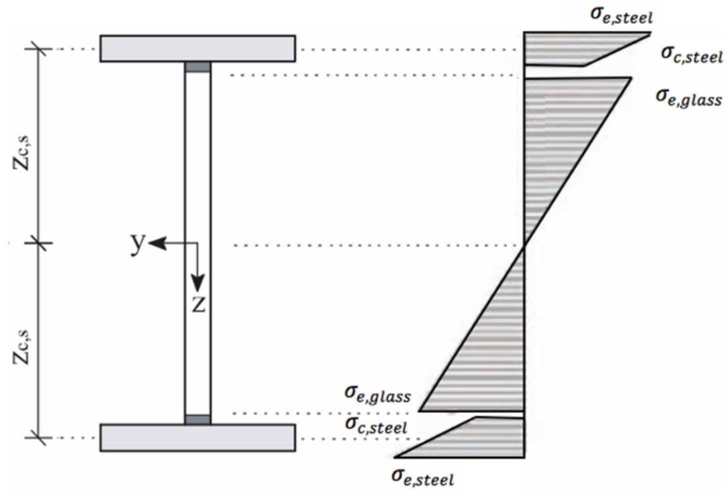


Fig. 4 Normal stress distribution along the cross section of hybrid beam.

where $M_{y,Ed}$ is the bending moment due by the external load, t_s is the thickness of the steel flange and h_g is the total height of the glass web. The average shear stress in the adhesive layer can be then calculated by means of Eq.(9), where V_{Ed} is the shear force due by the external load.

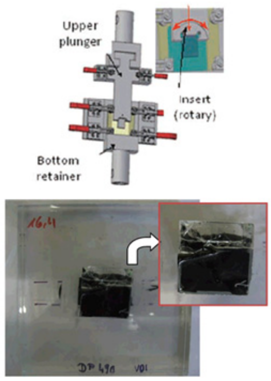
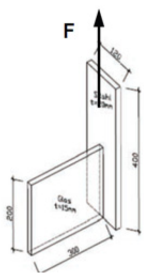
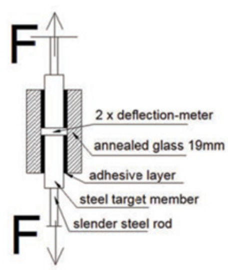
$$\tau = \frac{V_{Ed} * \gamma * z_{c,s} * A_S}{I_{y,eff} * b} \tag{9}$$

2.2. Adhesives connections in hybrid steel-glass applications

Past literature studies showed that the load bearing performance of a hybrid beam significantly depend on the stiffness and resistance of the connection (Ungermann and Preckwinkel (2010) and Netusil (2011)). Since the bonded joint will mainly work as a semi-rigid horizontal shear connector between the glass web and the steel flanges, in terms of an analytical or a numerical simulation of a hybrid element, it is of the utmost importance to characterize the behaviour of the adhesive layer when subjected to shear. Therefore, aiming at that, specific small-scale shear tests have been performed based on similar investigations (Feldmann et al (2010)).

Within the *Innoglast* project, after the selection of some adhesives, uniaxial tension tests were performed in small-scale test specimens, in order to estimate some basic mechanical properties like the Young's modulus and the Poisson's ratio. The obtained stress-strain curves were not enough to characterize the adhesive due to the fact that, in the majority of the applications, the adhesive layer is subjected to shear. In order to have a complete knowledge of the adhesive behaviour, new tests were performed. The *Innoglast* final report (Feldmann et al (2010)) made reference to four different test setups, where only two of them are standardized, see Table 1.

Table 1: Tests performed during the Innoglast project to characterize the shear behaviour of the adhesives (adapted from Feldmann et al (2010)).

Single lap shear test (EN 1465 and EN 14869-2)	Block shear test (EN ISO 13445)	Push-Out shear test	Steel-glass shear connection test
			

Several adhesive typologies are currently produced by manufacturers and available on the market for structural glass applications and steel - glass connections. According to Feldmann et al (2010), these adhesives can be classified in flexible-elastic (i.e. silicones, modified silicones and polyurethanes) or rigid (i.e. epoxy resin, acrylates) types, depending on their modulus of elasticity and shear modulus. In any case, the selection of the most suitable adhesive to be used in the joint is not straightforward, in the sense that the bonded joint must be rigid enough to provide an optimal structural interaction between web and flanges to maximize stiffness and resistance, but, on the other hand, it has to be flexible enough to redistribute stress peaks in critical points and to mitigate the effects of different temperature elongation of steel and glass. Besides the pure structural aspects, other factors have to be taken in account when selecting an adhesive, like the resistance to temperature, UV or even the colour. Finally, the thickness of the adhesive is also conditioned by the geometrical imperfections of the surfaces to be bonded since these must be completely filled so that no voids are created. The major challenge of the connection design is to find the ideal adhesive thickness, which fulfils all the requirements above. In the case of the tests reported, the polyurethane Sikaforce 7710 L100 + 7010 was the selected adhesive to make the adhesive bond.

3. Full-scale tests on hybrid steel-glass beams

3.1. Layout and geometry

Full-scale bending tests were carried out to characterize the structural behaviour of laminated full-scale hybrid-beams reinforced on a four-point bending (4PB) test setup, see Fig. 5. Each beam was simply supported and laterally restrained at four different locations. Laminated glass webs were composed of two 10 mm annealed glass layers and a 1.52 mm SentryGlas® Plus (SGP) bonding film, while the steel flanges were made of S275 steel, see the cross-sectional detail in Fig. 5.

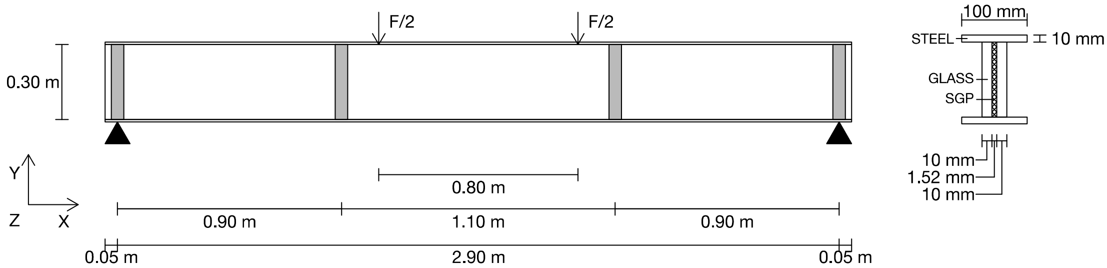
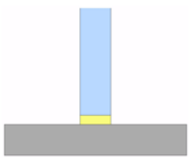


Fig. 5 Test setup and reference geometry for the tested full-scale hybrid beams (front-view and transversal cross-section).

Table 2: Specimens for full-scale tests

# Specimen	Joint	Adhesive thickness [mm]	Steel flanges type / cross-section [mm^2]	Glass web type / cross-section [mm^2]	Test
HB1		0.1	S275 100 × 10	Annealed glass (2×300) × 10	Monotonic short time
HB2		1.5			

3.2. Measurements and loading strategy

During the 4PB tests, different measurements were made in order to fully characterize the behaviour of the hybrid beams. Several displacement transducers and strain gauges were applied on the steel flanges and at both the sides of the glass web. Fig. 6 presents the full layout of strain gauges and displacement transducers. In this manner, the stress state and deformation behaviour of the tested hybrid beams were accurately described, as well any possible out of plane deformation due to misalignments and/or instability and the alignment / symmetry of the test layout were properly assessed. Additional information about the shear behaviour of the adhesive joints was also obtained, during the experiments, by measuring the deflections at the steel-glass interface.

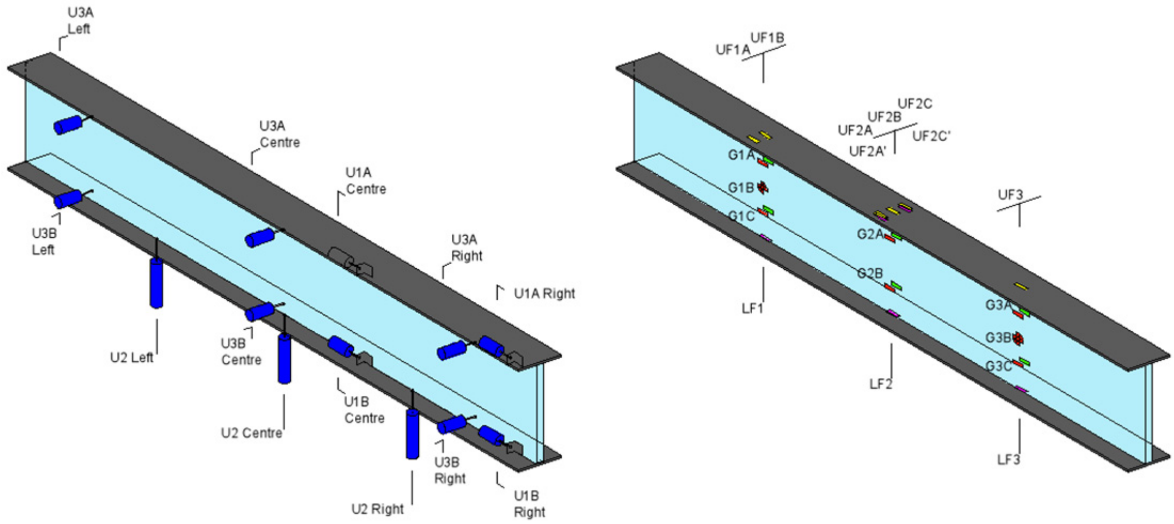


Fig. 6 Location of the displacement transducers (left) and the strain gauges (right) for the full-scale 4PB experiments – axonometry.

3.3. Optimization of the structural scheme

An attempt to optimize the dimensions of the hybrid beam cross-section was first carried out, based on the Möhler method. As mentioned above, the stiffness of the hybrid beam is closely related to the efficiency factor γ. In this sense, it can be obviously deducted that a higher resistance of the composite section is achieved with a greater degree of connection. However, this typology of hybrid beams is usually characterized by the presence of a flexible joint, so that the actual structural behaviour of the hybrid system is far from a rigid connection. Since the composite behaviour of the cross section depends not only on the properties of the materials involved, but also on the geometry adopted for them, it has become necessary to perform a simple parametric study of some parameters such as the thickness of the adhesive and the area of steel flanges to assess their impact in the connection degree. During the experimental campaign as it was always considered the same glass type with the same features and geometry, a total height of 300 mm and two float glass panels of 10 mm thickness, joined by a 1.52 mm thick SGP layer, the glass variables were subsequently pre-set in order to optimize the other parameters in study.

3.3.1. Ideal thickness of the adhesive

To find the ideal thickness of the adhesive, the dimensions of the steel flanges were necessarily set first. As a result, the nominal geometry of the 4PB full-scale tests was taken into account (A_s= 100 × 10 mm^2). To calculate the efficiency factor γ, the mechanical properties of the adhesive joint were then estimated. As in the case of the full-scale tests, the same adhesive width *b*= 21.52 mm was considered. The small-scale shear tests were then used to define the shear modulus *G* of the adhesive, which was set equal to 13 MPa for the analytical calculations (see Section 4). The adhesive thickness *d,* as a function of γ was finally estimated as:

$$\gamma = \frac{1}{1+\frac{\pi^2 * E_S * A_S}{l^2 * G * \frac{b}{d}}} = \frac{1}{1+\frac{\pi^2 * 210000 * (100*10)}{2900^2 * 13 * \frac{21,52}{d}}} \Leftrightarrow d = 1,13465\left(\frac{1}{\gamma} - 1\right) \qquad (12)$$

where *l* denotes the total length of the continuous adhesive joint and E_s= 210 GPa for steel.

Table 3: Variation of the ideal thickness *d* of the adhesive joint, as a function of the efficiency factor γ (Eq. (12)).

γ	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
d [mm]	-	10.212	4.539	2.648	1.702	1.135	0.756	0.486	0.284	0.126	0

By analysing Table 3, it is possible to notice that as the efficiency factor γ increases, there is a reduction on the corresponding adhesive thickness *d*. Theoretically, in presence of a fully rigid connection, the interaction between the flange and the web would be perfect in absence of any adhesive joint (*d* = 0). For the adhesive thickness in use at the time of 4PB tests (*d*= 1.5 mm), an efficiency factor γ ≈ 0.45 is expected.

3.3.2. Optimization of the steel flanges geometry

As a secondary step of the optimization approach, in order to maximize the load bearing capacity of the examined hybrid beams, further analytical calculations were carried out in accordance with Section 3.3.1. In this latter case, the same geometrical and mechanical properties of the glass flange and the adhesive joint were considered, with *d*=

1.5 mm, the final adhesive thickness. The correlation between the efficiency factor γ and the cross-sectional area A_s of the steel flanges was thus established as (see Table 4):

$$\gamma = \frac{1}{1+\frac{\pi^2 * E_S * A_S}{l^2 * G * \frac{b}{d}}} = \frac{1}{1+\frac{\pi^2 * 210000 * (A_S)}{2900^2 * 13 * \frac{21,52}{1,5}}} \Leftrightarrow A_s = 756{,}78291\left(\frac{1}{\gamma} - 1\right) \quad (13)$$

Table 4: Variation of the ideal cross-sectional area A_s of the steel flanges, as a function of the efficiency factor γ of the adhesive joint (Eq. (13)).

γ	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
A_s [mm^2]	-	6811.05	3027.13	1765.83	1135.17	756.78	504.52	324.336	189.196	84.087	0

As expected, to keep the same bending stiffness of the composite section, when the efficiency factor γ decreases from the state of a fully rigid connection ($\gamma = 1$), a greater steel area A_s is required to compensate the adhesive joint flexibility. As it increases, since the normal forces are introduced in the flanges through the adhesive joint, the bending stiffness tends to decrease. Hence, to preserve the same load carrying capacity it is necessary to increase the area of the steel section.

By establishing some relations between the steel flanges dimensions, it was also possible to assess the width that maximizes the bending stiffness of the hybrid beam for each efficiency factor γ, see Table 5. It is possible to notice that to keep the same bending resistance, by increasing the thickness-breadth ratio, the optimum width decreases. This is mainly due to the fact that the same inertia is being placed furthest from section's centre of gravity. However, high thickness-to-width proportions should be avoided because they would reduce the lateral stability of the beam.

Table 5: Optimization of the steel flanges width, according to the efficiency factor γ of the adhesive joint.

Thickness-to-width ratio	Optimal width of the steel flange		
	γ= 0.4	**γ**= 0.5	**γ**= 0.6
1/20	150.68	123.03	100.45
1/10	106.54	86.99	71.03
1/8	95.30	77.81	63.53
1/4	67.38	55.02	44.92
1/2	47.65	38.90	31.77

4. Push-out shear tests on small adhesive specimens

4.1. Geometry of the specimens

The test arrangement was based on the push-out shear experiments performed during the past *Innoglast* project, where a small steel plate was bonded to a glass piece. The dimensions of the adhesive layer were the same of the full-scale 4PB tests, with a total thickness of 1.5 mm, see Fig. 7. Accordingly, the assembly and bonding of the small-scale specimens was performed by fully reproducing the same conditions of the hybrid beams. In both cases, the adhesive cure was developed in 8 days. Two specimens with identical geometrical properties were tested (TS1 and TS2, in the following).

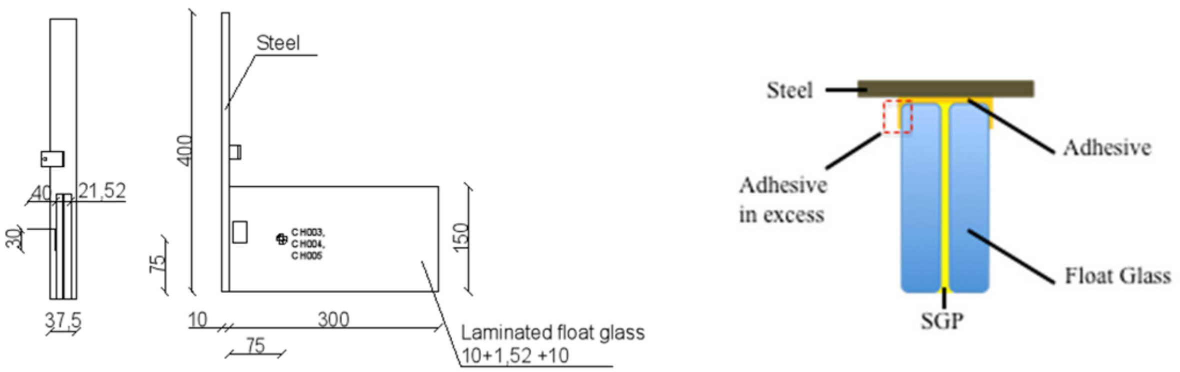
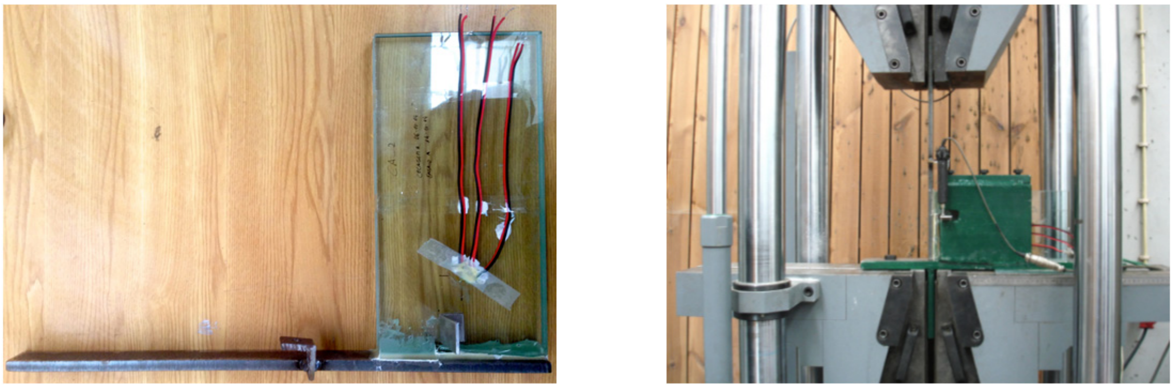


Fig. 7 Push-out shear test layout, nominal dimensions in millimeters.



a) b)

Fig. 8 Push-Out shear test a) test specimen (front view) b) test set up (lateral view).

4.2. Test setup and methods

The shear test specimens were designed as one-side adhesive joints, in order to directly measure the relative displacement between the steel and glass due to shear and tension. So, to evaluate the relative displacement in the adhesive layer, a displacement transducer was placed at half the total height of glass. At mid-height and 1/4 of the length of the glass specimen, strain gauges were also placed in order to accurately assess the stress state in glass. All the specimens were vertically orientated and placed inside a steel frame, which was responsible for restraining any lateral movement of the glass web (see Fig. 9). All the tests were carried out in displacement control conditions, with a load speed of 1 mm/min, see also (Firmo (2015)).

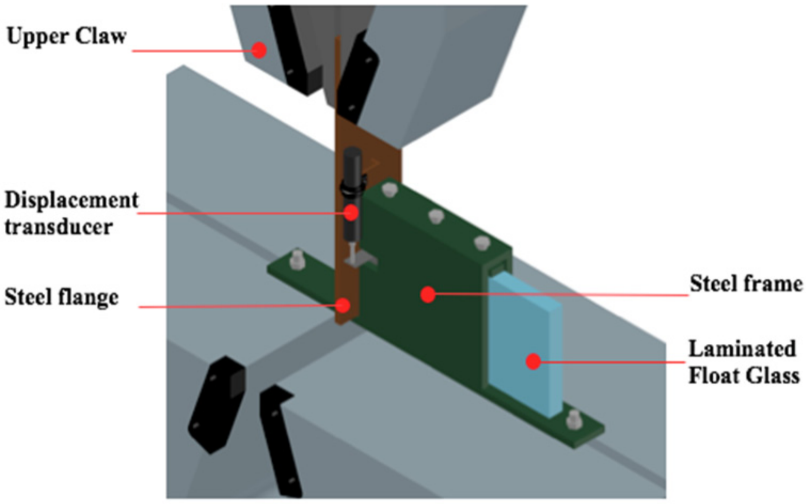


Fig. 9 Push-out shear test setup, detail (axonometry).

4.3. Results

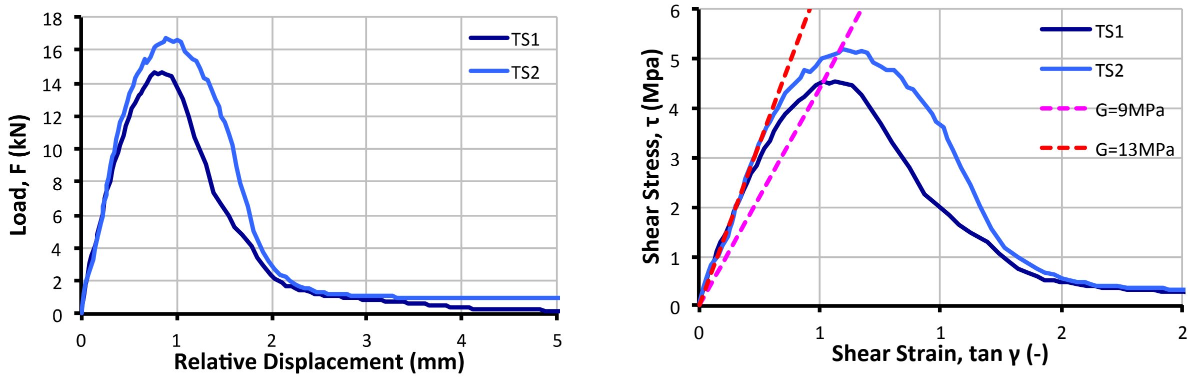
Fig. 10(a) shows the results in terms of load vs relative displacement between glass and steel. The discrepancy between TS1 and TS2 results might be explained by the small differences in the bonded area between the test specimens (e.g. due to the adhesive in excess on the lateral surface of glass). Since the connection relied exclusively on the shear strength of the adhesive layer, after the maximum load was attained there was a complete loss of stiffness, which corresponds to the instant of full detachment of the specimen from its support.

In order to obtain the shear stress and the corresponding distortion, a linear distribution of stress was considered in the bonded joint. This simplification was already performed in other studies (Netusil 2011), and it consists in assuming the bonded joint as an interlayer where its stiffness in the normal direction is different from the directions subjected to shear. Knowing the geometry of the adhesive layer and the load applied during the test, it was possible to calculate the corresponding shear stress. Analogously, based on the measurement of the slippage between the two materials, it was possible to find the distortion measured by the angle γ and the adhesive shear modulus G:

$$\gamma = arctan\left(\frac{v}{d}\right) \tag{10}$$

$$G = \frac{\tau}{tan\,\gamma} \tag{11}$$

The behaviour in terms of shear stress versus shear strain is depicted in Fig. 10b. As shown, the *G* value that best fits the tangent shear modulus of the adhesive (e.g. the value that should be considered in the Möhler method) is equal to ~13 MPa, which is within an acceptable range of values for this type of polyurethane. In the further comparisons, the obtained secant shear modulus was also considered obtained, e.g. 9MPa.



a) b)

Fig. 10 Push-out shear tests results. a) Load vs relative displacement and b) shear stress vs shear strain

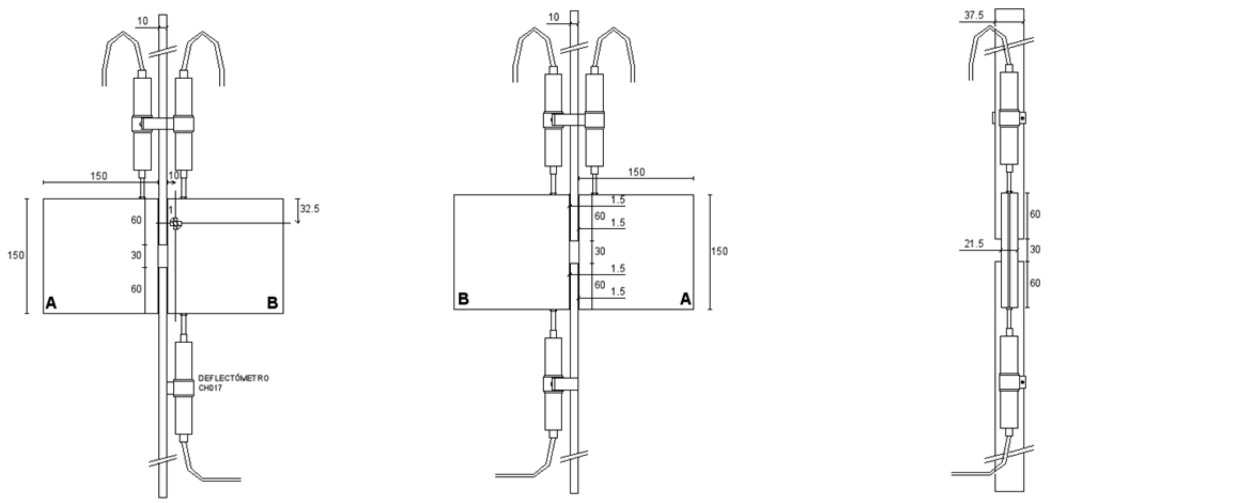
5. Simple shear tests

5.1. Layout, Geometry, Measurements and Load Strategy

Based on the steel-glass shear connection test performed in the *Innoglast* project, two simple shear tests were also performed on small adhesive specimens, to assess their behaviour when subjected to shear loads only. The test specimens were made of two metallic pieces connected by two laminated float glasses. The glue consisted of a 1.5 mm thick layer and has cured in the same time as the adhesive used in the full-scale test experiments, 8 days.

In order to assess the slippage on the steel-glass interface, two displacement transducers were placed at the top of each glass specimen. To evaluate the symmetry of the system an additional deflectometer was positioned at the bottom of the right glass sample. Multiple strain gauges were also considered to assess the glass stress state throughout the test, see Fig. 11.

The specimens were orientated vertically and placed in position. The lower claw of the universal testing machine fixed one of the steel flanges, blocking any kind movement, while the upper jaw was responsible for apply a vertical tensile force, see Fig. 12. All tests were carried out in displacement control with a load speed of 1 mm/min.



a) b) c)

Fig. 11 Simple shear test layout. a) Front view, b) back view and c) lateral view. Nominal dimensions in millimeteres.

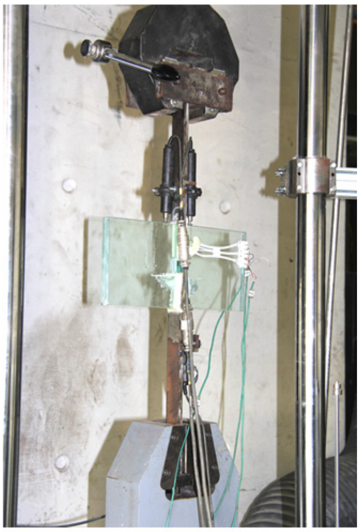
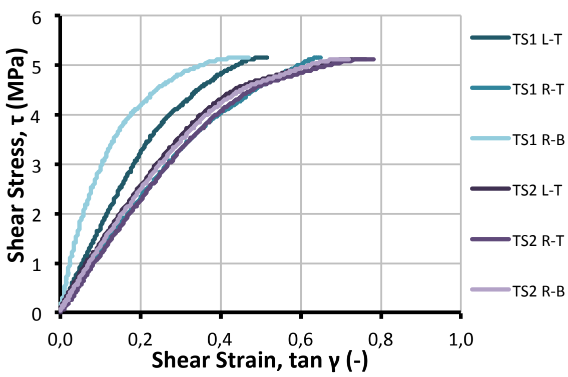


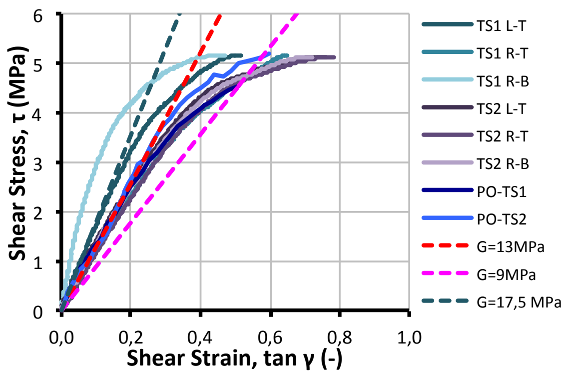
Fig. 12 Simple shear tests setup

5.2. Results

Fig. 13a shows the obtained test results in terms of shear stress and shear strain. A linear distribution of stress in the adhesive layer was again considered. In the first test specimen (TS1), the discrepancy between the measured experimental data could be explained with some minor misalignments in the test setup that were adjusted on the second experiment. In the case of the second test specimen (TS2), it is possible to notice a good agreement between the curves, especially the ones corresponding to the deflectometers placed at the top of the glass (L-T and R-T), which showed a slightly larger displacement at failure. Comparing the experimental outcome with the results of the push-out shear test is possible to observe that the value that still best fits the tangent shear modulus *G* of the adhesive is again 13 MPa. Consequently, this value was further considered to check the agreement between the experimental results and the Möhler method. In doing so, two additional values for the shear modulus were also considered to achieve a proper calibration of the analytical model and assess the sensitivity of its estimations to the *G* value. Based on the value obtained in the push-out shear tests, and since the simple-shear tests revealed a secant shear modulus in the range of ≈7-11 MPa, an average secant shear modulus of 9 MPa was taken into account. A further stiffer value of 17.5MPa was also considered to perform the comparative analyses between experimental and theoretical results.



a)



b)

Fig. 13 Simple shear tests results in terms of a) shear stress vs shear strain and b) comparison with the push-out shear test (Legend for the measurements: L= left; R= right; T= top; B-bottom; PO= Push-Out).

6. Simple hybrid steel-glass beams: analytical vs experimental results

Table 6 presents a summary of the results obtained on the hybrid steel-glass beams test series. Further information about the post-breakage response and the evolution of the crack pattern of each beam could be found in (Firmo et al (2015)).

Table 6: Experimental results of the 4PB tests on the simple hybrid beams.

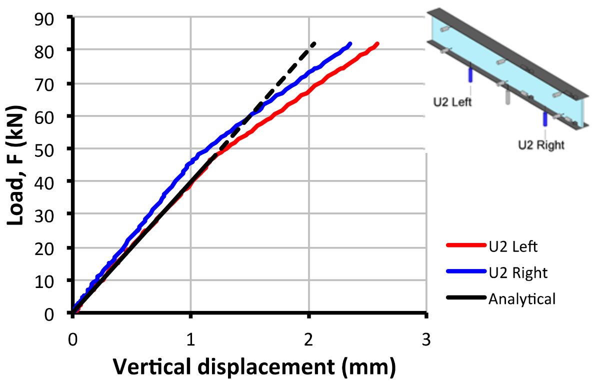
	HB1	HB2
Adhesive thickness [mm]	0.1	1.5
1st crack load [kN]	46.11	74.24
Maximum load [kN]	81.79	82.39
Residual load bearing capacity [%]	177	111
Displacement at 1st crack [mm]	1.82	4.47
Displacement at failure [mm]	3.81	9.63
Ductility [%]	209	215

Since the two hybrid beams had a different adhesive thickness *d*, the main differences registered between their bending response could be rationally justified by the effectiveness of the adhesive connection. By applying the Möhler method taking the adhesive shear modulus *G*= 13 MPa, it is in fact possible to notice that the efficiency factor of the glued joint of the second beam (HB2) is markedly lower than the HB1 beam, and typically representative of a flexible connection (γ= 0.431), see Table 7.

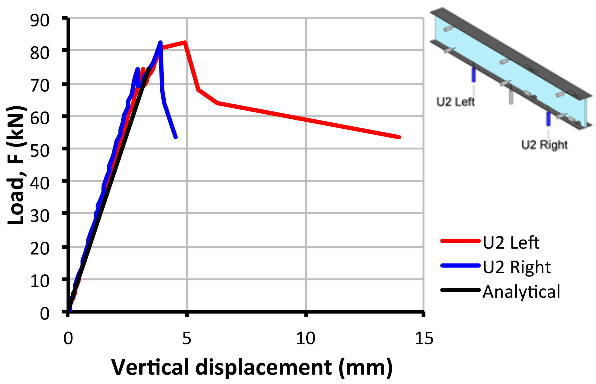
Table 7: Application of the Möhler method to the tested simple hybrid beams.

	HB1	HB2
Adhesive thickness [mm]	0.1	1.5
Shear Modulus *G* [MPa]	13	13
Stiffness of the joint *K* [N/mm^2]	2797.6	186.5
Efficiency factor γ	0.919	0.431

The influence of the adhesive joints flexibility was further assessed by accurate interpretation of the load-displacement test results. In the case of the HB1 with an almost fully rigid connection (γ= 0.919), the joint behaviour can be rationally associated to the linear elastic load-displacement response of the beam, both in the uncracked and cracked stages (see Figure 14(a)). In the case of the HB2 specimen with an increased thickness *d* of the adhesive joint, conversely, an almost flexible behaviour was found for the joint as also emphasized – during the HB2 full-scale experiment – by the slight loss of bending stiffness for the beam, immediately after the first glass cracking (Fig. 14(b)).



a)

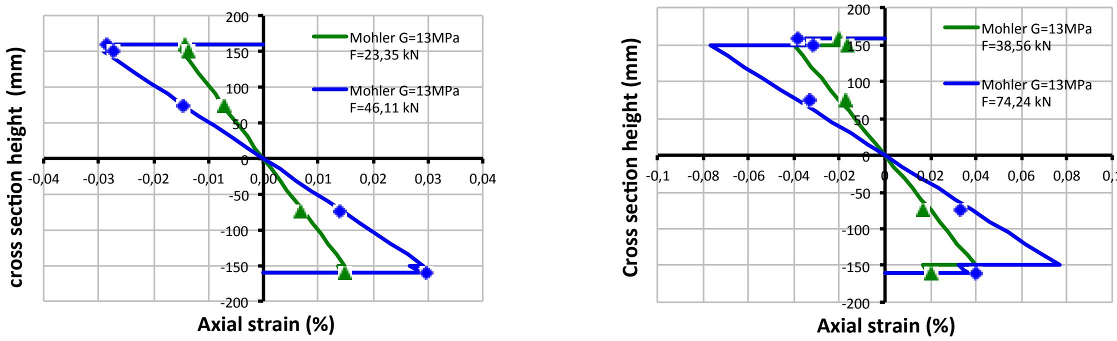


b)

Fig. 14 Comparison of the experimental results for the simple hybrid beams in terms of load vs displacement with the analytically derived results (*G*=13MPa). Beams a) HB1 and b) HB2.

Besides the advantages in the assembling procedure, the main interest in considering a lower stiffness and a higher load carrying capacity was to achieve a ductile behaviour through the development of larger displacements, guaranteed by the flexibility of the joint.

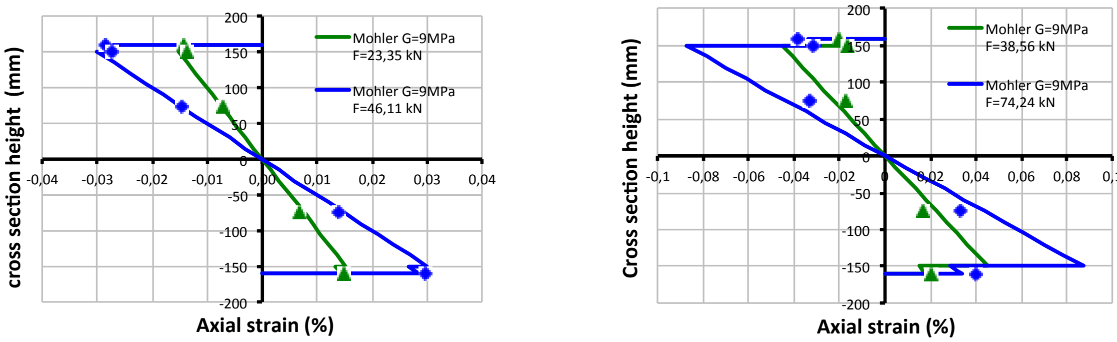
Another interesting aspect to analyse is the load responsible of the first glass cracking, which was markedly different in the two tests. From this point of view, the adhesive joint stiffness cannot in fact be disregarded since it caused a different strain distribution. For the beam with the highest connection degree (HB1) the first crack has occurred for a glass stress of approximately 20 MPa while in the second hybrid beam (HB2) it emerged for a 46 MPa tensile glass stress, which is similar to the values usually considered in the literature for float glass (~45 MPa), see Fig. 15.



a) b)

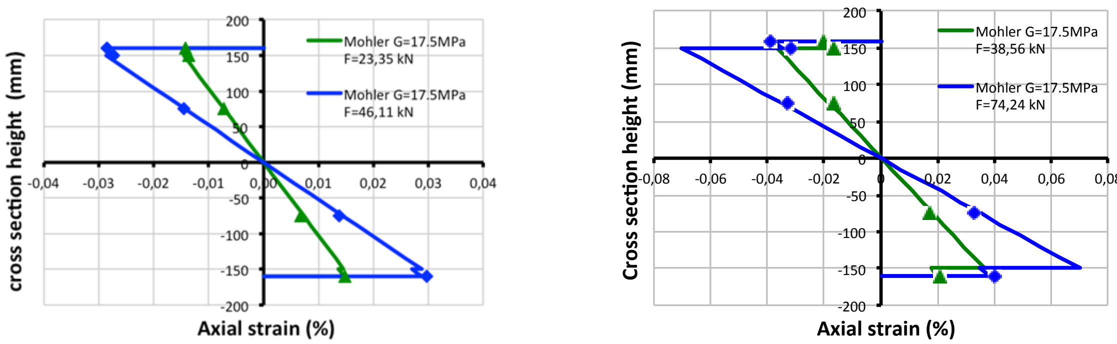
Fig. 15 Axial strains at the beam mid-span section and comparison with the Möhler method calculations, with *G*= 13 MPa. Beams a) HB1 and b) HB2.

In Figures 16 and 17, the same experimental analytical comparison is proposed. In these latter cases, however, the evolution of analytically calculated axial strains is proposed by considering two different values for the shear modulus of the adhesive, e.g. *G*=9 MPa (Fig. 16) and *G*=17.5 MPa (Fig. 17).



a) b)

Fig. 16 Axial strains at the beam mid-span section and comparison with the Möhler method calculations, with *G*= 9 MPa. Beams a) HB1 and b) HB2.



a) b)

Fig. 17 Axial strains at the beam mid-span section and comparison with the Möhler method calculations, with *G*= 17.5 MPa. Beams a) HB1 and b) HB2.

A further comparison between experimental and analytical results is also summarized in the Table 8, in terms of maximum deflection at beam's mid span (U2 Centre) and stresses in the glass web (G2A and G2C) at the occurrence of first cracking. The experimental values of stress in the glass web and in the steel flanges were obtained, specifically, by averaging the strain gauges measurements.

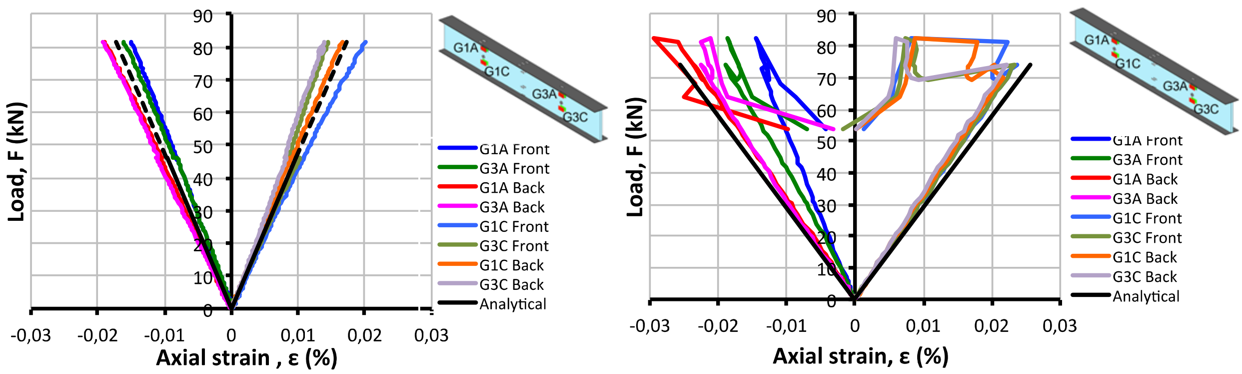
In the case of the HB2 beam it is possible to notice, again, that the analytical calculations carried out on the base of the secant shear modulus would markedly overestimate the expected deflections of the beam. By considering a stiffer modulus (*G*=17.5 MPa), it is possible to observe a decrease of the relative errors in terms of stresses along the beam height, compared to the experimental measurements. In any case, the best comparative calculations in terms of stress and deflection is obtained considering the shear modulus taken from the small-scale shear tests (*G* = 13 MPa), hence further emphasizing the fundamental role of adhesives as well as their influence on the structural response of the full hybrid systems.

Table 8: Comparison between the experimental results and the Möhler method.

1st crack	HB1							HB2						
	Exp	G=9	Δ[1]	G=13	Δ[1]	G=17.5	Δ[1]	Exp	G=9	Δ[1]	G=13	Δ[1]	G=17.5	Δ[1]
$\delta_{U2\ Centre}$ (mm)	1,82	1,73	4,9	1,69	7,4	1,66	8,8	4,47	5,054	-13,1	4,46	0,2	4,05	9,3
σ_{G2A} (MPa)	-10,1	-10,5	-3,3	-10,2	-0,7	-10,06	0,9	-23,0	-30,6	-33,0	-27,0	-17,3	-24,5	-6,6
σ_{G2C} (MPa)	9,6	10,5	-8,7	10,2	-5,9	10,06	-4,3	23,0	30,6	-32,8	27,0	-17,1	24,5	-6,5
σ_{LF2} (MPa)	20,8	19,9	4,1	20,1	3,4	20,19	2,9	28,1	24,0	14,5	26,1	7,2	27,5	2,2

[1]Δ= 100 × (Experimental-Analytical)/Experimental [%]

As a final stage of a comparative study, the load - strain curves of the strain gauges placed both in symmetrical and analogous positions were analysed and compared with an analytical curve calculated using a 13 MPa shear modulus. Fig. 18 depicts a rather good correlation between the experimental data but shows also a bit of asymmetry and out of plane deformation. Since there were out-of-plane displacements that induced an additional load case, the Möhler's assumption of a perfect system is no longer entirely correct, which somehow explains the differences recorded in Table 8.

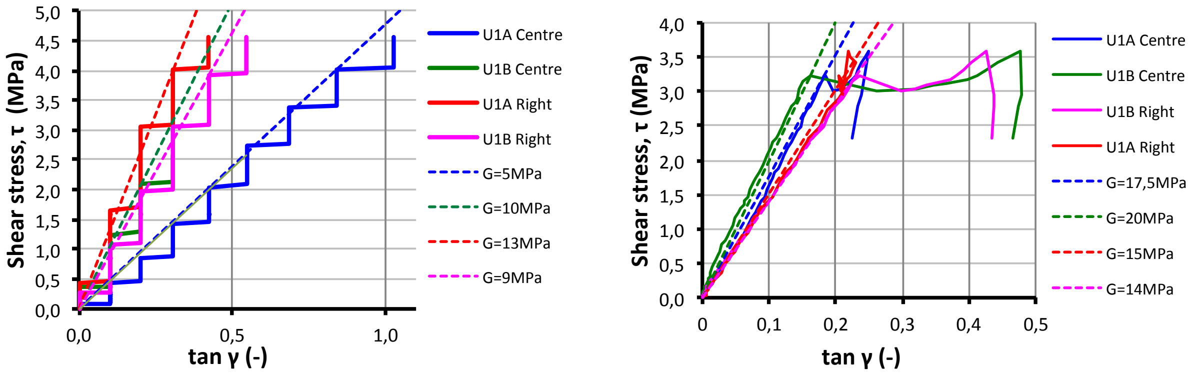


a) b)

Fig. 18 Comparison of the experimental results in terms of load vs axial strain, with the corresponding analytical results for the beams a) HB1 and b) HB2.

Other important aspect is the fact that the Möhler method does not take into account any transfer of shear forces through the lamination film between the two glass panes. Thus, it could also justify the fact of the analytical results for the glass web are always stiffer and more resistant than the experimental values.

Considering a linear distribution of stresses in the adhesive layer, the values of the slip between the flange and the web were transformed in a shear stress- shear strain relation. It is concluded that there is a significant difference between the measurements near the support and near the load introduction points. In Fig. 19 it is possible to observe a linear behaviour of the adhesive until the failure of the beams. In the HB2 test experiment the adhesive layer revealed to be slightly stiffer when compared to the small scale-shear tests. This fact is more noticeable in the curves corresponding to the displacement transducers placed near the load introduction points (Fig. 19b)). In the first hybrid beam tested, the differences recorded to the small-scale shear tests could be justified by the different glue thickness used in the experiments (Fig. 19a)).



a) b)

Fig. 19 Shear stress vs shear strain a) HB1 b) HB2.

7. Conclusions

The aim of the present paper was to establish a comparison between the experimental results obtained for steel-glass hybrid beams and the analytical predictions derived from the Möhler formulation, being this latter often considered for the assessment of the structural behaviour of timber and composite structures. Small-scale shear tests were performed in order to assess the main mechanical adhesive properties of interest. The so obtained values were then implemented in the Möhler method to estimate the load bearing capacity of the hybrid beams. However, it has been observed that the model has the restriction that only a linear stiffness of the adhesive can be included. Since the adhesive behave nonlinear, the execution of small-scale tests was a very important step to assess a range of values that fits best the stiffness of the adhesive.

The comparative study between analytical and experimental results showed that the best adjustment in terms of stress and deformability was obtained considering the tangent shear modulus taken from the small-scale shear tests. As shown, considering an initial, and consequently stiffer value for the shear modulus of the adhesive could lead to an unsafe design due to the fact that is being assumed a higher degree of shear interaction. Otherwise, it was also shown that when the secant shear modulus is taken into account, due to the increase of the joint flexibility, the analytical model struggled to find a good arrangement with the experimental data. The current study, as a result, showed that with small-scale shear tests and an appropriate calibration procedure of the analytical model a rather close agreement could be found with full-scale tests. By do not taking into account some unexpected events, like out-of-plane displacements, finally, it was shown that the Möhler method is an adequate model for a feasible calculation of hybrid steel-glass beams since it provides accurate results, with generally less than 10% errors.

Acknowledgements

Financial support from the Portuguese Foundation for Sciences and Technology (Fundação para a Ciência e Tecnologia) under contract grant PTDC/ECM/116609/2010, and, within ISISE, project UID/ECI/04029/2013 is gratefully acknowledged.

The authors would like to thank Sosoares, responsible for providing the glass beams used for the experimental tests; Ideal Mondego Metallurgical for providing the steel flanges and Cristalmax, responsible for cutting the test specimens. A word of gratitude is also expressed to SIKA for providing the adhesive, insight and expertise that has greatly assisted the research.

The ongoing COST Action TU1403 "Adaptive Facades Network" (2014-2018) is also gratefully acknowledged for providing scientific networking between the involved researchers and for funding a Short-Term Scientific Mission of the first author to University of Trieste, Italy.

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