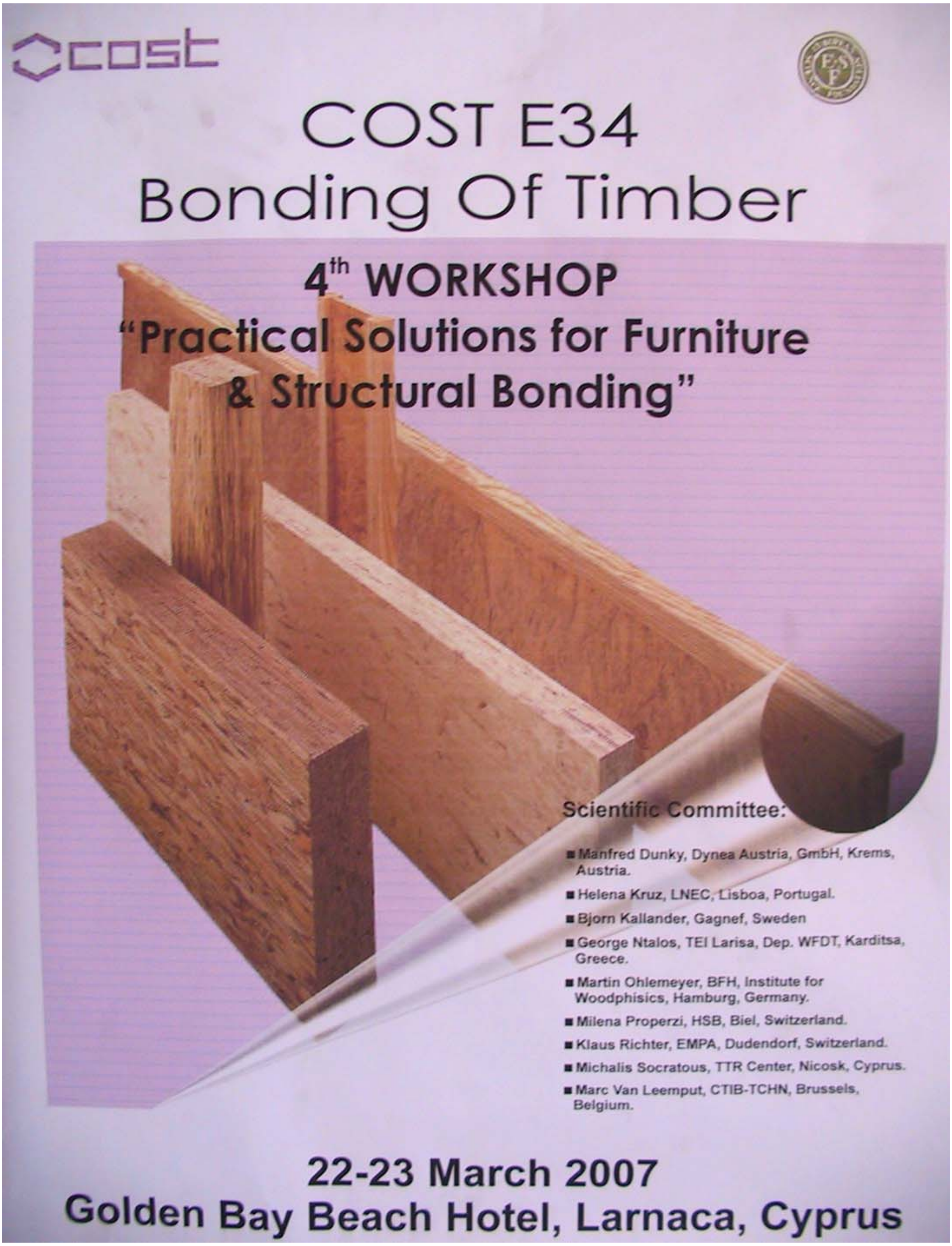
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Experimental studies on structural timber glass adhesive bonding

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Abstract: *The utilization of timber in building structures has been increasing in the last years, partly due to technological developments in this field. New tectonic concepts such as prefabricated and industrialised systems arose, though very different from the ones presented by traditional solutions. Hence, the combination of timber with other constructive materials is emerging. Steel, composites materials or glass can be combined with timber, in order to obtain resistant products, highly typified, standardised and with low behavioural variation.*

The structural utilization of timber glass composite solutions is a daring construtive system, which although still in a very early stage, already presents an important potential of applicability in architecture. In order to fully benefit from composite timber glass cross sections, an adequate bonding between these two elements is essential. With the purpose of achieving the ideal balance between strength and flexibility, an extensive set of experimental tests is being carried out at the University of Minho.

This presentation focus on the analysis of results regarding shear stress tests with timber glass bondings, using adhesive as structural bonding system. In these tests, various adhesives were applied, including different trades and adhesive types such as silicone, methacrylate, polyurethane, acrylics and superflex polymers.

Introduction

The technical evolution has been responsible for a significant rise in the structural utilization of timber in construction. Prefabricated industrialised systems currently present an area of strong architectural and constructive development. The uniformity, traditionally inherent in this concept, is nowadays superimposed by the feasability of unitary series. As a complement, the increasing resort to composite solutions diversifies the range of functional, expressive and structural solutions of products, leading to results that any material alone, with its limitations, could not achieve. Therefore, any composite solution will aim at enhancing the intrinsic increased value of its components and the simultaneous minimization of the disadvantages that each material, separately, presents. This is the central idea behind composite systems and also the starting point for the development of the present research.

Structural timber-glass composite solutions present all conditions for, in a near future, assume great architectural significance. First of all, it will allow benefiting from natural lighting in a way not much explored so far, with consequent advantages at other levels. On the other hand, the transparency of glass, associated with its structural employment, could achieve the most transcendent features of this

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material, magic and illusion. Also at a structural level, glass compression capacity and timber tension resistance must be enhanced, the same way that accumutaded and tensile stresses must be avoided on glass surfaces. Simultaneously, the specificities of natural behaviour of timber have to be assumed, understood and contextualised.

However, no matter what the object of the strutural composite system is – beams, columns, plates or slabs –, another aspect must be taken into consideration: the bonding system. While assuming a role which is as important as, or even more important than the two original elements, the bonding system will be the main responsible for the unity of the set and, at the same time, preserve the diversity of components. As far as the present research is concerned, the structural adhesive bonding was chosen as the bonding system since it presents a superior guarantee of effectiveness regarding the above mentioned intention. Uniform distribution of forces, reduction of fragilization of materials by avoiding drilling, averting of high peak stresses and aim at the ductility in the unity of the set were the criteria for this decision.

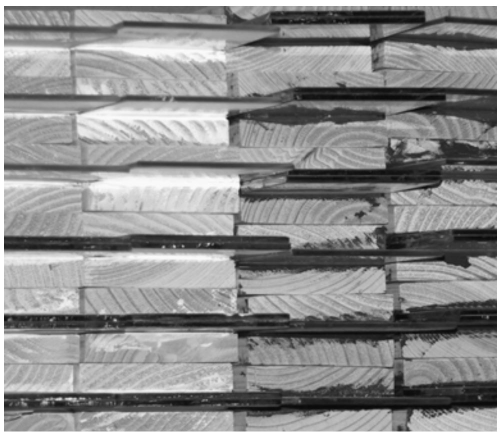
It is also of great importance that the adhesive brings together strength and flexibility. That is the path to its structural employment, necessarily subject to transmission of heavy loading. The adhesive must also allow bending, expansion and shrinkage of timber, according to loading and humidity variations. Given the basic difference of characteristics between glass (brittle) and timber (ductile), it is believed that this could be the best way of enhancing the performance of the different composing elements in a unitary set.

Nowadays, there are still few examples of buildings constructed, in which structural load transfering by means of adhesives is applied. The research now presented fits in a wider project, whose main objectives are the feasability and optimization of architectural potentialities of timber glass constructive solutions.

Materials and Methods

Given the unpredictability resulting from the many variables related to timber glass structural adhesive bonding system, it would be impossible to firmly move towards a technical and pratical solution without producing a wide set of experimental tests, which could reveal most of the possibilities.

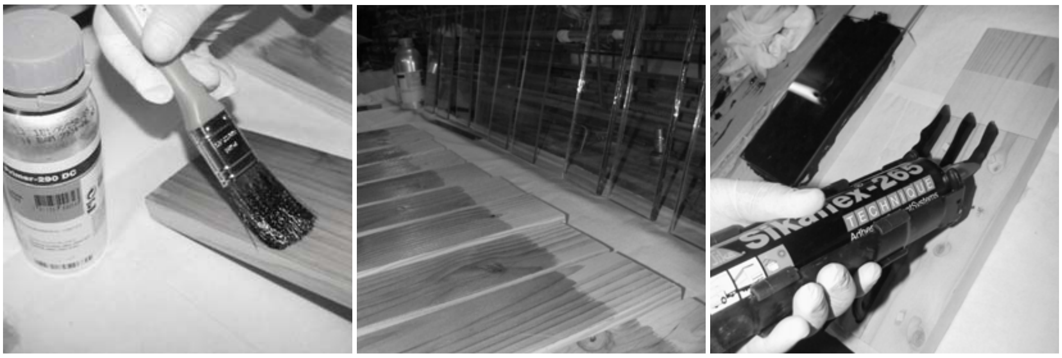
Hence, shear stress tests were carried out, according to the implementation of some important variables. Based on such tests, the results of a set of six different products are hereby presented.



Figures 1 and 2: Adhesives and specimens used in the set of experimental tests

All six products, shown on figure 1, represent different types of adhesives: polyurethane, superflex polymers, silicone, methacrylate and acrylic – in two-component format and bi-adhesive tape.

These adhesives, suggested for this purpose by the manufacturing companies themselves, within their range of products, gave rise to 54 specimens – figure 2 –, tested according to variables presented on Table 1: primers utilization and glass type. It is also important to state that, when composing and preparing the specimens – sequence of figures 3, 4 and 5 –, and apart from the use of primers, glass plates were duly degreased with dimethyl ketone and dried. Timber elements were cleaned of dust with compressed air.

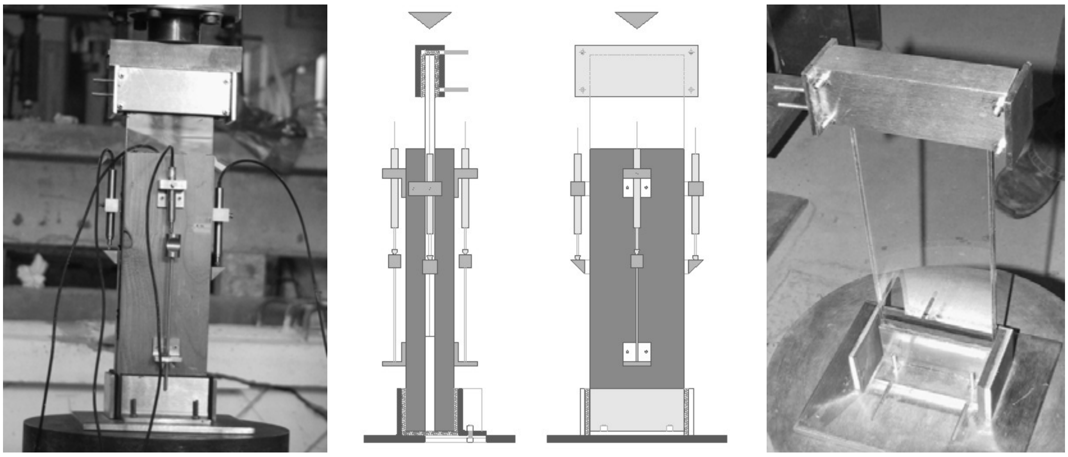


Figures 3, 4 and 5: Preparation of specimens – treatments and adhesive application

Table 1: Products and variables applied to the set of experimental tests

Adhesive Type	*Product*	*Cp^{s}*	*Primers*	*Glass Type*	*Specimen series*
Polyurethane	Sikaflex®265	1C	-	Laminated	A04; A05; A06
			Sika®Activator Sika®Primer290DC	Tempered	A07; A08; A09
				Laminated	A10; A11; A12
Silicone	Sikasil®SG-20	1C	-	Laminated	B04; B05; B06
			Sika®Primer290DC	Tempered	B07; B08; B09
				Laminated	B10; B11; B12
Superflex Polymers	Sista Solyplast SP101	1C	-	Laminated	C04; C05; C06
			Generic Primer	Tempered	C07; C08; C09
				Laminated	C10; C11; C12
Methacrylate	Sikafast®5211	2C	-	Laminated	D04; D05; D06
			Sika®ADPrep	Tempered	D07; D08; D09
				Laminated	D10; D11; D12
Acrylic	3M™ Scotch-Weld™ DP-810	2C	-	Laminated	E04; E05; E06
			3M Glass Silane Generic Primer	Tempered	E07; E08; E09
				Laminated	E10; E11; E12
Acrylic Tape	3M™ VHB™ 4910F	-	-	Laminated	F04; F05; F06
			3M Glass Silane Generic Primer	Tempered	F07; F08; F09
				Laminated	F10; F11; F12

According to the scheme of tests used, as presented in figures 6 and 7, specimens were submitted to shear loading, in series of three, at the speed of 15 microns/s. This leads to the collection of data regarding strength resistance; timber glass relative displacement allowed by the adhesive and deformation of timber following the longitudinal orientation of the grain, resulting from loading transmission through the adhesive. The loading is applied by means of metalic grips, adjustable to the dimensional variation of specimens and internally covered with neoprene, which prevents glass from cracking. Each specimen, made up of a glass plate fixed between two timber boards, presents a total contact surface of 40 000 mm^2 (200mm x 100mm x 2). The area of this surface, though not limiting of the results obtained, proved exaggerated as far as adhesives of greater resistance and stiffness are concerned. The end result was glass failure, very common among adhesives of great resistance which, many times, proved stronger than the materials themselves.



Figures 6, 7 and 8: Test scheme; glass behavioural characterisation test

The types of glass used in tests – 5.5.1 laminated glass and 5 mm tempered glass – were also tested, as shown in figure 8, so as to check their level of resistance and behavioural variability. In the end, high uniformity was revealed.

The timber employed was *Pseudotsuga Menziessi*, or Coast Douglas Fir, a type of softwood, properly dried, sawn and polished.

Results

The set of tests was prepared in order that the data obtained could directly be compared. Taking that into account, figure 9 presents a comparison between several load/relative displacement curves, representative of different adhesive performances. The balance between load-bearing capacity and flexibility of each case is, thus, highlighted.

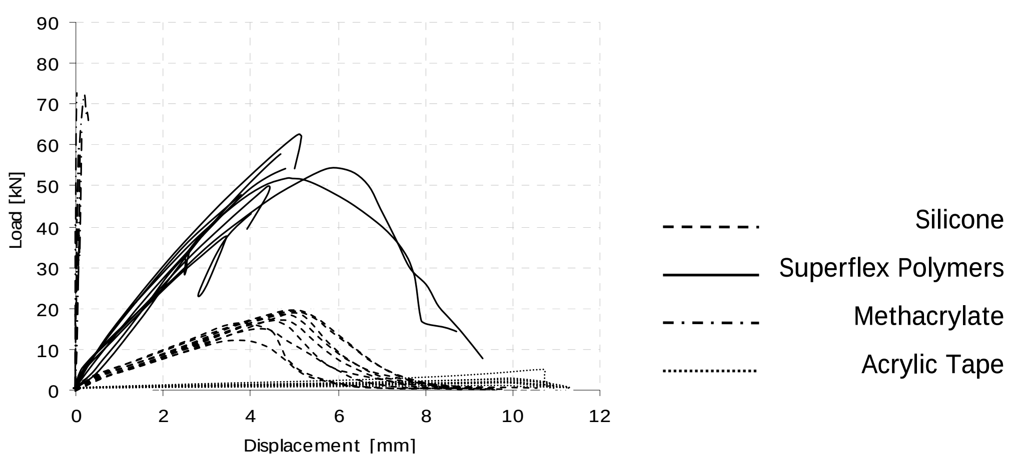


Figure 9: Load/relative displacement graph comparing adhesives B, C, D and F

Table 2: Summary of results

Product	*Specimen series*	*Max. Load kN (average)*	*Displacement mm (average)*	*Failure mode*[1]
Sikaflex®265	A04; A05; A06	68,37	5,11	G
	A07; A08; A09	39,45	5,80	G
	A10; A11; A12	15,35	4,26	C; Ag
Sikasil®SG-20	B04; B05; B06	15,86	3,90	Aw; Ag; C
	B07; B08; B09	19,60	4,84	Aw; Ag; C
	B10; B11; B12	20,05	4,91	Aw; Ag; C
Sista Solyplast SP101	C04; C05; C06	60,15	4,96	G
	C07; C08; C09	45,41	3,78	G
	C10; C11; C12	54,62	5,20	Aw; C; G
Sikafast®5211	D04; D05; D06	71,51	0,08	G
	D07; D08; D09	49,76	0,09	G
	D10; D11; D12	62,31	0,15	G
3M™Scotch-Weld™DP-810	E04; E05; E06	87,94	0,05	Ag; C; G
	E07; E08; E09	57,12	0,01	G
	E10; E11; E12	73,44	0,05	Aw; C; G
3M™ VHB™ 4910F	F04; F05; F06	1,95	9,60	Aw; C
	F07; F08; F09	1,30	10,06	Aw; C
	F10; F11; F12	3,28	10,37	Aw; C

[1]*Failure mode*: **Aw**–Wood Adhesion; **Ag**–Glass Adhesion; **C**-Cohesion; **G**-Glass failure

Table 2 conveys a summary of some of the most important results obtained, that is, the maximum loading average for each series of specimens, as well as the registered timber glass relative displacement average at the maximum loading referred points.

Strength and relative timber glass displacement

Figure 9 illustrate the curves of all tests carried out with silicone, superflex polymers, methacrylate and acrylic tape. These tests unveiled the existence of three different groups: adhesives highly resistant and insufficiently flexible in this context – methacrylate (and also two-component acrylic adhesive); highly flexible adhesives, yet insufficiently resistant to the loading they could be subject to in real situations – silicone and acrylic tape – and, finally, adhesives that balance both key factors in this research: strength and flexibility – this being the case of superflex polymers. One can clearly observe this situation in figure 10.

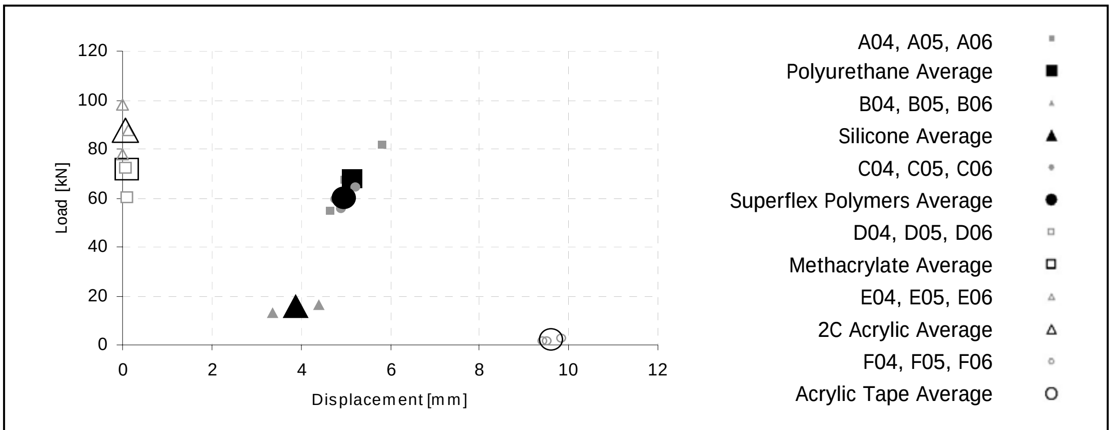


Figure 10: Maximum loading resistance and respecting displacement – all adhesives

Figures 9 and 10 also demonstrate that one could search for a suitable solution in the latter of the referred groups, the superflex polymer group, to which polyurethane also belongs. Figure 11 compares these two adhesives, and introduces another important aspect – behavioural variability. It is possible to observe that superflex polymer, contrary to polyurethane, presents in all circumstances uniformity convergent with safety criteria, essential in this kind of structure. However, it is pertinent to refer that variation in polyurethane fundamentally results from already mentioned variables applied to the test. This also highlights the influence of such variables, as will be observed further on.

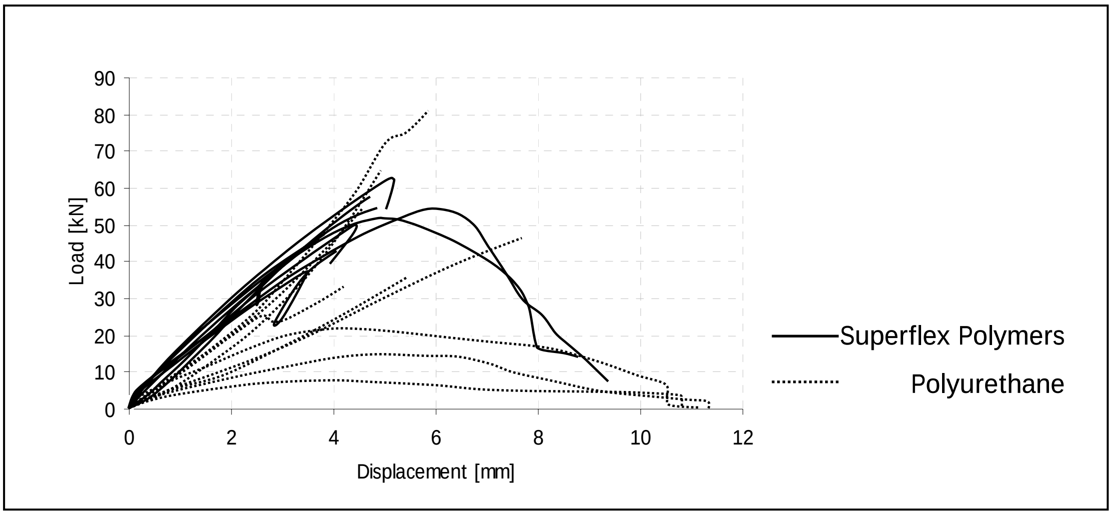


Figure 11: Load/relative displacement graph comparing adhesives A and C

Nevertheless, one must underline that flexibility of adhesives is relative, subject to arising diverse interpretations if observed in a wide range or according to its contextualization in their specific group. Taking, as an example, the results obtained for methacrylate, which in figure 9 – and comparing with other curves in the same graph –, seems to superimpose on the Y-axis, it is possible to conclude that, in the tested context, this adhesive is extremely rigid and resistant, as demonstrated by the repeated glass failure. Apart from that, and within its specific group, this adhesive can be considered relatively flexible when compared to others. As shown in figure 12, timber glass relative displacement regarding two-component acrylic adhesive is merely of centesimal fractions of mm. However, methacrylate registered twice the relative displacement when compared to the latter. In any case, this relative flexibility seems insufficient to being considered applicable in this context, due to the inherent characteristics of the materials and the intended scope of application.

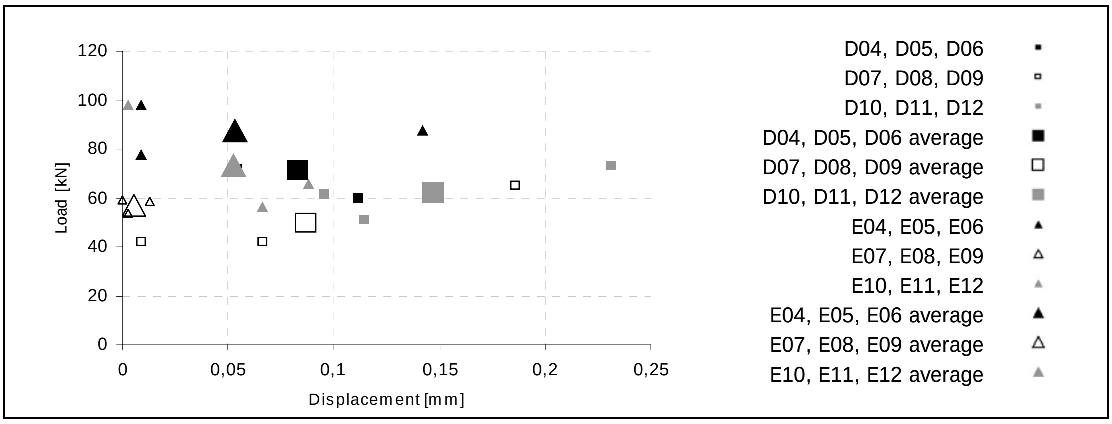
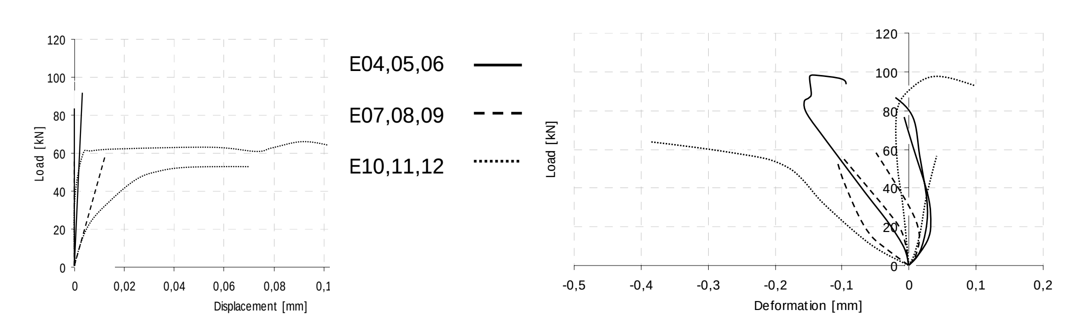


Figure 12: Maximum loading resistance and respecting displacement – methacrylate (D) and 2C acrylic (E) series

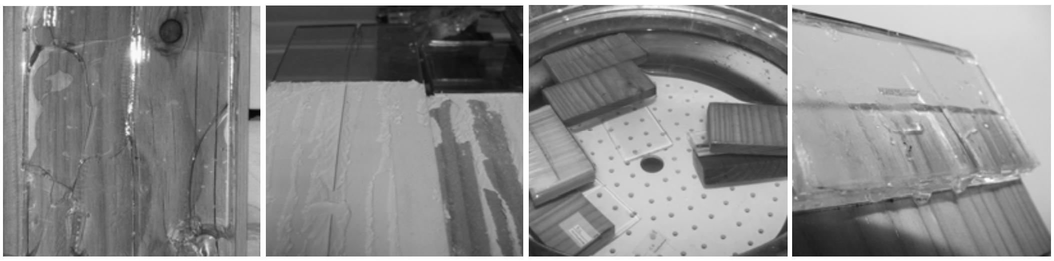
In fact, glass has low tension resistance, whereas timber is ductil, hygroscopic, of variable dimension and influenced by atmospheric agents to which it is exposed. Therefore, if the adhesive is not able to minimally absorb the various resulting stresses, it will not efficiently play the role of interface, as it will not prevent from a direct confrontation of different behaviours of materials.

Strength and timber deformation – consequences

As a logical conclusion, the greater the loading endured by the adhesive, the greater the strength to which both timber and glass will be submited. Conversely, a comparison between the graphs below – figures 13 and 14 –, regarding two-component acrylic adhesive, shows that longitudinal deformation of timber is higher than timber glass displacement. As a consequence of the anisotropic character of timber, this longitudinal shrinkage has repercussions in its tangential expansion. This is precisely the occurrence that must be minimised, as it is responsible for the application of tension stress on the glass surface in contact with timber. Figures 15 and 16 illustrate this failure mode. Even without applying external loading, the same occurrence can take place during normal specimen saturation in water, as shown in figures 17 and 18.



Figures 13 and 14: Load/relative displacement and load/deformation (of timber) graphs regarding acrylic adhesive – comparison of X-axis data



Figures 15, 16, 17 and 18: Failure modes, due to loading or water saturation

A highly resistant adhesive – tolerating stressing up to 15/20 MPa – even if considered exceedingly flexible within its group can, under certain circumstances, easily fail due to the particular characteristics of the materials under study. Limiting the tangential dimension of timber in contact with glass would surely represent a valid solution for this situation.

Since behavioural uniformity of the used types of glass was initially verified, it is important to note that the occurrence described in the previous paragraph originates discrepancies within data presented on table 2 concerning the specimens which collapsed through glass. This leads to the conclusion that the type of adhesive directly influences the failure of glass itself.

Failure modes and primers utilization

In the tests carried out, different failure modes were observed, as characterized in table 2, according to the type of adhesive and variables implemented. In general, it is possible to perceive that, in adhesives of higher resistance, glass always ended up collapsing. However, except for methacrylate, situations occur in which, besides glass, collapse takes place simultaneously with adhesion break – either with glass or timber – and/or cohesion break of the ahdesive itself.

According to figures 19 to 22, failure mode patterns can be observed in two of the most resistant adhesives – superflex polymers and two-component acrylic. In the first case, only noticed in series C10, 11 and 12, which shows that the best results regarding this adhesive are obtained without any primer use, collapse involved glass break, glass adhesion break and cohesion break. Hence, it was possible to observe a sliding pattern in the cohesion break of this adhesive – figure 20. Similarly, two-component acrylic adhesive also stood heavier loading without surface treatment. However, this adhesive presents three significant differences: adhesive break occurred in series E10, 11 12, but also in E04, 05, 06, regarless of the fact that in the latter it took place under strength rates superior than those in series E10, 11, 12 and also series C04, 05, 06. Series E10, 11, 12, in which primers were applied, collapsed through timber adhesion – figure 21 – whereas series E04, 05, 06, where primers were not used, collapsed through glass adhesion – figure 22. Ultimately, the post-collapse surface of this adhesive did not indicate any sliding. Instead, it was possible to observe an apparent vitrification.

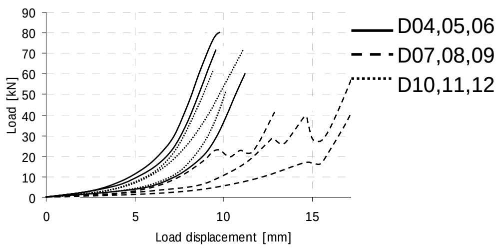
Figures 19, 20, 21 e 22: Failure modes – superflex polymers and 2C acrylic

Based on these examples, one may then conclude that surface treatment has a decisive influence in the adhesive bonding failure. Still, depending on the adhesive observed, that influence may be positive or negative, thus improving or worsening its performance. The use of primers is not always advisable. For each situation there is an ideal solution which, should it imply total absence of primer treatment, can surely ba an important advantage – of time and cost – in the employment of adhesive.

Glass type influence

Tempered glass, though more resistant to superficial stresses than laminated glass, presents two considerable and decisive disadvantages in relation to the latter: brittle properties and an irregular surface, as shown in figure 24. These characteristics prevent tempered glass from being considered an adequate solution for the intended situation. The results obtained demonstrate that, from certain loads onwards, there are oscillations in the loading/displacement curves of the loading unit – figure 23 –, which do not occur with laminated glass. Moreover, the superior resistance it holds – despite the differences in thickness used in both types of glass – becomes irrelevant when the occurrence illustrated in figures 15 to 18 takes place. Due to the characteristics of tempered glass, the occurrence mentioned results in its immediate collapse, even before the applied loading can affect the adhesive bonding. As shown in table 2, except for polyurethane, all series corresponding to tempered glass with primer treatment – 07, 08, 09 – always resisted less than series with laminated glass – 10, 11, 12.

In the case of bi-adhesive acrylic tape, the difference is of less than half the effectiveness, due to the incapaciy for compensating superficial imprecisions, as observed in figure 25. This irregularity in the glass surface tends to affect, more than any other, fluid adhesives, as one may apprehend from the difference obtained in the case of two-component acrylic adhesive, the greatest registered (57,12 kN to 73,44 kN), as shown in table 2.



Figures 23, 24 and 25: Load/Loading unit displacement graph – methacrylate; tempered glass; bonding irregularities – bi-adhesive acrylic tape with tempered glass

Both analysed variables – primers utilization and glass type – directly influence the performance of adhesives and lead to conclusions regarding the behavioural uniformity each presents, according to the mentioned variables – figure 26. Behavioural uniformity is an important safety factor, which must be guaranteed.

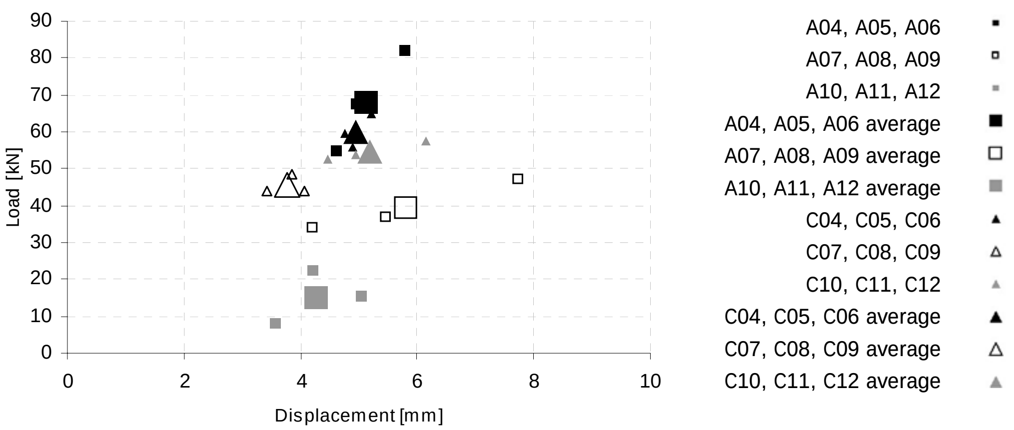


Figure 26: Maximum loading resistance and respecting displacement – polyurethane (A) and superflex polymers (C) series

Safety precautions

Safety is a crucial and indispensable aspect. It implies deformability or ductility criteria, instead of brittle characteristics, unable to absorb tensions, usually much resistant but easy to suddenly and unexpectedly collapse. The behaviour of the structural element in periods ranging from the first cracking to the maximum loading resistance, and from this to collapse, is of essential importance in this context, where the possible maximum margin of time should be kept and any fragile tendency avoided. This applies to adhesives and the materials themselves. In this case, the elementary choice of laminated glass - usually less resistant than tempered glass - results from safety concerns.

Conclusion

The bonding solution pointed out in the present research can be a practical system regarding the structural use of several timber glass composite elements. Depending on the geometry of the composite cross section, the specific mechanical characteristics of its components and the loading involved, it may be necessary to apply a more rigid or ductile adhesive.

This paper summarises the results of 54 laboratorial tests on shear stress, involving different types of adhesives. The results obtained, concerning strength and flexibility, demonstrate a wide range of mechanical behaviours - from extremely rigid to significantly ductile – and support the feasibility of this solution to the applications envisaged.

This solution, however, must undergo other tests in order to be accepted as a structural constructive solution: temperature and relative humidity variation, UV radiation, ageing, aesthetics and applicability are considering aspects. The work hereby presented is a stage in a long path towards the technical and scientific validation that is intended to be achieved. Its main purpose is the practical, safe and generalised implementation of an innovative, daring and promissing constructive system.

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