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Structural Transparency – A New Wood Plastic Composite Girder

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Transparency is one of the significant features of modern architecture. By utilising transparent materials the feeling of lightness can be conveyed. This paper shows the possibility of employing transparent plastic as a load-bearing element. In order to be able to use a new material as part of the building structure it is essential to know its mechanical behaviour under various conditions like different temperatures, environmental impacts or the load duration. Proposals for the design of structural elements that consist of these materials are still rare up to now since plastics are still fairly new to the building industry. By combining transparent with conventional building materials it is possible to merge transparency and strength in a girder that comprises a combination of transparent thermoplastics and wood.

Keywords: PMMA, transparency, composite girder, Plexiglas, plastics

1. Introduction

Using transparent plastic material is not very common in modern Architecture. But light, filigree structures are becoming increasingly more significant. In doing so it is not only lightness in terms of weight but most importantly in terms of the impression it makes. By utilising transparent materials the user is given the feeling of lightness. Along with glass as a load-bearing, transparent element there is also the possibility of employing transparent plastic as a load-bearing element.

There are some examples using transparent plastic material in bearing structures. In huge aquariums for examples the plastic material gives the possibility to be next to the maritime wildlife.

Figure 1: Aquarium with PMMA tunnel.

2. Material characteristics of PMMA

Plastics you can use as transparent bearing structures are rare. One of the possibilities is Polymethylmethacrylate, abbreviated PMMA and known as acrylic or Plexiglas®. It is a highly transparent thermoplastic material. Compared with other plastics it is very hard, has a very high transparency and is extremely weatherproof; it is brittle and prone to stress cracking when unmodified. There are many manufacturing processes. Sheets are primarily poured between two sheets of glass or extruded. The mechanical properties are dependent on the load duration and the temperature amongst other things. The basic material properties of PMMA you can see in Table 1.

Table 1: Material Properties PMMA.

	Extruded PMMA	Cast PMMA	Unit
Young's Modulus	≥ 2900	≥ 3000	MPa
Tensile strength	≥ 60	≥ 70	MPa
Tensile strain	≥ 2	≥ 4	%
Flexural strength	100 - 115	100-115	MPa
Density	1.19	1.19	g/cm^3
Thermal expansion coefficient	7 x 10-5	7 x 10-5	K-1

The strain occurring from an external load is made up of three different parts. The first part is an energy elastic strain that occurs as a direct result of a load and goes away just as quickly when the load is removed. The second part is an entropic elastic strain. Under this strain the microstructure of the PMMA changes to a lower energy state. This strain is also reversible. The third part is an irreversible viscous yielding.

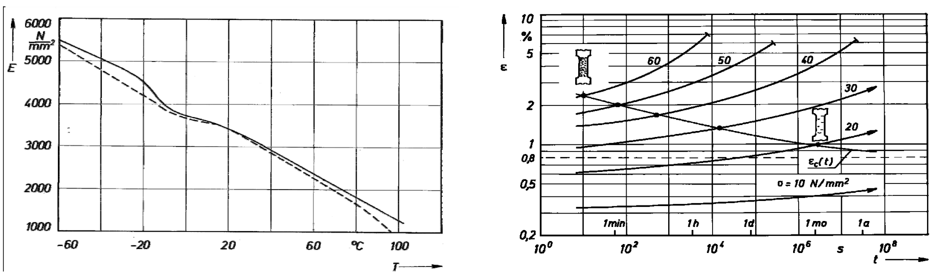

Figure 2a: Temperature dependency of modulus of elasticity and creep strength curve, b: deterioration curve of PMMA (Evonik Röhm GmbH).

In creep testing the strain increased steadily under a constant load. Figure 2b shows excellent examples of the creep strength curve and deterioration curve for PMMA cast sheets. Even under lower load, material damage would occur after a finite time period. In the construction project this load is so small that a life span of at least 40 years without damage is to be expected. As already described by the term "thermo-plastic", PMMA is also very heavily dependent on temperature. The microstructure is loosened by increasing temperature. An excellent example of the dependency of the modulus of elasticity (Young's modulus) on temperature is shown in Figure 2a.

3. Compatibility of the materials

The described composite girder system functions like the double-T section common in steel-girder construction. The timber chords situated on the top and bottom withstand the tensile and compressive forces while the PMMA acts as a web, maintains the space between the two chords and resists shear forces (see Figure 3). Through this combination the girder appears light and is largely transparent. Each of the twin timber chords are bolted with the Plexiglas® between them.

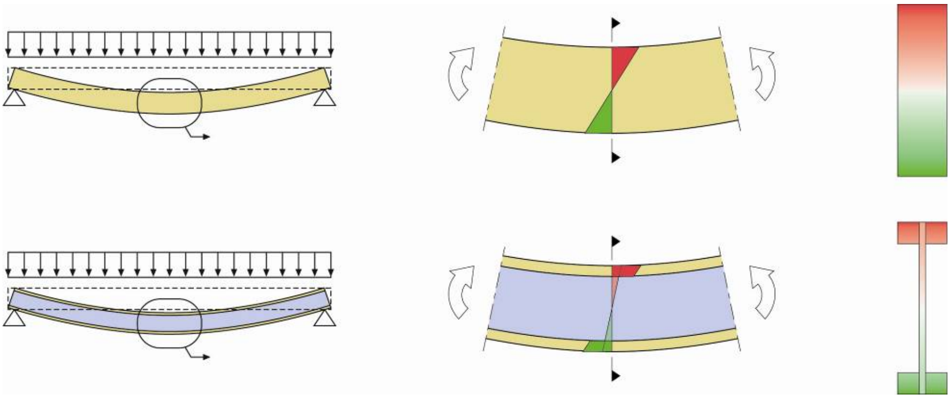

Figure 3: Flexural stress distribution in a simple beam and in the composite girder.

When combining different materials in a composite girder the ratio of the material stiffness is of great importance. The distribution of the flexural stresses in the structural elements depends on the relation of their Young`s moduli. Due to the favorable ratio of the modulus of elasticity of wood (10.000 MPa) and PMMA (3.000 MPa), the flexural edge stresses that occur in the PMMA are lower than in the timber (see Figure 4). Due to the relatively high influence of creeping under high axial loads material damage could occur in the PMMA sheets otherwise after a finite time period. Before the relatively brittle material PMMA can tear at the tensile edge the timber will absorb the normal forces. In addition, the combination of the plastic sheets with the stiffer timber increases the bending stiffness of the girder. By contrast the ratio of the modulus of elasticity of wood and glass is disadvantageous. The maximum edge stresses that occur in the glass panels are about seven times as high as the stresses in the timber. The glass breaks even before the wood is used to its full capacity.

In the use of plastics there are various problem areas that have to be considered. The thermal expansion of PMMA, for example, is very high at $70 \cdot 10^{-6}$ 1/K (see table 1). Reactive forces arise due to the differential expansion and the fixed connections to the timber determined by the composite system. These forces are compensated for in part through a resilient connection (see Figure 5). Hence the PMMA webs are joined with the wood chords using bolts. The flexible connection to the wood contributes to reducing the stress peaks in the PMMA due to specific ductility in the connection. Much of the force is absorbed however by both materials.

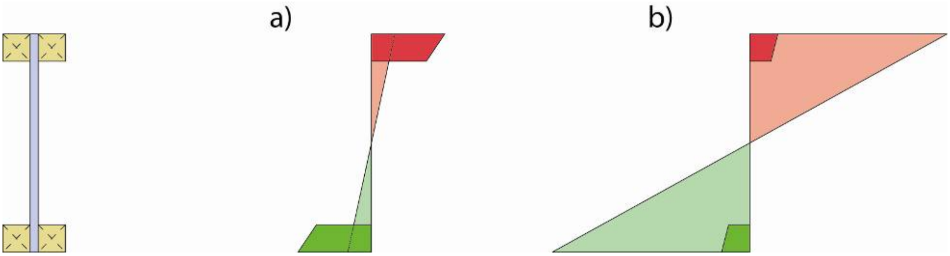

Figure 4: Flexural stress distribution: a) wood PMMA composite, b) wood glass composite.

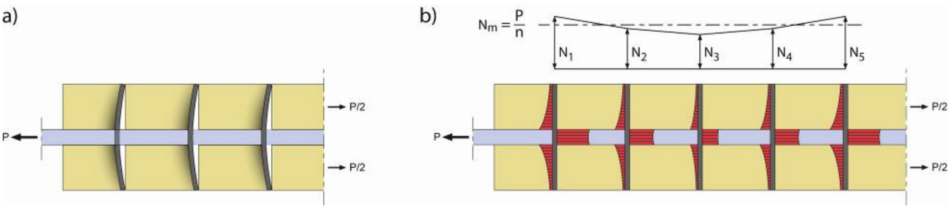

Figure 5: Resilient connection between wood and PMMA.

Another issue that has to be considered when combining PMMA with conventional materials is an environmental stress cracking that can occur when PMMA comes in direct contact with some other materials. Most of the wood species that were examined reduced the allowable stresses for the plastic significantly (see Figure 6). In order to still be able to use both materials in a composite girder thin metal sheets must separate both materials. These metal sheets can easily be combined with the flashing that is usually installed as weather protection on the upper side of the timber chords.

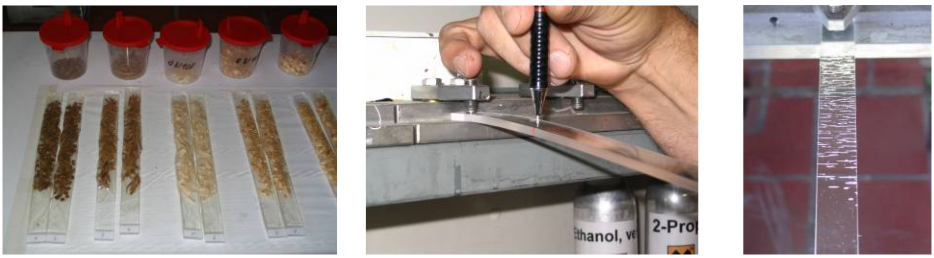

Figure 6a, b and c: Environmental stress cracking tests with wood PMMA specimen.

4. Design Concept for PMMA

There are only few guidelines how to use the plastic material in a bearing structure. The material properties for short term loads are regulated in a standard. Except this there are no further standards how to design or engineer with the Thermoplastics. The existing guidelines are not introduced by the authorities. The two guidelines existing in Germany is the “BÜV-Empfehlung” and the European ETAG 010.

The “BÜV-Empfehlung” deals with load bearing plastic components in civil engineering and was designed by a group of the BÜV. This guideline suggests the use of partial safety factors. For the resistance of the plastic material some modification factors A_{mod} are introduced. Those factors consider the duration of load exposure, the temperature and aggressive mediums who could have an effect on the material properties. Those factors depend on the sort of plastic and are specified in the guideline.
The ETAG 010 was designed by the European Organisation for Technical Approvals (EOTA) manly for self supporting roof kits. The concept with modification factors is nearly the same. An additional dependence of the character of failure is included. At the end both guidelines compare the load capacity and the load.

5. Mechanical Processing of PMMA

The proper mechanical processing of PMMA is very significant for its use in load-bearing structures, as mistakes made here can lead to a reduced capacity. Machining affects the overall behavior of plastic parts. Thus, the stress that may be generated on the inside of machined areas can cause problems during subsequent work steps such as bonding, for example. This internal stress – just like that in molded parts – has to be relieved by annealing.

PMMA can be processed very well with many conventional machines that have a high rotational speed. PMMA should be worked with HSS, carbide or diamond tools. Carbide tools are known to have the longest life, but it must be borne in mind that the pigments incorporated also in more densely colored Plexiglas® may reduce any tool life very noticeably. Blunt tools cause burred edges, chipping, material stress, etc. Cutters must always be sharply ground, paying particular attention to the clearance and rake angles. Tools previously used on wood or metal should therefore not be employed for plastics. For example twist drills cannot be used on PMMA unless the point angle is reduced from normally 120° to between 60 and 90°. The rake angle must be ground down to between 4 and 0° (see Figure 7).

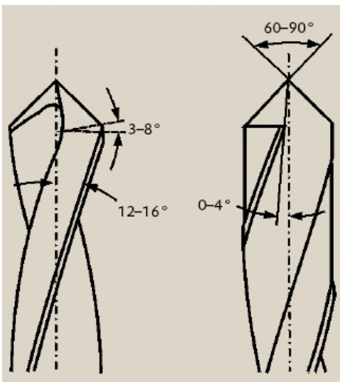

Figure 7: Geometry of drills for PMMA (Evonik Röhm GmbH).

When processing the most important thing to ensure is that the tools have sufficient cooling. High temperatures that occur during processing lead to embedded tensions.

When a cooling agent is used, its compatibility with PMMA must be observed. After processing the PMMA can be freed of tension through sufficient tempering.

The load-bearing capacity of the bore holes for the bolted connections is highly dependent on the quality of the bore hole. The quality of the bore holes can be divided into different categories (see table 2). For sheet material up to 25mm, grade I to II is acceptable. For thicker material, grade I to III can be assumed.

Table 2: Quality of borehole.

Grade	Area of borehole	Chamfer	$\sigma_{R,k}$ [MPa]
I	Nearly transparent, clean	Neither conchoidal fracture nor notches exist	100
II	To some extent lightly smudgy, noticeable with fingernail	Lightly conchoidal fracture at uncritical point, lightly chatter mark exist	70
III	Highly smudgy, clearly visible and noticeable	conchoidal fracture exist or small notches at uncritical point, chatter mark exist	40
IV	Highly smudgy with notches normal to area	Notches at critical point exist, strong chatter marks	-

6. Suitable fasteners for a bolted connection in PMMA

Due to the ease and suitability of their use in construction, dowelled connections have been widely used in steel and wood construction. With this connection type the forces that are transferred are applied perpendicular to the screw axis through bearing pressure in the area of the contact surface on the perimeter of the bore hole in the PMMA panel. Due to the high ductility of steel, the calculation of the bolted connection in steel construction can be based on a simplified engineering model that assumes a uniformly distributed bearing pressure.

The prerequisites are not sufficiently fulfilled when building with relatively brittle PMMA plastic at normal service temperatures. As a result known design procedures can not simply be carried over due to the various material behaviours and the resulting failure mechanisms they cause. The transfer of the bolt force leads to high localised stress peaks in the plastic. PMMA is not in sufficient measure able to transfer these by plasticization and breaks without warning when overstrained. The bolt force generates radial and tangential stress components in the area around the bore hole in the PMMA. The break is triggered by the maximum tangential stress on the perimeter of the bore hole. This corresponds to the maximum principal tensile stress.

In order to identify the most suitable fastener for the wood to PMMA connection various dowels and screws have been investigated. Figure 8 shows the test setup. The selection of the fasteners was based on commonly used dowels in timber constructions. In addition to the various connector types different dowel diameters were tested. The observed failure modes of the different connections are dependent upon the type and geometry of the explored connection.

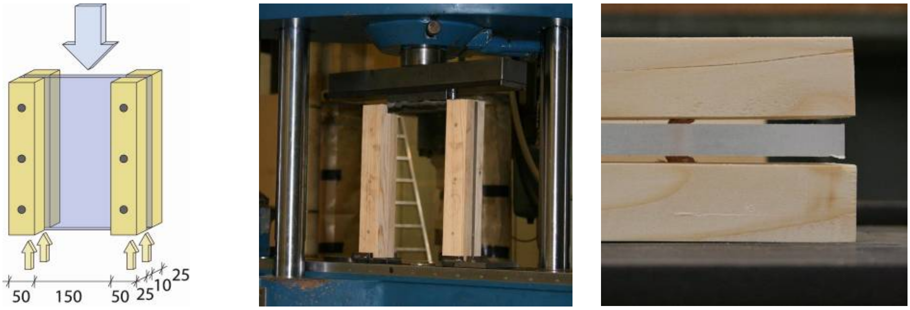

Figure 8a, b and c: Test setup with wood PMMA specimen.

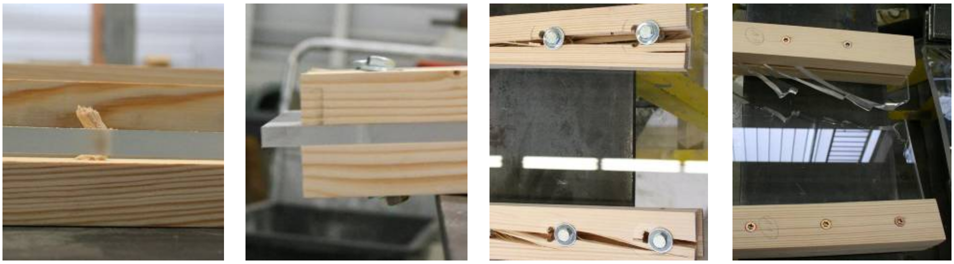

Figure 9a, b, c and d: Various wood PMMA specimens and corresponding failure modes.

Figure 9 illustrates a selection of different fasteners and the corresponding failure modes. Wood dowels can only transfer small loads and shear off spontaneously. Due to the yielding capacity of the steel bolts their use leads to a very ductile behavior of the connection. Furthermore the highest loads could be observed for the different bolted connections. Driving a drift pin into the wood PMMA specimen as well as the thread of a wood screw can hurt the edge of the bore hole in the PMMA sheet. For this reason the PMMA breaks without warning. Figure 10 shows the loads displacement diagrams for different dowelled connections.

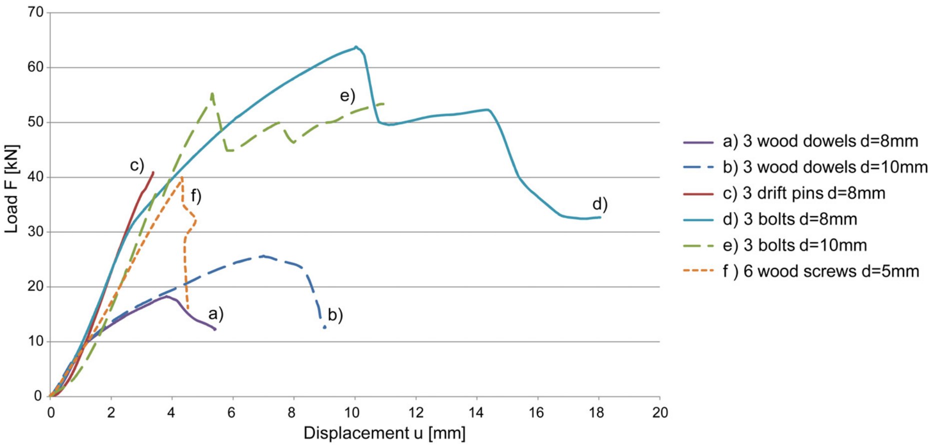

Figure 10: Load displacement diagrams of the investigated fasteners (selection).

7. Examples

As a prototype for the newly developed composite girder system the 26m long palace moat bridge in Darmstadt was built, which connects the inner courtyard with the recently constructed conference centre to the east (see Figure 11). The residential palace, over whose moat the bridge was constructed, is located in the center of Darmstadt and together with Mathildenhöhe makes up one of the significant historical landmarks of Darmstadt. A significant portion of the structure is made of Plexiglas®.

Figure 11: Prototype – palace moat bridge in Darmstadt, Germany.

A very close consultation with historical preservation consultants and local authorities was necessary during the planning of the footbridge. It was through their early inclusion that it became possible to implement the palace moat bridge project in this historically significant setting. The shape of the bridge was not permitted to upstage the palace. The architectural design accommodates the height difference between the two bridge embankments by incorporating two "kinks" in the bottom chord of the support structure. The top chord is horizontal. Due to conditions set by heritage consultants it was not possible to transmit loads from the bridge to the existing structure. As a result the bridge is supported independently on two pairs of columns and a 100 millimeter wide gap between the bridge and the existing structure ensures healthy clearance at both ends.

The main girders are positioned 4 meters apart from one another. Between them is a 1.6 meter wide footpath. In order to give the bridge structure more lightness and to avoid the impression of a transparent tunnel a 1 meter wide space between the main girders and the footpath was incorporated. In this way the risk of damage to the PMMA sheets could also be reduced. The design clearly separates the main bridge girders from the secondary structure. For the secondary structure steel was used exclusively with the exception of the Siberian larch footpath surface. It was only in the main structure that plastic in combination with glued laminated timber was used.

The lateral loads due to wind are transmitted to the bottom chord level through a horizontal Vierendeel truss. These steel I-beams also have the function of transferring the loads from the walkway to the main girders. In addition reactive forces are created due to temperature variations and the differing expansion of the materials.

Each of the twin timber chords 2-150x200mm were screwed together with the Plexiglas® laying between them. The 70 millimeter thick PMMA sheets carry the shear forces as webs of the main girders. The sheets have dimensions of 3 by up to 8 meters and are butt jointed in the midspan at the point of the lowest shear forces. The residual low shear forces at these butt joints have to be transmitted into the timber chords through the bolted connections.

The entire bridge was prefabricated at the factory of the wood construction company carrying out the work. The machining of the PMMA sheets such as sawing, drilling, etc. took place with tools specified by the manufacturer on a six-axis CNC machine also located there. Subsequently each of the four sheets was connected to the 26 meter long twin wood chords using bolts. The load-bearing capacity of bolted connections was analyzed at the TU Darmstadt through testing. The creation of the bore holes was supervised and monitored by the university as well as by the PMMA manufacturer. Seven coats of varnish with a total thickness of 1 millimeter were applied to the timber as weather protection and flashing was installed on the upper side. The bridge was then transported to the Darmstadt palace in one piece with trailer trucks. With great public interest it was lifted into position within a short time that night and mounted on the steel columns that had been installed that same evening (see Figure 12b). The bridge is inspected semi-annually for defects.

Figure 12a: Clearance between bridge and existing building, b: Bridge assembly.

The composite transparent plastic and timber girder system offers many opportunities not only for pedestrian bridges but also as structural components in buildings (see Figure 13a). Through the variety of composite girders with plastic it is possible, for example, to integrate the illumination in the structure (see Figure 13b) or to create etched images and to illuminate them through the material. In doing so the light is fed into the edge of the PMMA and emerges from machined (e.g. etched) surfaces. Furthermore bridges in different curved forms are feasible and have been investigated since PMMA can take on almost any shape.

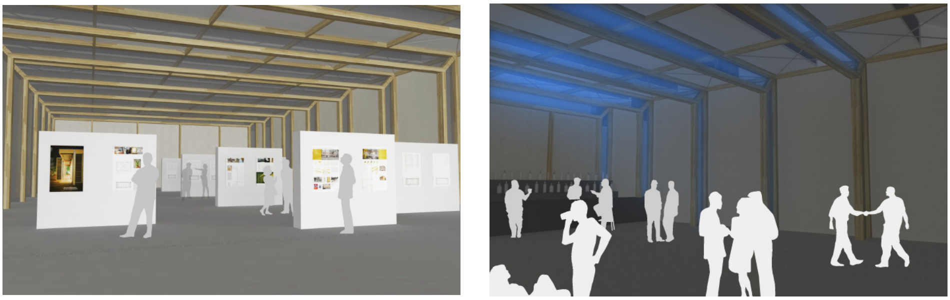

Figure 13a and b: Use of the composite girder as a structural building component.

8. Conclusion

The possibilities with plastic materials are not fully used by now. The developed composite girder tries to use the load bearing capacity of Plexiglas in a new way. The first step with the Example Schlossgrabenbrücke Darmstadt was made but every new structure has its own needs.

In research work at the Technical University of Darmstadt in cooperation with the industry partner Evonik Röhm GmbH designing with the transparent thermoplastic Plexiglas® was analyzed. As a result design methods and guidelines for mechanical processing of PMMA are presented in this paper.

Through the variety of composite girders with plastic it is possible, for example, to create etched images and to illuminate them through the material. In doing so the light is fed into the edge of the PMMA and emerges from machined surfaces. A bridge in a curved form is also possible.