Design guide
A1 (Acrylic One) structures
Active Composite Technologies (ACT) has developed Acrylic One (A1) composites. Since 20 years this material has been successfully applied in various products and applications. Besides the well-known benefits of composites (freedom of shape, light weight and strong), A1 has a superior fire resistance and absence of smoke generation during fire. This makes A1 unique for certain applications.

ACT commissioned Dr. Ir. Albert ten Busschen, technical director of Poly Products to write the present design guide to have a clear methodology for designing products and verify structural behaviour such as strength and stiffness. Poly Products has over 10 years of experience in the use of A1 in several products. Moreover, this firm has an extensive knowledge of product design, composite mechanics, production and installation.

For a critical review this report has been pre-screened by Ir. P.A. Joosse. He is an expert in composite design and the use of design methodology according to the Eurocodes. Moreover, he has been one of the authors of the recently reviewed CUR-recommendation 96 (2017) for the structural design of fibre reinforced polymer composites. We are Ir. P.A. Joosse very grateful for his critical review.

Dr. Ir. Albert ten Busschen
Technical Director Poly Products
Werkendam, 20 December 2018
In the Rentmeesterkwartier in Nijmegen an apartment building had to be renovated. In total 1800 m² of façade elements were installed that fulfill the fire requirements. A special surface texture was requested. Moreover, the elements should have a maximum weight of 15 kg/m² and must be easy to install. This lead to the selection of A1 from which panels have been manufactured. The panels were screwed directly to rules on the building. Screws were coated in the same colour as the panel and a recess in the surface at the screw location made the screw less visible.

Both the good reaction to fire (A2) and the low smoke production during fire (s1) are superior to that of e.g. polyester-based laminates. This makes it possible that products made with A1 can be applied in interior projects and in critical facade applications. Typical interior projects that were possible by using A1 with respect to fire performance are the 'Tulip walls' and the 'Auditorium'. These projects were realized by Poly Products. Typical exterior projects that were possible by using A1 with respect to fire performance are the façade elements for La Place in Amsterdam and the façade elements of the apartment building in Nijmegen. These projects were realized by BeConcrete, for La Place in Amsterdam 35 façade-elements have been produced using A1. The requirements on fire performance in combination with freedom of shape and low weight resulted in the choice for A1.

In the following table a comparison is made of laminates based on A1 and several other materials. These materials include glass reinforced laminates based on a standard polyester resin and a polyester resin with the highest possible flame-retardancy (FR), polyester concrete and wood-based panels.
A1 is typically a composite that excels in fire behaviour. However, mechanical performance and moisture resistance are on a significantly lower level than composites based on glass reinforced polyester or glass reinforced epoxy. To illustrate this, in the following table properties of a glass reinforced A1-laminate are compared with a glass mat reinforced polyester (UP) laminate (indicative values).

<table>
<thead>
<tr>
<th>Mechanical performance</th>
<th>Strength (MOR*) in MPa</th>
<th>E-modulus (MOE*) in GPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1 laminate (standard)</td>
<td>43</td>
<td>4</td>
</tr>
<tr>
<td>Polyester laminate (glass mat)</td>
<td>120</td>
<td>8</td>
</tr>
<tr>
<td>Polyester laminate (glass fabric)</td>
<td>400</td>
<td>15</td>
</tr>
<tr>
<td>PVC (wall cladding)</td>
<td>80</td>
<td>3</td>
</tr>
<tr>
<td>Plywood</td>
<td>40</td>
<td>10</td>
</tr>
<tr>
<td>OSB</td>
<td>20</td>
<td>3</td>
</tr>
<tr>
<td>MDF</td>
<td>15</td>
<td>2</td>
</tr>
<tr>
<td>Particle board</td>
<td>15</td>
<td>3</td>
</tr>
<tr>
<td>Cement-wood board (1000 kg/m³)</td>
<td>12</td>
<td>7</td>
</tr>
<tr>
<td>HPL (1350 kg/m³)</td>
<td>70</td>
<td>9</td>
</tr>
<tr>
<td>Mineral based panel (1100 kg/m³)</td>
<td>25</td>
<td>4</td>
</tr>
<tr>
<td>Mineral wool panel (100 kg/m³)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Concrete (2400 kg/m³)</td>
<td>2</td>
<td>30</td>
</tr>
</tbody>
</table>

*) Determined by bending test in direction with highest degree of reinforcement.

To quantify the term ‘no permanent moisture contact / high humidity’ the time scale in which moisture uptake by A1 must be considered. When A1 is brought in contact with moisture (e.g. by immersion) or with a high relative humidity, the process of moisture uptake takes one to several weeks, depending on the thickness of the A1 product. Therefore, the exposition to moisture or high humidity of A1 should be limited to several days maximum. With all above considerations in mind, the field of application of composites built up with A1 can be described as follows:

**Indoor applications:**
- dry areas (average RH under 75%)

**Outdoor applications:**
- facade applications
- art objects (dry and ventilated)

With respect to outdoor applications some further remarks have to be made. In case of facade applications the A1 products should not make direct contact with the ground to avoid moisture uptake. To quantify this, the A1 products in a façade should have a minimum vertical distance from the ground of 20 mm. In general for outside applications horizontal planes and locations where rain and snow can collect should be avoided.

For outside applications the durability of A1 has been investigated by TNO in 2008 and by SHR Timber Research in 2016. In outside applications the use of the specific sealer for A1 is important for maintaining the surface quality. However, for the structural performance the sealer has been found to have no influence. Moreover, it is possible to use an anti-graffiti coating.
For determining the design properties of A1 composites that are reinforced with triaxial reinforcement the orientation of the reinforcement is important. In case all reinforcement layers are stacked in the laminate with the same orientation, there will be directions that are reinforced with glass fibre bundles but there will be also a direction (the 90º direction) in which there are no reinforcement bundles oriented.

It may be expected that the direction in which there are no fibres oriented performs less strong and less stiff than the reinforced directions (0º, +45º and -45º directions). Depending on the requirements and on the quality control possibilities different approaches of the orientation of the reinforcement layers are possible:

- Controlled orientation
  - All reinforcements same orientation
  - Alternating orientation of reinforcements
- Uncontrolled orientation (random reinforcement orientation)

In this design guide for two extreme situations the design properties are determined. These properties are determined by testing laminates with 5 reinforcement layers in which the layers are oriented in a controlled manner with all reinforcements having the same orientation. Mechanical testing has been performed both on specimens oriented in the 0º direction (reinforced) and in the 90º direction (non-reinforced).

The design values obtained by the tests in 0º direction give the highest possible performance that can be obtained by controlled orientation in production where all reinforcements have the same direction and are oriented in the direction in which the mechanical load acts. The design values obtained by the tests in 90º direction give the lowest possible performance and is a safe design level for cases where an alternating reinforcement orientation is used or when the orientation is uncontrolled (random). The following figure shows schematically the directions of reinforcement in a laminate with controlled orientation of the reinforcements and the reinforcement all having the same orientation.
4. DESIGN VALUES FOR MECHANICAL PROPERTIES

For the design with reinforced A1 composite products the following laminate properties for quasi-static loading are important:

- In-plane tensile properties (E-modulus and strength) in 0° and 90° direction
- Bending properties (E-modulus and strength) in 0° and 90° direction
- Interlaminar shear strength (ILSS) and interlaminar tensile strength (*)

*) Interlaminar strengths do not depend on reinforcement direction.

Above properties have been tested by SHR. The test results are described in Appendix B and refer to SHR test report 18.0387. Using the design method, the test results are used to determine the design parameters. This procedure is described in Appendix A. The summary of the design parameters is given in the table below. These are valid for applications within the scope described in this report.

In case of possible vibrations of the structure (e.g. resonance that is induced by wind), it is recommended to analyse the eigenfrequencies of the structure. For this analysis it is recommended to use both the E-modulus for bending for stiffness calculations (1363 MPa / 477 MPa) and the E-modulus for bending for global stability calculations (901 MPa / 315 MPa).

A specific remark is made on the linear thermal expansion of A1 laminates. The coefficient of linear thermal expansion of the material has been determined by TNO to be $5 \times 10^{-6} \degree$C (see TNO report of 2008). This value is significantly lower than of other materials. This results in relatively small dilation provisions necessary. In the following table values of the coefficient of linear thermal expansion are given.

### Design Details and Mounting Methods

For designing with A1 attention has to be paid to several aspects of design details. In the following, design details and mounting methods are given. Also limits are given to what is thought to be functional for a good design. It does not necessarily mean that when the recommendations of this design guide are not followed the design is not good. What is written in this guide is to the opinion of ACS and the author a good way for designing with reinforced A1 products.

Many design details are determined by the fact that A1 for structural parts is always processed with reinforcement layers (triaxial glass fabric) that is built up together with the resin into a laminate in a mould. Because the application of the reinforcement layers in a mould, the radius of the mould surface should have a minimum radius. When the radius in a product becomes too small either part of an outer product edge will be non-reinforced (and therefore weak) or an inner product edge will suffer from badly impregnated reinforcement. Therefore, as a general rule product edges should have a radius $R$:

$$ R \geq 5 \text{ mm} $$

It must be remarked that the making of products with A1 with edges with a smaller radius or even sharp edges is not difficult from production point of view but the structural performance (strength) of such edges will possibly be low.

Furthermore, when products are made with flat parts the free span of these parts ($p$) should not be too large. This depends on the thickness of the laminate. Also the total length between two supports ($s$) should not be too large. For parts that are only supported at one side the length of the free span ($q$) is limited. However, an extra flange allows for a larger free span. Schematic illustrations on the next page show the meaning of the parameters $p$, $q$ and $s$. In the table below the maximum values for the parameters are given in relation to the laminate thickness. The values are given for three thicknesses that will cover a range of thicknesses that will be often used for laminates made with A1.

### Design Values for Mechanical Properties

<table>
<thead>
<tr>
<th>Property and unit</th>
<th>0° direction</th>
<th>90° direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>In-plane tension</td>
<td>E-modulus, stiffness (MPa)</td>
<td>1228</td>
</tr>
<tr>
<td></td>
<td>E-modulus, glob. stab. (MPa)</td>
<td>812</td>
</tr>
<tr>
<td></td>
<td>E-modulus, loc. stab. (MPa)</td>
<td>625</td>
</tr>
<tr>
<td></td>
<td>Tensile strength (MPa)</td>
<td>29</td>
</tr>
<tr>
<td>Bending</td>
<td>E-modulus, stiffness (MPa)</td>
<td>1363</td>
</tr>
<tr>
<td></td>
<td>E-modulus, glob. stab. (MPa)</td>
<td>901</td>
</tr>
<tr>
<td></td>
<td>E-modulus, loc. stab. (MPa)</td>
<td>693</td>
</tr>
<tr>
<td></td>
<td>Flexural strength (MPa)</td>
<td>11</td>
</tr>
<tr>
<td>ILSS</td>
<td>Shear strength (MPa)</td>
<td>1.50</td>
</tr>
<tr>
<td>Transverse strength</td>
<td>Tensile strength (MPa)</td>
<td>0.27</td>
</tr>
</tbody>
</table>

### Design Values for Mechanical Properties

<table>
<thead>
<tr>
<th>Laminate thickness (mm)</th>
<th>Maximum span of flat surface (mm)</th>
<th>Maximum free span length (mm)</th>
<th>Maximum length between supports (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Without flange</td>
<td>With flange</td>
<td>Without flange</td>
</tr>
<tr>
<td>3</td>
<td>300</td>
<td>100</td>
<td>200</td>
</tr>
<tr>
<td>5</td>
<td>400</td>
<td>150</td>
<td>250</td>
</tr>
<tr>
<td>7</td>
<td>500</td>
<td>200</td>
<td>300</td>
</tr>
</tbody>
</table>

![Diagram showing design parameters](image)
5. DESIGN DETAILS AND MOUNTING METHODS

For flanges, the minimum and maximum length depends on the thickness. Also for multiple flanges minimum and maximum lengths are dependent on the laminate thickness. In all cases the minimum radius of the corner at the mould side is 5 mm. The following figures and tables give the numbers.

Stiffeners can be realised during the hand lay-up process by incorporating profiles in the laminate. Such a profile then acts as a core material in a local sandwich build up. Suitable materials that can be used as a core material for stiffeners are plywood, solid wood, aluminium profiles, EPS foam and PET foam. When a core material is used, the outside surface of it should be pre-wetted with resin during laminating to ensure good adhesion with the reinforced layers.

It is recommended to use wood-based core materials only for A1 products in indoor applications. Moreover, when wood-based materials are used as a core material, the top side of the resulting structure can also be used for connecting other parts by screwing.

The following pictures show methods to incorporate profiles as a core in a laminate.

<table>
<thead>
<tr>
<th>Laminate thickness (mm)</th>
<th>Flange length (mm)</th>
<th>Minimum radius (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>30</td>
<td>5</td>
</tr>
<tr>
<td>5</td>
<td>40</td>
<td>5</td>
</tr>
<tr>
<td>7</td>
<td>50</td>
<td>5</td>
</tr>
</tbody>
</table>

Joggles are often used to fit a product into a neighbouring element. The space between the joggle and the adjacent element can be kept open (air) in order that surface irregularities will not hinder the free movement. On the contrary, for a glued space the thickness of the space should be limited to a maximum to avoid a too thick adhesive layer.

<table>
<thead>
<tr>
<th>Laminate thickness (mm)</th>
<th>Minimum radius (mm)</th>
<th>Space dimensions (thickness and overlap)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Open (air)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Maximum h (mm)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Maximum overlap (mm)</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>7</td>
</tr>
<tr>
<td>7</td>
<td>5</td>
<td>9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Laminate thickness (mm)</th>
<th>Flange length (mm)</th>
<th>Flange length (mm)</th>
<th>Flange length (mm)</th>
<th>Minimum radius (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>30</td>
<td>100</td>
<td>30</td>
<td>100</td>
</tr>
<tr>
<td>5</td>
<td>40</td>
<td>150</td>
<td>40</td>
<td>150</td>
</tr>
<tr>
<td>7</td>
<td>50</td>
<td>200</td>
<td>50</td>
<td>200</td>
</tr>
</tbody>
</table>
6. REFERENCE PROJECTS

Tulip panels Amsterdam

In 2006 Fokkema Architects made a design for an internal curved wall for the new office of IGZ (national office for health inspection) in Amsterdam. Besides that, the wall has a complex shape (the radius of curvature varies from place to place) also relief pictures of tulips were to be incorporated in the surface. Because of these requirements on shape and surface finish the only possible material for making this wall is a fibre reinforced composite.

Because of requirements on fire behaviour and smoke development the use of well-known synthetic resins for making composite products (polyester, epoxy) is not possible. But A1 could easily meet the fire and smoke requirements and can be laminated in a mould so that the different curvatures and the surface finish are possible.

In 2007 Poly Products has developed a method for realizing the curved walls. The method consisted in the making of cylindrically shaped panels with different curvatures. These panels were to be mounted on a wood-based back-structure. It was important that the method allowed for easy installation and flexibility in adjusting to ensure that the edges fit smoothly to the neighbouring panels.

Most panels have a width of 1200 mm. By using a flexible silicone mould layer with the tulip print, panels with different curvatures could be made by placing this layer on a curved substructure. Thus, panels were made with a radius varying from $-6000$ mm (concave) to $+6000$ mm (convex). For easy mounting the elements were provided with two or three steel angle piece at the back of the panel on the top. By hanging these angle pieces on a wooden back structures the element could be adjusted until it fitted well, see figure below.

Because of requirements on fire behaviour and smoke development the use of well-known synthetic resins for making composite products (polyester, epoxy) is not possible. But A1 could easily meet the fire and smoke requirements and can be laminated in a mould so that the different curvatures and the surface finish are possible.

After the element was positioned and fixed with the angle pieces on top, an wooden alignment block with a layer of gap filling adhesive was moved from the bottom by using a thin, long screw, see picture ‘positioning’ below. Then, by sliding a temporary fixation block over the screw the alignment block can be temporarily fixed until the adhesive is solidified. The last picture ‘end result’ shows the result after removing the screw and the temporary fixation block.

In order to make the connection with the neighbouring elements flush on the lower part of the element a glued alignment block has been used.
Auditorium Amsterdam

In 2007 Erick van Egeraat Architects (EEA) made a design for a covering of the auditorium inside the Mahler building that was built in Amsterdam. Again, because of the complex shape to be realised in combination with the requirements on fire behaviour the choice to use A1 was obvious.

In 2008 Poly Products has developed a method for realizing and mounting of the elements. Each element has been laminated with A1 in a mould. In the inner part of the element 36 mm plywood strips have been incorporated as mounting beams. While still in the mould, strips of 18 mm plywood strips were screwed to these beams. The plywood strips, 6 or 8 per element and extending from the back of the element were used later on for mounting the element in the building.

The principle of the mounting of an element to the building structure is based on the fixation of the protruding 18 mm plywood strips at the back of the element to wood beams that have been installed to the building structure, see figure below.

For the dilatation gap between two elements that are in line with each other in first instance it was designed to realize this by means of a joggle. However, this would involve additional inserts in each mould. Moreover, to obtain a situation that is nicely flush from one element to the other would become difficult. And there would be the risk of damaging the joggle during mounting of the element when the joggle of one element had to be fitted into the internal space of the neighbouring element. With the connection of two elements as depicted below it is illustrated how this has been solved with another detailing.

Instead of a joggle, both elements were provided with a flat head plane. On one of the elements spacer rubbers were stuck to provide the desired dilatation distance. Near the visible edge, a white, compressible rubber strip has been stuck at a fixed distance of the outer edges. The principle is depicted in the figure below.
Façade panels Amsterdam

In 2017 Rijnboutt architects has designed the Fletcher Amsterdam Olympic Hotel. In the facade elements have been designed with a concrete look between the windows. These elements are oriented both horizontally and vertically. The building company Van Wijnen Lelystad has investigated the possibility to use thin-walled profiles for these elements together with Poly Products. By using thin-walled profiles, a low weight can be realised that facilitates the mounting process and reduces the requirements on the anchoring of the elements to the building.

Of the horizontal elements different types have been produced. The type that was most critical in wind loading will be considered in the following. The figure shows the cross-section of this element and relevant dimensions.

For the structural evaluation specially the wind forces are important to evaluate. In the following this is described for the given profile.

Wind loading on the element

The maximum height for the elements is 47 meter above ground level. The building is located in a non-built environment in Amsterdam. According to Eurocode NEN-EN 1991-1-4 these parameters determine a design wind pressure of:

\[ p_d = 1.34 \text{kPa} = 1340 \text{ Pa} = 1340 \text{ N/m}^2 \]

For wind suction, the so-called external pressure coefficient amounts to:

\[ C_{pe} = -1.4 \]

For wind suction, the so-called external pressure coefficient amounts to:

\[ C_{pe} = -1.4 \]

Because the wind loading is dynamical, the load factor is:

\[ \gamma_w = 1.5 \]

The projected area of one meter of the profile is:

\[ A = 0.53 \text{ m}^2 \]

From this, the design force, \( F_d \), for one meter of profile can be calculated:

\[ F_d = p_d \cdot |C_{pe}| \cdot \gamma_w \cdot A = 1340 \cdot 1.4 \cdot 1.5 \cdot 0.53 = 1491 \text{ N} \]

Strength of connection to the building

The strength of the connection of the profile to the building is determined by the method of connecting. A screw with a diameter of 5 mm and a shaft length of 60 mm is selected for this. For spreading the load, a washer is used with a diameter of 29 mm. Screw and washer are shown in the photo below.

The elements are mounted with these type of screws to rulers of spruce. With an effective depth of the screw in the spruce ruler of 29 mm, the pull-out strength is 1821 N (according to EN 1995 for wood structures). For this pull-out strength a material factor is to be used of \( \gamma_m = 2 \). Thus, the design pull-out strength of a screw, \( F_{pull} \), is:

\[ F_{pull} = 1821 \cdot \gamma_m = 1821 \cdot 2 = 911 \text{ N} \]

Another aspect to consider is the pull-through strength of the screw and washer through the A1 flange. In the figure below it is illustrated how the screw and washer can be pulled through.

An interlaminar shear stress in the laminate with occur as a result of the force. The area of the fracture, \( A_f \), is determined by the length of the fracture, \( b = 75 \text{ mm} \), and the thickness of the laminate, \( t = 5 \text{ mm} \). The shear stress distribution over the thickness will be parabolical and results in the following fracture force, \( F_f \):

\[ F_f = \frac{2}{3} \cdot \frac{d}{t} \cdot A_f = \frac{2}{3} \cdot \frac{1.50}{5} \cdot 75 \cdot 5 = 375 \text{ N} \]

This means that one set of two screws is necessary for every 1/1.99 = 0.50 meter. Thus, along the flange the screws should therefore have a distance of 500 mm maximum. In the project the maximum distance of the screws is selected to be 500 mm. Moreover, the maximum distance of screws near the end of the profile is selected to be 90 mm. Because the lengths of the elements vary, sometimes the distance between two screws is less than 500 mm. A typical screw pattern in the project is illustrated.
In order to avoid accumulation of moisture due to condensation, an opening is created between the element and the building structure.

The elements have been produced from polyester moulds using hand lay-up. For stiffening of the element in width direction aluminum profiles have been incorporated in the back-side of the elements. These aluminum profiles also have been used to release the product from the mould and for further handling and transportation.

These ventilation openings are realized by placing 3 mm EPDM-rubber strips between the element and the building during mounting.

Façade elements La Place Amsterdam

The old façade of the building had to be replaced. First the old façade has been scanned by 3D-laser-scanning. In this manner the façade could be rebuilt exactly in the same dimensions and with the same details. From the scanned data, a 3D-model has been made with all 35 A1-elements to be made.

For each element to be made a direct mould has been produced by NedCam. The direct moulds were made of an EPS-base with a PU-paste layer that was milled to the exact dimensions.

In the moulds the elements have been produced using A1. These were build up by starting with a non-reinforced resin layers, followed by laminating four layers of triaxial glass reinforcement of 160 g/m². After curing an aluminum mounting structure is connected to the back of the panel by laminating. Including the mounting structure the elements have a surface weight of 20 kg/m².

Because of the low weight the elements were easy to install. In this manner the façade of La Place in Amsterdam has been built.
**Bridge elements Amersfoort**

For a fly-over over the railway in Amersfoort the side elements have been designed as concrete elements. However, such elements would weigh 900 kg per meter bridge-edge. Because the total length of elements is 200 meter this would result in a weight of 180 tonnes. This was not acceptable. Therefore the elements have been made of A1 with a surface that has a concrete look. By using an integrated aluminum mounting structure the element made of A1 weighs only 150 kg per meter. This is more than 80% lighter than the concrete elements.

The A1 elements have been laminated in a mould, see photo below. Still in the mould, the aluminum mounting frame is connected to the A1 elements by laminating. In this manner the aluminum frame could be positioned accurately, which was important for the mounting of the assembly at the steel structure on the bridge edge. The second photo below shows how this aluminum structure can be connected to the bridge edge.

Additional advantages occurred as a result of the low weight of the A1-elements. Significant savings on the complete mounting system became possible because of the low weight. Moreover, the transportation to the building site and the mounting of the elements was significantly cheaper as a result of the low weight. The mounting time of the elements was 50% shorter than it would be the case when concrete elements would have been used.

It was very important that the steel structure on the bridge edge was adjusted accurately. In this manner, the aluminum structure could be connected directly to it and resulted in a perfect alignment of the elements. The photo’s below show the process of mounting of the elements at the bridge edge in Amersfoort.

The final result is a bridge edge built up from elements that are accurately aligned. A concrete look is realized by using A1 that has 80% less weight than a bridge edge that would be made of concrete.
7. SUMMARY OF DESIGN METHOD FOR A1

Field of application

Relatively dry and no permanent loading
- Maximum temperature of application: 115 °C
- Inside applications: areas with mean Relative Humidity (RH) below 75%
- Outside applications: no permanent moisture, no direct soil contact

A1 laminate with reinforcement
- First layer on mould: non-reinforced layer of 0.5 to 1.0 mm
- Reinforcement layers with triaxial glass fabric of 160 g/m²
- Minimum 3 layers and maximum 7 layers of reinforcement in a laminate
- Use of wood-based core materials only for A1 products in indoor applications
- Moulded edges must have a radius of R ≥ 5 mm
- Check detailing of flanges, joggles and inserts
- Verify the span of flat surfaces, free span length
- Outside applications: no permanent moisture, no direct soil contact
- Inside applications: areas with mean Relative Humidity (RH) below 75%

A1 laminate with reinforcement
- Relatively dry and no permanent loading
- Maximum temperature of application: 115 °C
- Inside applications: areas with mean Relative Humidity (RH) below 75%
- Outside applications: no permanent moisture, no direct soil contact

Design details
- The coefficient of linear thermal expansion reinforced A1 laminates is 5·10⁻⁶/°C.
- First layer on mould: non-reinforced layer of 0.5 to 1.0 mm
- Reinforcement layers with triaxial glass fabric of 160 g/m²
- Minimum 3 layers and maximum 7 layers of reinforcement in a laminate
- Use of wood-based core materials only for A1 products in indoor applications
- Moulded edges must have a radius of R ≥ 5 mm
- Check detailing of flanges, joggles and inserts
- Verify the span of flat surfaces, free span length
- Outside applications: no permanent moisture, no direct soil contact
- Inside applications: areas with mean Relative Humidity (RH) below 75%

Controlled lay-up: design values for 0° direction can be used (for the reinforced direction)

Other lay-up (alternating, random): design values for 90° direction can be used always, in any direction

A. Design method according to Eurocode

In Eurocode EN 1990 the generally accepted design method for structural parts is described. For the structural evaluation the incorporation of loads is described in Eurocode EN 1991. The incorporation of the material behaviour is only standardised for traditional materials like steel, concrete, wood, aluminium and masonry in Eurocodes EN 1992 to EN 1999. For A1 there is no description in the Eurocodes how to deal with this material specifically. However, EN 1990 describes a methodology how to determine material properties for the structural evaluation of a design by doing tests. For this, Annex D of this Eurocode is used: Annex D (informative) Design assisted by testing.

When following the assessment of a material property via the characteristic value (D7.2) for a certain material property X, a design value Xd can be determined from tests data in the following manner:

\[ X_d = \eta_t \cdot X_{k(n)} / \gamma_m \]

In this formula the parameters represent the following:

- \( X_d \): design value of material property X
- \( \eta_t \): conversion factor for temporary storage
- \( X_{k(n)} \): 5% characteristic value measured values
- \( \gamma_m \): material factor
- \( m_x \): mean value of measured values
- \( k_n \): factor for 5% characteristic value
- \( V_x \): coefficient of variation ( = s_x / m_x )
- \( s_x \): standard deviation of measured values

The value of \( k_n \) depends on the number of test samples that have been tested. These values are listed in Table D1 of the standard. In the following table some of these values are given assuming that the coefficient of variation (V) is unknown beforehand.

<table>
<thead>
<tr>
<th>Number tests (n)</th>
<th>5</th>
<th>8</th>
<th>10</th>
<th>16 (*)</th>
<th>20</th>
<th>Infinite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value of ( k_n )</td>
<td>2.33</td>
<td>2.00</td>
<td>1.92</td>
<td>1.82</td>
<td>1.76</td>
<td>1.64</td>
</tr>
</tbody>
</table>

*) The value of \( k_n \) is determined by linear interpolation between \( n = 10 \) and \( n = 20 \)

1. Conversion factor for temperature

As is customary for composites the conversion factor for temperature is set to 1 (no additional effect) in case the design temperature remains below 40 °C under the glass transition temperature \( T_g \) of the material (see also CUR-96).

\[ \eta_{t,T} = 1 \] for design temperature \( T_d < T_g – 40 \)

For A1 the glass transition temperature \( T_g \), is determined to be 155 °C and therefore it is recommended to allow for design temperatures up till 115 °C. In that case the conversion factor for temperature is 1.

2. Conversion factor for moisture

In case of A1 the scope for structural applications is limited to relatively dry environments. However, A1 is known to be sensitive for variations in moisture. A test series has been performed to compare mechanical performance of A1 laminates that have been stored at 50 % RH with laminates that have been stored at 86 % RH until equilibrium (both at room temperature). These results are listed in Appendix B.

For A1 it has been found that strength and stiffness will be lowered when stored at 86 % RH as compared to storage at 50 % RH. However, there is a difference in effect between 0° tested properties and 90° tested properties. This is evaluated in Appendix B and results in the following conversion factors for moisture.

\[ \eta_{t,M} = 0.75 \] for 0° properties
\[ \eta_{t,M} = 0.60 \] for 90° properties

8. APPENDIX

A. Design method according to Eurocode

In Eurocode EN 1990 the generally accepted design method for structural parts is described. For the structural evaluation the incorporation of loads is described in Eurocode EN 1991. The incorporation of the material behaviour is only standardised for traditional materials like steel, concrete, wood, aluminium and masonry in Eurocodes EN 1992 to EN 1999. For A1 there is no description in the Eurocodes how to deal with this material specifically. However, EN 1990 describes a methodology how to determine material properties for the structural evaluation of a design by doing tests. For this, Annex D of this Eurocode is used: Annex D (informative) Design assisted by testing.

When following the assessment of a material property via the characteristic value (D7.2) for a certain material property X, a design value Xd can be determined from tests data in the following manner:

\[ X_d = \eta_t \cdot X_{k(n)} / \gamma_m \]

In this formula the parameters represent the following:

- \( X_d \): design value of material property X
- \( \eta_t \): conversion factor for temporary storage
- \( X_{k(n)} \): 5% characteristic value measured values
- \( \gamma_m \): material factor
- \( m_x \): mean value of measured values
- \( k_n \): factor for 5% characteristic value
- \( V_x \): coefficient of variation ( = s_x / m_x )
- \( s_x \): standard deviation of measured values

The value of \( k_n \) depends on the number of test samples that have been tested. These values are listed in Table D1 of the standard. In the following table some of these values are given assuming that the coefficient of variation (V) is unknown beforehand.

<table>
<thead>
<tr>
<th>Number tests (n)</th>
<th>5</th>
<th>8</th>
<th>10</th>
<th>16 (*)</th>
<th>20</th>
<th>Infinite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value of ( k_n )</td>
<td>2.33</td>
<td>2.00</td>
<td>1.92</td>
<td>1.82</td>
<td>1.76</td>
<td>1.64</td>
</tr>
</tbody>
</table>

*) The value of \( k_n \) is determined by linear interpolation between \( n = 10 \) and \( n = 20 \)

1. Conversion factor for temperature

As is customary for composites the conversion factor for temperature is set to 1 (no additional effect) in case the design temperature remains below 40 °C under the glass transition temperature \( T_g \) of the material (see also CUR-96).

\[ \eta_{t,T} = 1 \] for design temperature \( T_d < T_g – 40 \)

For A1 the glass transition temperature \( T_g \), is determined to be 155 °C and therefore it is recommended to allow for design temperatures up till 115 °C. In that case the conversion factor for temperature is 1.

2. Conversion factor for moisture

In case of A1 the scope for structural applications is limited to relatively dry environments. However, A1 is known to be sensitive for variations in moisture. A test series has been performed to compare mechanical performance of A1 laminates that have been stored at 50 % RH with laminates that have been stored at 86 % RH until equilibrium (both at room temperature). These results are listed in Appendix B.

For A1 it has been found that strength and stiffness will be lowered when stored at 86 % RH as compared to storage at 50 % RH. However, there is a difference in effect between 0° tested properties and 90° tested properties. This is evaluated in Appendix B and results in the following conversion factors for moisture.

\[ \eta_{t,M} = 0.75 \] for 0° properties
\[ \eta_{t,M} = 0.60 \] for 90° properties

A. Design method according to Eurocode

In Eurocode EN 1990 the generally accepted design method for structural parts is described. For the structural evaluation the incorporation of loads is described in Eurocode EN 1991. The incorporation of the material behaviour is only standardised for traditional materials like steel, concrete, wood, aluminium and masonry in Eurocodes EN 1992 to EN 1999. For A1 there is no description in the Eurocodes how to deal with this material specifically. However, EN 1990 describes a methodology how to determine material properties for the structural evaluation of a design by doing tests. For this, Annex D of this Eurocode is used: Annex D (informative) Design assisted by testing.

When following the assessment of a material property via the characteristic value (D7.2) for a certain material property X, a design value Xd can be determined from tests data in the following manner:

\[ X_d = \eta_t \cdot X_{k(n)} / \gamma_m \]

In this formula the parameters represent the following:

- \( X_d \): design value of material property X
- \( \eta_t \): conversion factor for temporary storage
- \( X_{k(n)} \): 5% characteristic value measured values
- \( \gamma_m \): material factor
- \( m_x \): mean value of measured values
- \( k_n \): factor for 5% characteristic value
- \( V_x \): coefficient of variation ( = s_x / m_x )
- \( s_x \): standard deviation of measured values

The value of \( k_n \) depends on the number of test samples that have been tested. These values are listed in Table D1 of the standard. In the following table some of these values are given assuming that the coefficient of variation (V) is unknown beforehand.

<table>
<thead>
<tr>
<th>Number tests (n)</th>
<th>5</th>
<th>8</th>
<th>10</th>
<th>16 (*)</th>
<th>20</th>
<th>Infinite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value of ( k_n )</td>
<td>2.33</td>
<td>2.00</td>
<td>1.92</td>
<td>1.82</td>
<td>1.76</td>
<td>1.64</td>
</tr>
</tbody>
</table>

*) The value of \( k_n \) is determined by linear interpolation between \( n = 10 \) and \( n = 20 \)
3. Conversion factor for creep
In case of A1 the scope for structural applications is limited to situations with no significant permanent loading. Allowed loadings are non-permanent, e.g. wind loading. It must be checked that permanent loading because of weight is negligible. In these cases no creep effects are to be expected and the conversion factor for creep is set to 1:

\[ \eta_{ct} = 1 \]

4. Conversion factor for fatigue
For composites it is customary to use the following conversion factor in case of cyclic (fatigue) loading (see also CUR-96):

\[ \eta_{cf} = 0.9 \]

Thus, for the design for applications where the temperature remains under 115 °C, that are relatively dry and impose no significant permanent loading on the structure, the conversion factor can be calculated from the above conversion factors to be:

\[ \eta = \eta_{ct} \cdot \eta_{cf} \cdot \eta_{ct} \cdot \eta_{cf} = 1 \cdot 0.75 \cdot 1 \cdot 0.9 = 0.68 \]

For 0º properties and for direction-independent (interlaminar) properties:

\[ \eta = \eta_{ct} \cdot \eta_{cf} \cdot \eta_{ct} \cdot \eta_{cf} = 1 \cdot 0.60 \cdot 1 \cdot 0.9 = 0.54 \]

For 90º properties

In the same manner the material factor is evaluated. This factor consists of a part that takes into account the possible uncertainties in the determination of the property. For the determination of the property from tests this factor is:

\[ \gamma_{M} = 1.15 \] (when determined from tests)

When the property is determined from theoretical models or literature references this factor would be 1.35 (more uncertainty than with testing). But this is not the case here.

For the variations in the manufacturing method it is assumed that the product is made by means of hand lay-up. Furthermore, it is assumed that the product is fully cured. It then depends on the expected coefficient of variation what material factor is to be used. Because it is clear from the tests that the coefficient of variation is generally larger than 10 %, the values from the CUR-96 are adopted for the higher coefficient of variation. Then, with this manufacturing method the factor is (see also CUR-96, Table 2.2):

\[ \gamma_{M} = 1.0 \] For stiffness

\[ \gamma_{M} = 1.5 \] For strength and global stability (buckling)

\[ \gamma_{M} = 2.0 \] For local stability (wrinkling)

Combining the two factors, the material factor becomes:

\[ \gamma_{m} = \eta_{M} \cdot \gamma_{M} = 1.15 \cdot 1.0 = 1.15 \] (stiffness)

\[ \gamma_{m} = \eta_{M} \cdot \gamma_{M} = 1.15 \cdot 1.5 = 1.73 \] (strength, glob. stability)

\[ \gamma_{m} = \eta_{M} \cdot \gamma_{M} = 1.15 \cdot 2.0 = 2.30 \] (local stability)

Taking above parameters in consideration and using the data from a test series of n tests (with accompanying value for k), the formula for the design property becomes:

\[ X_{d} = \left( \frac{\eta_{m}}{\gamma_{m}} \right) \cdot X_{n} \]

\[ X_{d} = \left( \frac{\eta_{m}}{\gamma_{m}} \right) \cdot m_{X} \cdot \left( 1 - k \cdot V_{X} \right) \]

Because the conversion factor depends on the direction of the property considered (0º and 90º) and the material factor depends on the type of mechanical analysis considered (stiffness, strength, global stability and local stability), first a table is made of the coefficient (\( \eta_{m} / \gamma_{m} \)).

### 8. APPENDIX

#### 3. Conversion factor for creep

<table>
<thead>
<tr>
<th>Test (AM)</th>
<th>Property and unit</th>
<th>0º direction</th>
<th>90º direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>In-plane tension</td>
<td>E-modulus (MPa)</td>
<td>2312</td>
<td>57</td>
</tr>
<tr>
<td></td>
<td>Tensile strength (MPa)</td>
<td>550</td>
<td>18</td>
</tr>
<tr>
<td>Bending</td>
<td>E-modulus (MPa)</td>
<td>3726</td>
<td>43</td>
</tr>
<tr>
<td></td>
<td>Flexural strength (MPa)</td>
<td>2984</td>
<td>43</td>
</tr>
<tr>
<td>ILSS</td>
<td>Shear strength (MPa)</td>
<td>4.5</td>
<td>32</td>
</tr>
<tr>
<td>Transverse strength</td>
<td>Tensile strength (MPa)</td>
<td>0.8</td>
<td>7.4</td>
</tr>
</tbody>
</table>

#### 4. Conversion factor for fatigue

<table>
<thead>
<tr>
<th>Design values</th>
<th>Property and unit</th>
<th>0º direction</th>
<th>90º direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>In-plane tension</td>
<td>E-modulus, stab. (MPa)</td>
<td>1228</td>
<td>215</td>
</tr>
<tr>
<td></td>
<td>E-modulus, glob. stab. (MPa)</td>
<td>812</td>
<td>142</td>
</tr>
<tr>
<td></td>
<td>E-modulus, loc. stab. (MPa)</td>
<td>625</td>
<td>105</td>
</tr>
<tr>
<td>Bending</td>
<td>E-modulus, stab. (MPa)</td>
<td>1363</td>
<td>901</td>
</tr>
<tr>
<td></td>
<td>E-modulus, glob. stab. (MPa)</td>
<td>477</td>
<td>315</td>
</tr>
<tr>
<td></td>
<td>E-modulus, loc. stab. (MPa)</td>
<td>693</td>
<td>233</td>
</tr>
<tr>
<td>ILSS</td>
<td>Flaxural strength (MPa)</td>
<td>11</td>
<td>6</td>
</tr>
<tr>
<td>Transverse strength</td>
<td>Shear strength (MPa)</td>
<td>1.50</td>
<td></td>
</tr>
</tbody>
</table>

#### 5. Interlaminar shear strength (ILSS, *)

- The laminate panels have been made without a gelcoat-layer (non-reinforced resin layer) and without any other additives.
- Laminates were cut up on a flat, smooth panel as a mould.
- All reinforcement layers have been stacked with the same orientation.
In a preliminary test programme different laminate thicknesses have been tested but the laminate thickness did not appear to have a significant influence on mechanical properties. Therefore, for the determination of the mechanical properties for this design guide test laminates have been made using 5 reinforcement layers. As described in the chapter on the laminate structure, these laminates have been build up by hand laminating, starting with a non-reinforced A1 layer of 0.5 to 1.0 mm thickness, followed by laminating the reinforcement layers.

In this manner 4 laminates have been made by means of hand lay-up on a flat plate with dimensions 600 x 1000 mm. After solidification the plates have been released and stored in a manner that both sides could ventilate for evaporation of moisture in the laminate.

Specimens for testing have been cut by means of water jetting, see photograph of specimens that are cut from one of the plates.

Tensile tests
The tensile tests have been performed according to ISO 527-4 by testing strips of 50 x 250 mm. For clamping, tabs have been applied on the ends of the strips. Testing is performed with a speed of 1 mm/min until fracture. Sets of n = 8 specimens have been tested, both in 0° and 90° directions and conditioned in two ways. The results are given in the table below.

<table>
<thead>
<tr>
<th>(n = 8 per set)</th>
<th>Strength Mean value (MPa)</th>
<th>V.C. (%)</th>
<th>E-modulus Mean value (MPa)</th>
<th>V.C. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>23 °C, 50% RH</td>
<td>0° - direction 56.54</td>
<td>6.4</td>
<td>2312</td>
<td>5.3</td>
</tr>
<tr>
<td></td>
<td>90° - direction 18.13</td>
<td>6.0</td>
<td>550 (*)</td>
<td>8.2</td>
</tr>
<tr>
<td>20 °C, 86% RH</td>
<td>0° - direction 47.36</td>
<td>4.5</td>
<td>2138</td>
<td>9.0</td>
</tr>
<tr>
<td></td>
<td>90° - direction 13.24</td>
<td>4.9</td>
<td>473</td>
<td>6.8</td>
</tr>
</tbody>
</table>

* For the test series only 7 measurements for E-modulus could be used.

The percentage of property loss when the results are compared of conditioning at a high humidity level with conditioning at a standard humidity level is given in the table below.

<table>
<thead>
<tr>
<th>Property in humid condition</th>
<th>Test</th>
<th>Loss compared to standard condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strength</td>
<td>0°</td>
<td>16 %</td>
</tr>
<tr>
<td></td>
<td>90°</td>
<td>27 %</td>
</tr>
<tr>
<td>E-modulus</td>
<td>0°</td>
<td>8 %</td>
</tr>
<tr>
<td></td>
<td>90°</td>
<td>14 %</td>
</tr>
</tbody>
</table>

In the following the type of tests performed is described and the summary of the results. A detailed report on the tests and the test results is given by SHR (report 18.0387).

Conditioning
All specimens have been conditioned for 1 month at SHR Research. Half of the specimens were conditioned in the standard laboratory conditions (23 °C, 50% RH) and the other half in a relatively humid condition (20 °C, 86% RH).

Flexural tests
The flexural tests have been performed according to ISO 14125 by testing strips of 50 x 100 mm in three-point bending with a support length of 64 mm. The results are given in the table below.

<table>
<thead>
<tr>
<th>(n = 16 per set)</th>
<th>Strength Mean value (MPa)</th>
<th>V.C. (%)</th>
<th>E-modulus Mean value (MPa)</th>
<th>V.C. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>23 °C, 50% RH</td>
<td>0° - direction 43.05</td>
<td>17.6</td>
<td>3726</td>
<td>21.3</td>
</tr>
<tr>
<td></td>
<td>90° - direction 31.97</td>
<td>22.7</td>
<td>2984</td>
<td>35.5</td>
</tr>
<tr>
<td>20 °C, 86% RH</td>
<td>0° - direction 33.92</td>
<td>15.9</td>
<td>2705</td>
<td>24.8</td>
</tr>
<tr>
<td></td>
<td>90° - direction 20.67</td>
<td>22.4</td>
<td>1700</td>
<td>20.2</td>
</tr>
</tbody>
</table>

The loss in strength and stiffness in the 0° - direction is at the order of 25 % when going from a standard condition to a relatively humid condition. This results in a conversion factor 𝜈𝑀 of 0.75 for the 0° properties (75 % retention).

The loss in strength and stiffness in the 90° - direction is in the order of 40 % when going from a standard condition to a relatively humid condition. This results in a conversion factor 𝜈𝑀 of 0.60 for the 90° properties (60 % retention).

Interlaminar shear tests (ILSS)
The interlaminar shear tests have been performed according to ISO 14130 by testing strips of 30 x 40 mm in three-point bending with a short support length of 20 mm. Only samples conditioned in the laboratory condition and oriented in 90° direction have been tested. The results are given in the table below.

<table>
<thead>
<tr>
<th>(n = 16)</th>
<th>Strength (ILSS) Mean value (MPa)</th>
<th>V.C. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>23 °C, 50% RH</td>
<td>90° - direction 4.53</td>
<td>8.2</td>
</tr>
</tbody>
</table>

Generalisation of the effect of humidity
Considering the analysis of the effect of humidity both in the tensile tests and in the flexural tests the following conclusions are made.

Clearly the loss in properties due to a higher humidity is higher in case of the 90° direction than in case of the 0°-direction. Moreover, the effect is stronger for the flexural properties than for the tensile properties.

These results are generalized in the following, pragmatic approach.
Interlaminar tensile tests (‘dolly test’)

The interlaminar tensile tests have been performed according to the so-called ‘dolly test’. This done on four test strips of 50 x 300 mm on which five metal cylinders were glued. Only samples conditioned in the laboratory condition and oriented in 90° direction have been tested. The results are given in the table below.

<table>
<thead>
<tr>
<th>(n = 20)</th>
<th>Strength (interlaminar tension)</th>
<th>Mean value (MPa)</th>
<th>V.C. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>23 °C, 50% RH</td>
<td></td>
<td>0.81</td>
<td>7.4</td>
</tr>
<tr>
<td>90° - direction</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

C. Literature

Eurocode – Basis of structural design

Eurocode – Actions on structures

CUR 96 Recommendation ‘Vezelversterkte kunststoffen in bouwkundige en civieltechnische toepassingen.’

Outdoor Durability of Acrylic One

Classification to Reaction to Fire Performance in Accordance with EN 13501

Duurzaamheid van Acrylic One gevelbekleding
SHR-rapport 15.0175-1 (2016)

Classification of Reaction to Fire Performance in Accordance with EN 13501-1:

Mechanical properties of Acrylic One laminates
SHR report 18.0387 (2018)
The information in this user manual is considered accurate. The user needs to ascertain the suitability of the product for the application the user wishes to apply. When in doubt, the user needs to carry out tests to ascertain the suitability of the product.