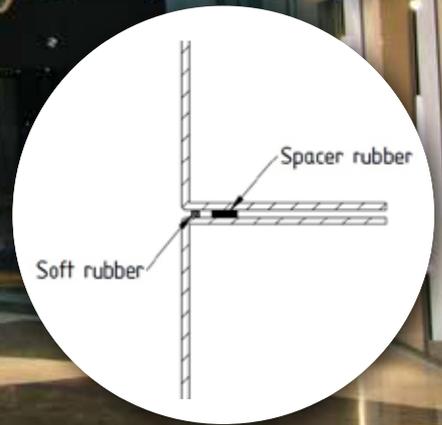
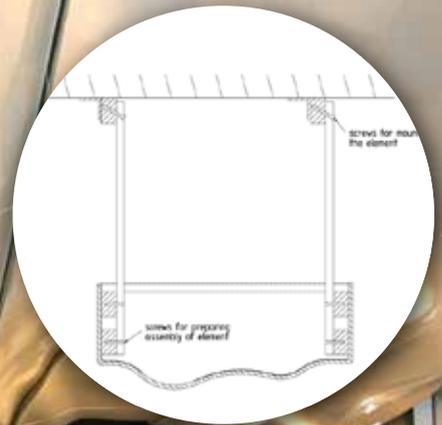
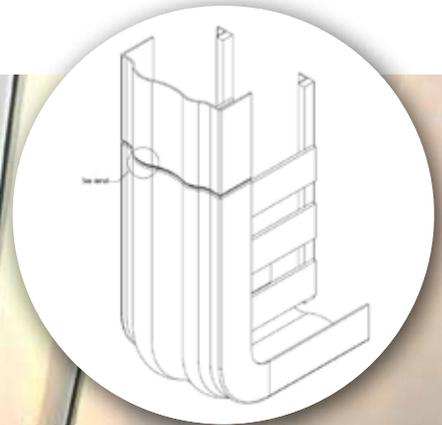
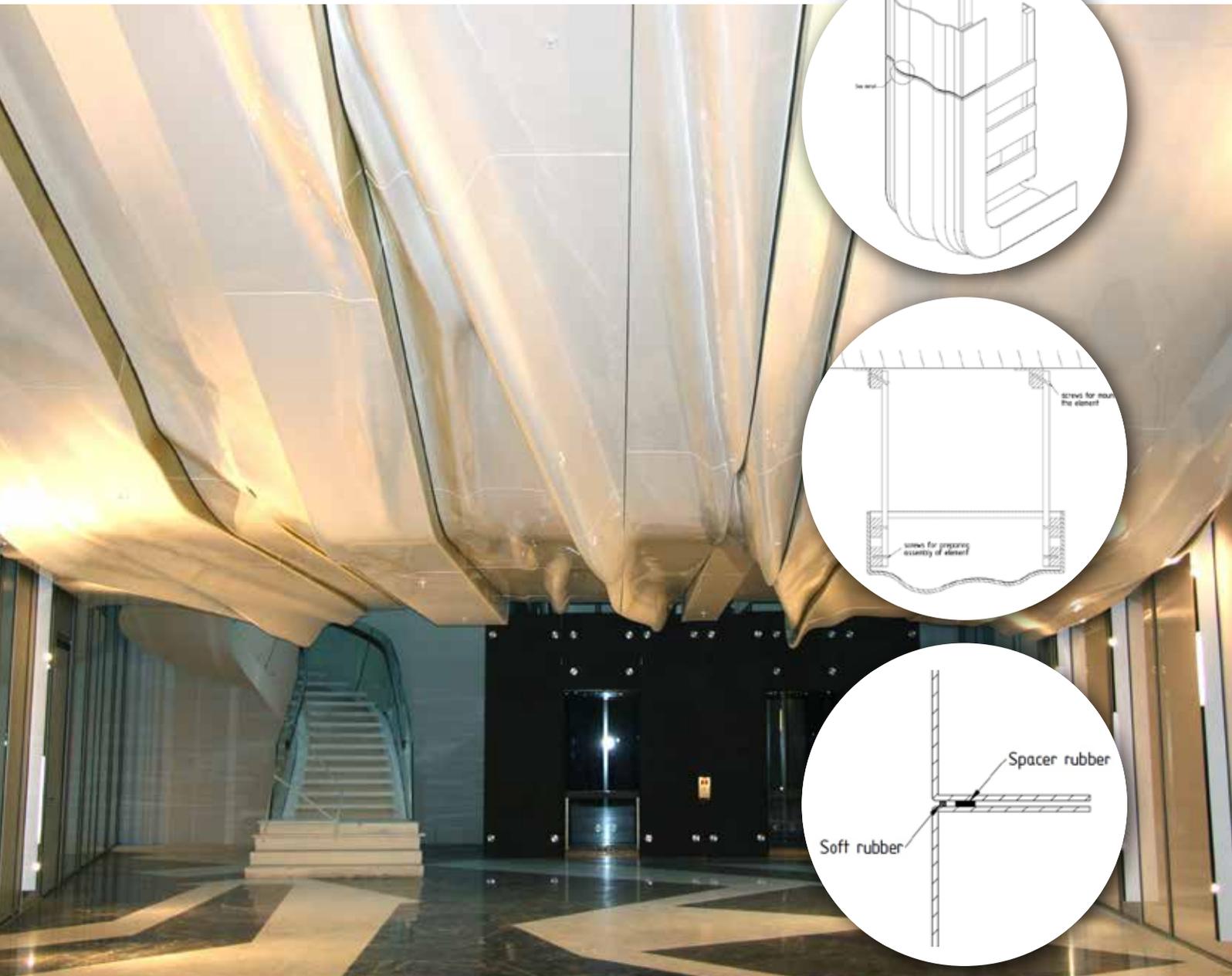




Design guide

A1 (Acrylic One) structures



PREFACE

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

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1. INTRODUCTION

Acrylic One (A1) is a two-component resin. The components are a powder component based on calcium sulphate (CaSO₄) and an acrylate-based liquid. After mixing of these components the resin can be processed to make products. The resin is water-based and does not generate the emission of VOC's (Volatile Organic Solvents). Typically the time the resin is liquid after mixing of components (pot life) is 20 minutes but can be lengthened by using a retarder or can be shortened by using an accelerator. Additional filler (e.g. sand) can be added to the mixture as well. In the liquid state the resin can be processed in different ways: casting, application on a substrate, spraying and laminating together with reinforcement in a mould. Specially in combination with a glass fibre reinforcement, thin-walled products can be made with a complex shape and with a low weight. Because of the short curing time, short production times are possible. This enables an efficient production process.

Besides the advantages of A1 of making complex-shaped, light-weight products in an efficient manner, a very important property of A1 is the performance in reaction to fire. This performance has been reported to be B – s1, d0 according to the European standard EN 13501 (report Efectis of 2006) and even A2 – s1, d0 in case the A1 compound is filled with 25% sand (report Efectis of 2017). This is a superior fire performance when compared with composite products that are based on traditional synthetic resins or when compared with wood-based materials.



Auditorium (Mahler, Amsterdam)



Tulip walls (IGZ, Amsterdam)

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 both were realized by Poly Products.

Typical exterior projects that were possibly by using A1 with respect to fire performance are the facade elements for La Place in Amsterdam and the facade elements of the apartment building in Nijmegen. These projects both were realized by BeConcrete, for La Place in Amsterdam 35 facade-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.

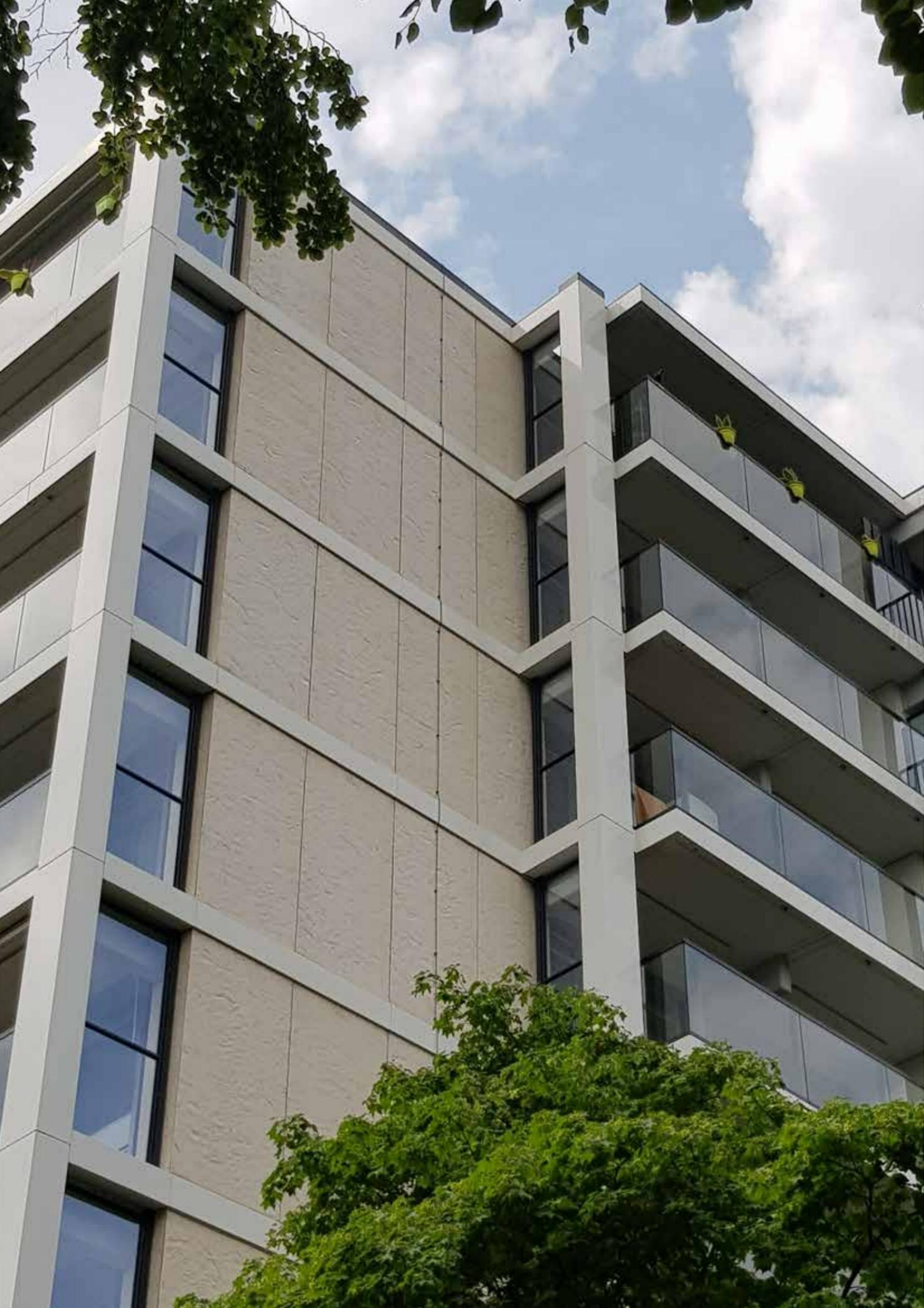


In the Rentmeesterkwartier in Nijmegen an apartment building had to be renovated. In total 1800 m² of facade elements were installed that fulfill the fire requirements. A special surface texture was requested. Moreover, the elements should have a maximum weight of 15 kg/m² and must be easy to install. This led 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.



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 frame-retardancy (FR), polyester concrete and wood-based panels.

Fire performance (EN 13501)	Reaction to fire	Smoke	Droplets
A1 laminate (standard)	B	s1	d0
A1 laminate (25% sand filled)	A2	s1	d0
Polyester laminate (standard)		D	s3 d0
Polyester laminate (flame retarded)	B	s3	d0
PVC (wall cladding)	B	s2	d0
Plywood (600 kg/m ³)		D	s2 d0
Plywood (600 kg/m ³ , flame retarded)	B	s1	d0
OSB (600 kg/m ³)		D	s2 d2
MDF (600 kg/m ³)		D	s2 d0
Particle board (600 kg/m ³)		D	s2 d0
Cement-wood board (1000 kg/m ³)	B	s1	d0
High Pressure Laminate (1350 kg/m ³)		D	s2 d0
HPL (1350 kg/m ³ , flame retarded)	B	s1	d0
Mineral based panel (1100 kg/m ³)	A2	s1	d0
Mineral wool panel (100 kg/m ³)	A1	s1	d0
Concrete (2400 kg/m ³)	A1	s1	d0



2. APPLICATIONS AND SCOPE

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).

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

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

Moreover, composites built up with A1 show a significant water uptake in conditions with a high moisture content. In these conditions the mechanical performance is further reduced and creep deformation under permanent loading is accelerated. However, when dry again the original mechanical performance is regained. These considerations lead to the following field of application of composite built up with A1:

Relatively dry applications:
 - no permanent moisture contact
 - no permanent high humidity

Avoiding creep deformations:
 - no permanent loading

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.

3. LAMINATE STRUCTURE AND REQUIREMENTS

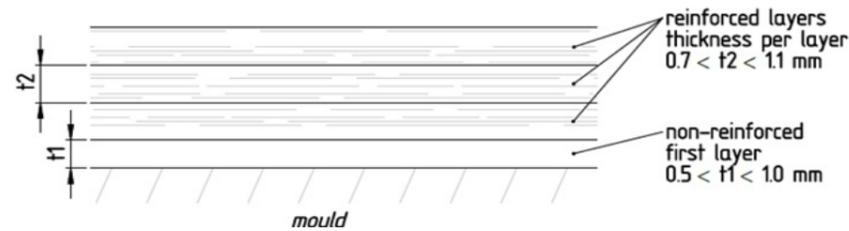
An A1 structure is built up by laminating reinforcement together with the A1 resin in a mould. In order to avoid dry spots in the product surface, the laminating must be started by the application of a non-reinforced resin layer of 0.5 to 1.5 mm thickness (0.8 to 2.4 kg per m²). The thickness of this layer depends on the application method and the use of additives in the resin, e.g. sand.

After a short time of gelation of this layer (see production instructions of A1) the reinforcement layers are applied together with the resin. For each triaxial glass fabric layer of 160 g/m² about 1.0 to 1.7 kg of resin per m² is needed. Each such a layer will build up a thickness of 0.7 to 1.1 mm.

The triaxial reinforcement has glass bundles in the weft direction of the structure (called 0° direction) and at angles of +45° and -45° with the weft direction. There is no reinforcement oriented in the warp direction (called 90° direction).

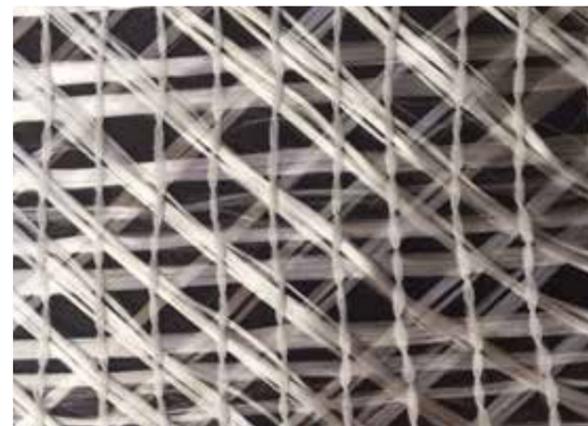
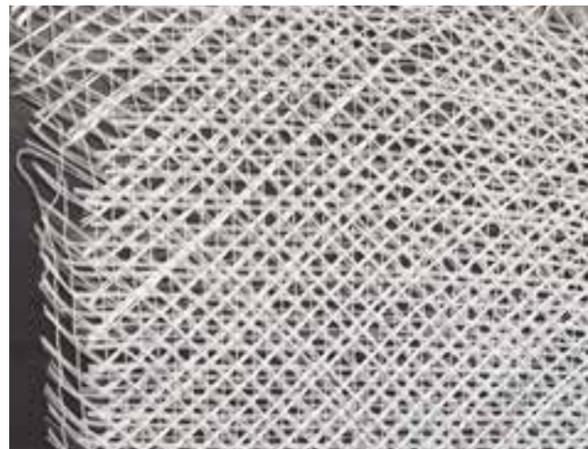
As can be seen from the photographs, the fibre bundles are oriented in weft direction (horizontal direction in the photographs, called 0° direction) and in directions +45° and -45° with the weft direction. In the warp direction (vertical direction in the photographs, called 90° direction) there are no glass fibre bundles oriented. However, the stitch-yarns are oriented in the warp direction.

Schematic laminate build-up



The general instructions for A1 are that a minimum of 2 reinforcement layers should be used in a laminate. However, for structural applications of A1 (for which this design guide applies) a minimum of 3 reinforcement layers should be used. There is no maximum amount of reinforcement layers. A1 does generate some exothermic heat during curing but not to an extent that it may cause material degradation or fire risks. During curing of thick laminates a maximum exothermic peak temperature has been found of only 50°C. However, when thick laminates are required, the use of core materials (e.g. foam or wood) should be considered.

- Start with a non-reinforced layer of 0.5 to 1.5 mm thickness
- Subsequent reinforcement layers in a laminate: minimum 3 layers



3. LAMINATE STRUCTURE AND REQUIREMENTS

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 90° 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 (0°, +45° and -45° directions). Depending on the requirements and on the quality control possibilities different approaches of the orientation of the reinforcement layers are possible:

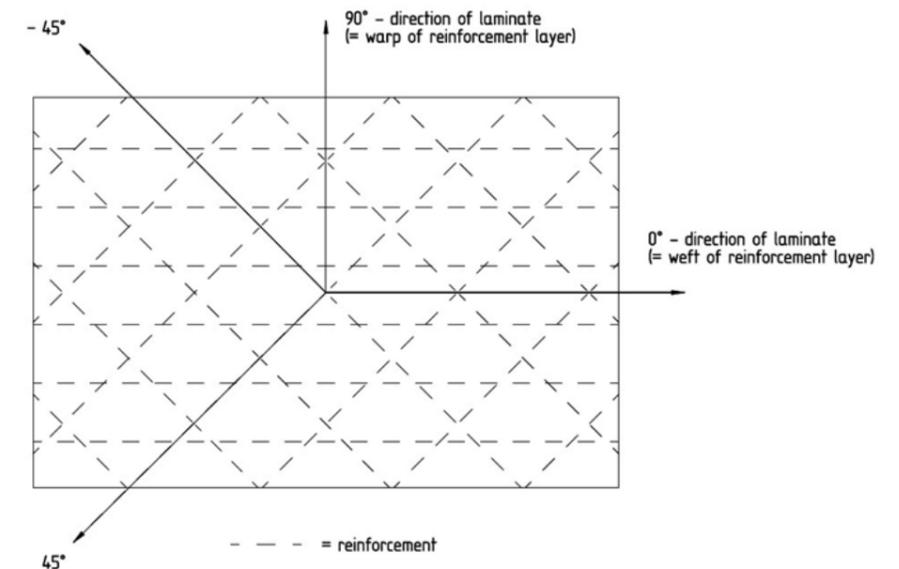
Controlled orientation

- 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 0° direction (reinforced) and in the 90° direction (non-reinforced).

The design values obtained by the tests in 0° 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 90° 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).

Design values	Property and unit	0° direction	90° direction
In-plane tension	E-modulus, stiffness (MPa)	1228	215
	E-modulus, glob. stab. (MPa)	812	142
	E-modulus, loc. stab. (MPa)	625	105
	Tensile strength (MPa)	29	7
Bending	E-modulus, stiffness (MPa)	1363	477
	E-modulus, glob. stab. (MPa)	901	315
	E-modulus, loc. stab. (MPa)	693	233
	Flexural strength (MPa)	11	6
ILSS	Shear strength (MPa)		1.50
Transverse strength	Tensile strength (MPa)		0.27

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 $5 \cdot 10^{-6} / ^\circ\text{C}$ (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.

Material	Coefficient of thermal expansion (in $10^{-6} / ^\circ\text{C}$)
A1 laminate	5
Glass (window plate glass)	8
Concrete	12
Steel	12
Aluminum	23
Polyester laminate (glass mat)	24
PVC	80
HDPE	200

5. 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.

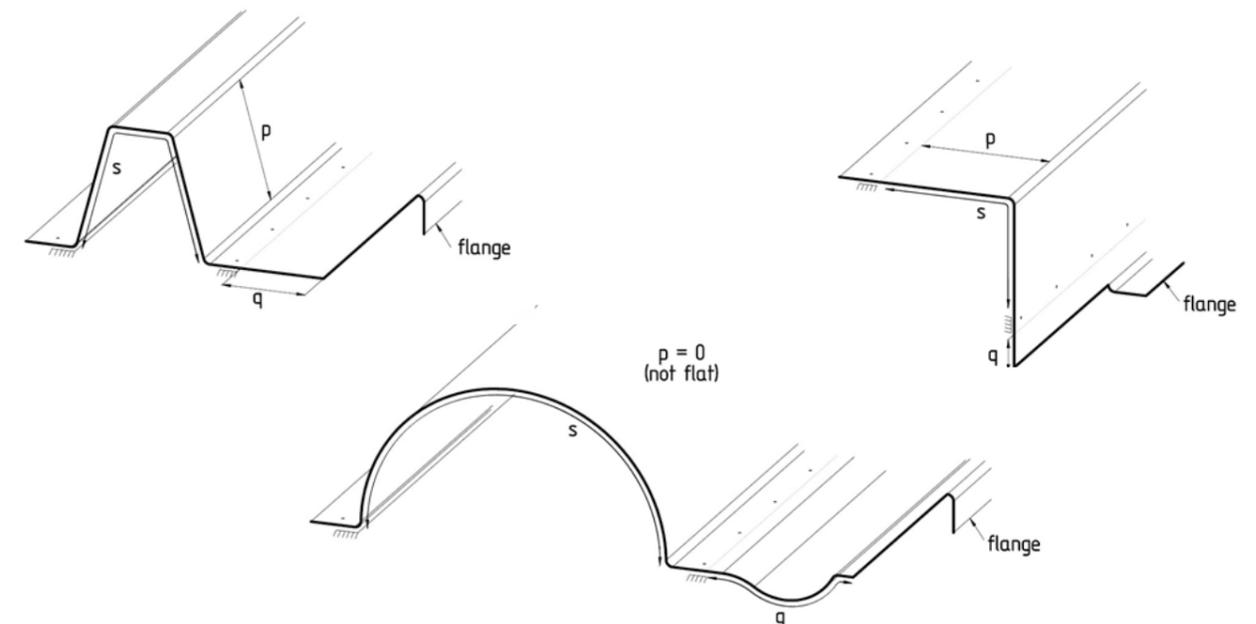
Many design details are determined by the fact that A1 for structural parts is always processed with reinforcement layers (triaxial glass fabric) that is built up together with the resin into a laminate in a mould. Because the application of the reinforcement layers in a mould, the radius of the mould 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.

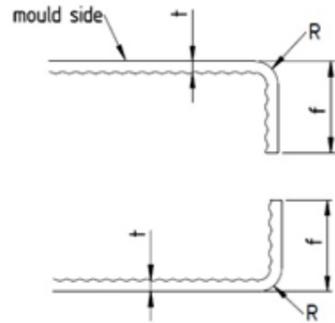
Furthermore, when products are made with flat parts the free span of these parts (p) should not be too large. This depends on the thickness of the laminate. Also the total length between two supports (s) should not be too large. For parts that are only supported at one side the length of the free span (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.

Laminate thickness t (mm)	Maximum span of flat surface p (mm)	Maximum free span length q (mm)		Maximum length between supports s (mm)
		Without flange	With flange	
3	300	100	200	1000
5	400	150	250	1250
7	500	200	300	1500



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.

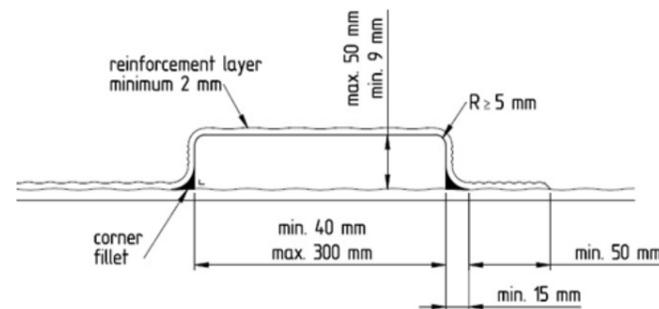
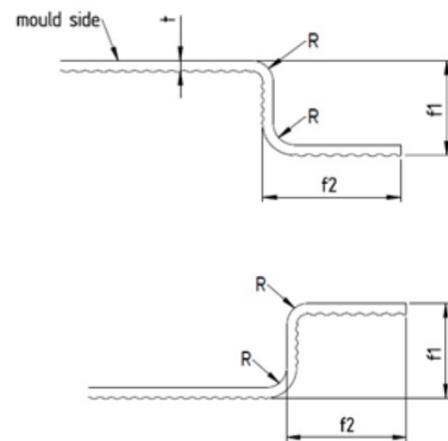
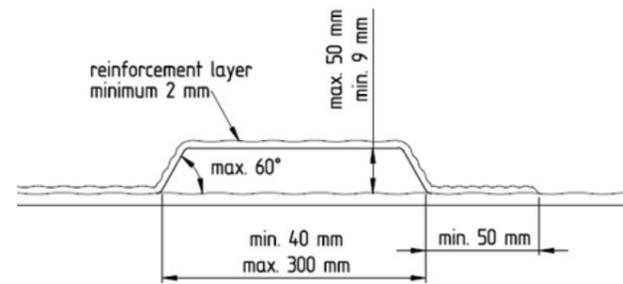


Laminate thickness t (mm)	Flange length f (mm)		Minimum radius R (mm)
	Min.	Max.	
3	30	100	5
5	40	150	5
7	50	200	5

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, aluminum 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.

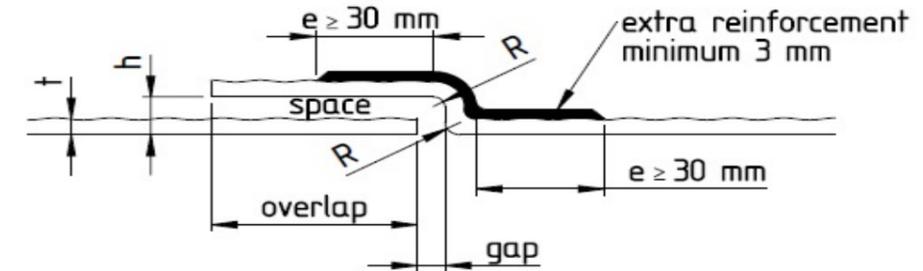


Laminate thickness t (mm)	Flange length f_1 (mm)		Flange length f_2 (mm)		Minimum radius R (mm)
	Min.	Max.	Min.	Max.	
3	30	100	30	100	5
5	40	150	40	150	5
7	50	200	50	200	5

5. DESIGN DETAILS AND MOUNTING METHODS

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) to allow for undisturbed play (dilatation) between the elements. But also the space can be used to glue the two elements together. The thickness of this space

should be kept to a minimum in case of an open space (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.



Laminate thickness t (mm)	Minimum radius R (mm)	Space dimensions (thickness and overlap)			
		Open (air)		Glued	
		Minimum h (mm)	Maximum $overlap$ (mm)	Maximum h (mm)	Minimum $overlap$ (mm)
3	5	5	30	8	40
5	5	7	30	10	50
7	5	9	30	12	60

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.



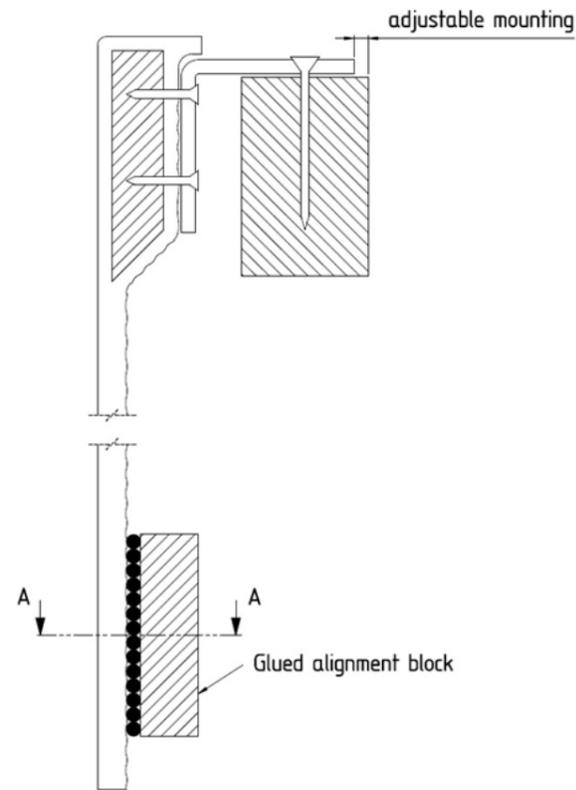
Rendering of curved walls with tulip pictures by Fokkema

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.



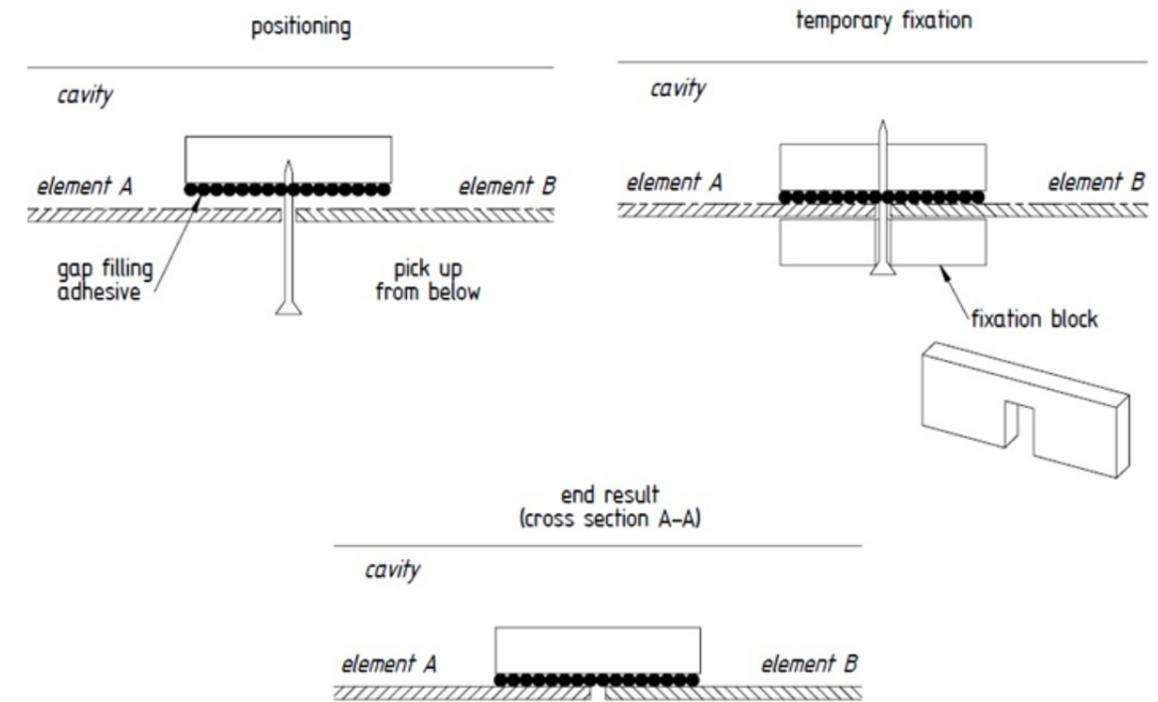
In order to make the connection with the neighbouring elements flush on the lower part of the element a glued alignment block has been used.



6. REFERENCE PROJECTS

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 fixa-

tion 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.



6. REFERENCE PROJECTS

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.



Rendering of outside surface of auditorium by EEA

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.

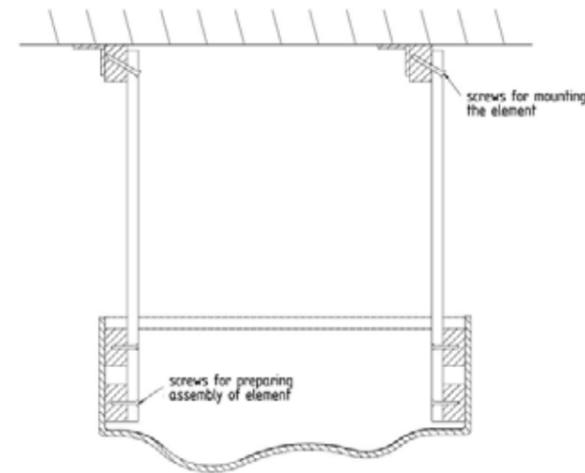


Element laminated and 36 mm plywood beams positioned to the sides



Further interior stiffening of laminate and 18 mm plywood strips connected

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.

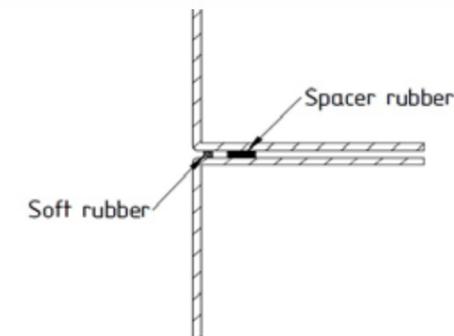
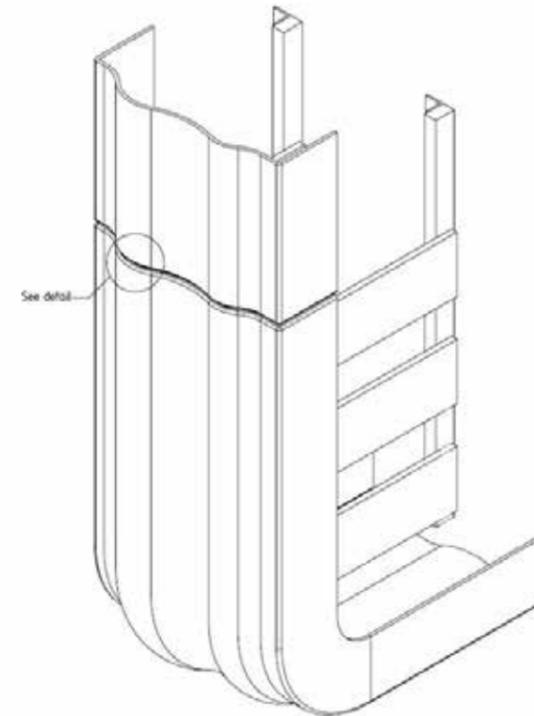


The 18 mm protruding plywood strips have a relatively high strength and stiffness in vertical direction in which direction they have to carry the weight of the element. In lateral direction these strips behave relatively flexible which makes the alignment with the adjacent elements relatively easy.



6. REFERENCE PROJECTS

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.

During mounting of an element it could be softly placed on the previous element that was provided with the spacer rubbers and the strip of white, soft rubber. This is shown in the photo below.

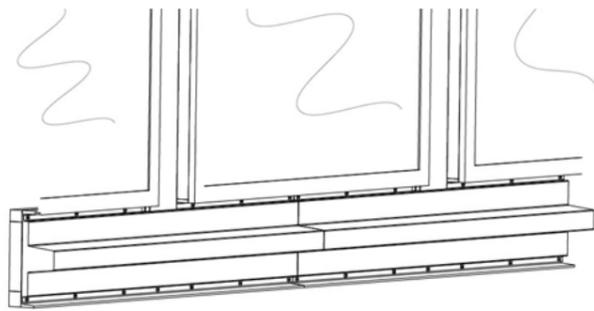


6. REFERENCE PROJECTS

Façade panels Amsterdam

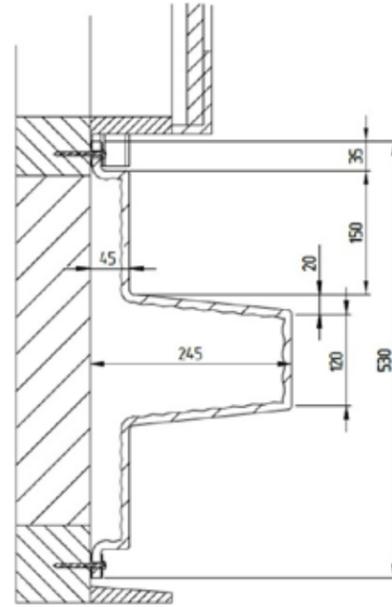
In 2017 Rijnbout architects has designed the Fletcher Amsterdam Olympic Hotel. In the facade elements have been designed with a concrete look between the windows. These elements are oriented both horizontally and vertically.

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 realized that facilitates the mounting process and reduces the requirements on the anchoring of the elements to the building.



Location of the horizontal elements in de façade

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:

$$\text{External pressure coefficient (wind suction)} = C_{pe} = -1.4$$

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

$$\text{Load factor} = \gamma_F = 1.5$$

The projected area of one meter of the profile is:

$$\text{Projected area of one meter profile} = A = 0.53 \text{ m}^2$$



6. REFERENCE PROJECTS

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

$$F_d = p_d \cdot |C_{pe}| \cdot \gamma_F \cdot A = 1340 \cdot 1.4 \cdot 1.5 \cdot 0.53 = 1491 \text{ N}$$

Strength of connection to the building

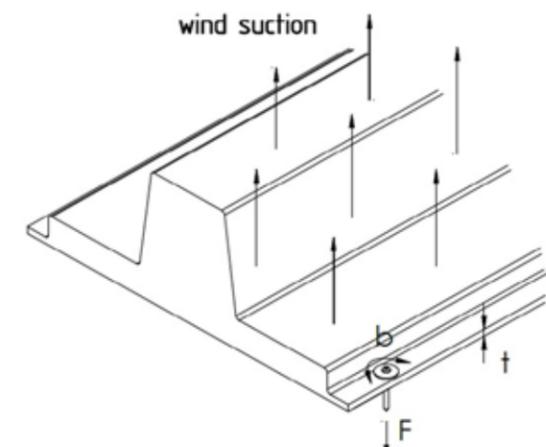
The strength of the connection of the profile to the building is determined by the method of connecting. A screw with a diameter of 5 mm and a shaft length of 60 mm is selected for this. For spreading the load, a washer is used with a diameter of 29 mm. Screw and washer are shown in the photo below.



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:

$$F_{pull} = 1821 / \gamma_m = 1821 / 2 = 911 \text{ N}$$

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 will occur as a result of the force. The area of the fracture, A_f , is determined by the length of the fracture, $b \approx 75 \text{ mm}$, 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 :

$$F_f = \frac{2}{3} \cdot \tau_d \cdot A_f = \frac{2}{3} \cdot 1.50 \cdot 75 \cdot 5 = 375 \text{ N}$$

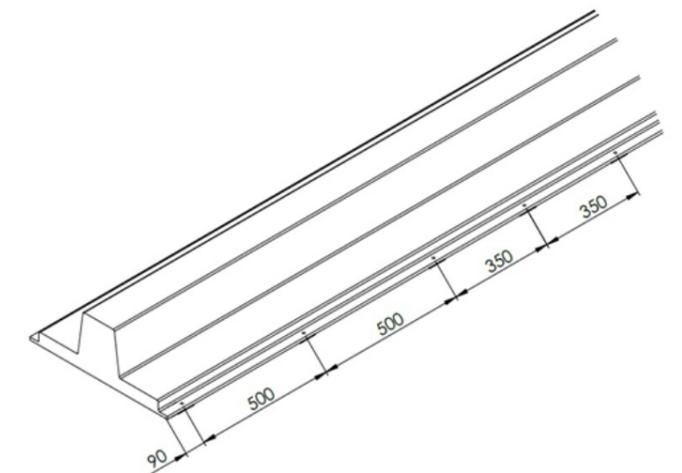
In this equation the design value for the interlaminar shear strength for A1, τ_d , is derived from the table on page 9. In this parameter already material factors are comprised. It is clear that the fracture force of pull through, F_f , is critical in the connection of the element to the building.

The screws are always placed in sets of two, each on one flange of the profile. When comparing the design load with the design strength of a set of two screws, the amount of screw sets per meter profile can be calculated:

$$\text{Amount sets per meter} = F_d / (2 F_f) = 1491 / (2 \cdot 375) = 1.99$$

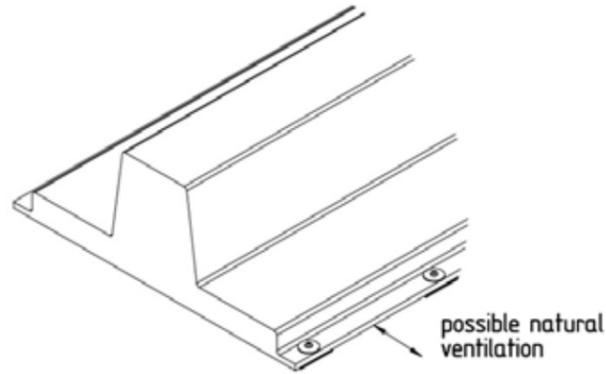
This means that one set of two screws is necessary for every $1/1.99 = 0.50$ meter. Thus, along the flange the screws should therefore have a distance of 500 mm maximum.

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.



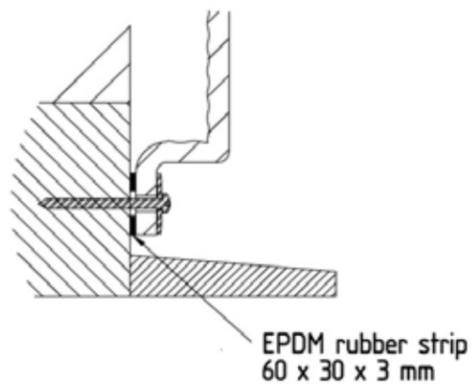
6. REFERENCE PROJECTS

In order to avoid accumulation of moisture due to condensation, an opening is created between the element and the building structure.



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

cross-section detail



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.



6. REFERENCE PROJECTS

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.



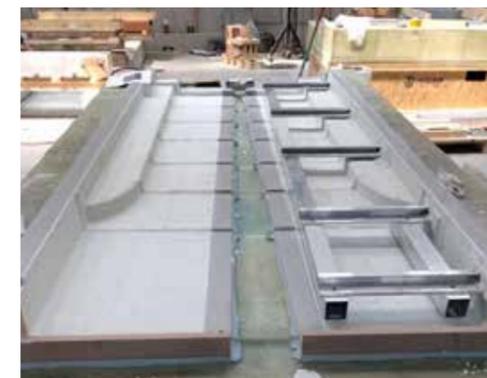
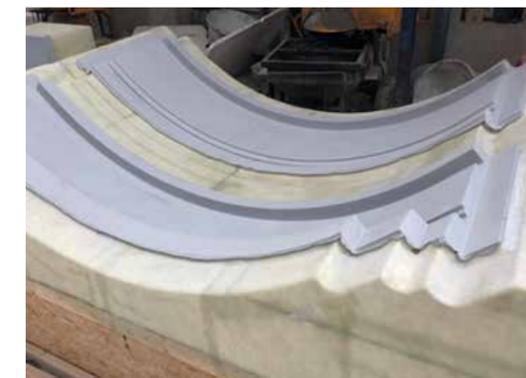
3D-model of the elements of the façade to be made

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.



6. REFERENCE PROJECTS

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.



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.

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.



A1 element laminated in the mould



Aluminum structure mounted to the steel structure (without A1 element)

6. REFERENCE PROJECTS

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 °
- 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

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 to be used (can be used always, in any direction)

The coefficient of linear thermal expansion reinforced A1 laminates is $5 \cdot 10^{-6} \text{ } / ^\circ\text{C}$.

Design details

- Moulded edges must have a radius of $R \geq 5 \text{ mm}$
- Verify the span of flat surfaces, free span length and unsupported total length
- Check detailing of flanges, joggles and inserts
- Use of wood-based core materials only for A1 products in indoor applications.

Design values	Property and unit	0° direction	90° direction
In-plane tension	<i>E-modulus, stiffness (MPa)</i>	1228	215
	<i>E-modulus, glob. stab. (MPa)</i>	812	142
	<i>E-modulus, loc. stab. (MPa)</i>	625	105
	<i>Tensile strength (MPa)</i>	29	7
Bending	<i>E-modulus, stiffness (MPa)</i>	1363	477
	<i>E-modulus, glob. stab. (MPa)</i>	901	315
	<i>E-modulus, loc. stab. (MPa)</i>	693	233
	<i>Flexural strength (MPa)</i>	11	6
ILSS	<i>Shear strength (MPa)</i>	1.50	
Transverse strength	<i>Tensile strength (MPa)</i>	0.27	

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, aluminum 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 X_d can be determined from tests data in the following manner:

$$X_d = \eta_c \cdot X_{k(n)} / \gamma_m = \eta_c \cdot m_x \cdot \{1 - k_n \cdot V_x\} / \gamma_m$$

In this formula the parameters represent the following:

X_d = design value of material property X

η_c = conversion factor

$X_{k(n)}$ = 5% characteristic value measured values

γ_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_x) is unknown beforehand.

Number tests (n)	5	8	10	16 (*)	20	Infinite
Value of k_n	2.33	2.00	1.92	1.82	1.76	1.64

*) The value of k_n determined by linear interpolation between $n = 10$ and $n = 20$.

Two factors need more explanation: the conversion factor, η_c , and the material factor, γ_m . The conversion factor is material specific and incorporates external effects on the material:

1) temperature, 2) moisture, 3) creep and 4) fatigue.

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). Thus:

$$\eta_{c,T} = 1 \text{ for design temperature } T_d < T_g - 40$$

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.

$\eta_{c,M} = 0.75$ For 0° properties

$\eta_{c,M} = 0.60$ For 90° properties

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:

$$\eta_{c,C} = 1$$

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):

$$\eta_{c,F} = 0.9$$

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:

$$\eta_c = \eta_{c,T} \cdot \eta_{c,M} \cdot \eta_{c,C} \cdot \eta_{c,F} = 1 \cdot 0.75 \cdot 1 \cdot 0.9 = 0.68$$

For 0° properties and for direction-independent (interlaminar) properties

$$\eta_c = \eta_{c,T} \cdot \eta_{c,M} \cdot \eta_{c,C} \cdot \eta_{c,F} = 1 \cdot 0.60 \cdot 1 \cdot 0.9 = 0.54$$

For 90° 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:

$$\gamma_{M1} = 1.15 \quad (\text{when determined from tests})$$

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):

$$\gamma_{M2} = 1.0 \quad \text{For stiffness}$$

$$\gamma_{M2} = 1.5 \quad \text{For strength and global stability (buckling)}$$

$$\gamma_{M2} = 2.0 \quad \text{For local stability (wrinkling)}$$

Combining the two factors, the material factor becomes:

$$\gamma_m = \gamma_{M1} \cdot \gamma_{M2} = 1.15 \cdot 1.0 = 1.15 \quad (\text{stiffness})$$

$$\gamma_m = \gamma_{M1} \cdot \gamma_{M2} = 1.15 \cdot 1.5 = 1.73 \quad (\text{strength, gl. stability})$$

$$\gamma_m = \gamma_{M1} \cdot \gamma_{M2} = 1.15 \cdot 2.0 = 2.30 \quad (\text{local stability})$$

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

$$X_d = (\eta_c / \gamma_m) \cdot X_{k(n)} = (\eta_c / \gamma_m) \cdot m_x \cdot \{1 - k_n \cdot V_x\}$$

Because the conversion factor depends on the direction of the property considered (0° and 90°) 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 (η_c / γ_m).

Coefficient (η_c / γ_m)	0° and interlaminar	90°
Stiffness	0.59	0.47
Strength and global stability	0.39	0.31
Local stability	0.30	0.23

The design method is specifically worked out for the following laminate properties of a reinforced A1 composite product:

- 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, *)
 - Interlaminar tensile strength (*)
- *) Interlaminar strengths do not depend on reinforcement direction.

Above properties have been tested on fully cured laminates (at least seven days after production, stored in a dry and ventilated room). Before testing the samples have been conditioned to laboratory conditions (23 °C and 50 % RH). The test results are described in Appendix B. The properties are based on the testing of a series of specimens, where the number of specimens (n) depends on the type of test. In the following table the results of the tests are summarized. Both mean value (m_x) and coefficient of variation (V_x) are given. Using the design method the test results are used to determine the design parameters that are summarized in the table below. For the E-modulus in tension, only 7 measurements could be used, thus $k_n = 2.08$ is used in this case (*).

B. Test programme and results

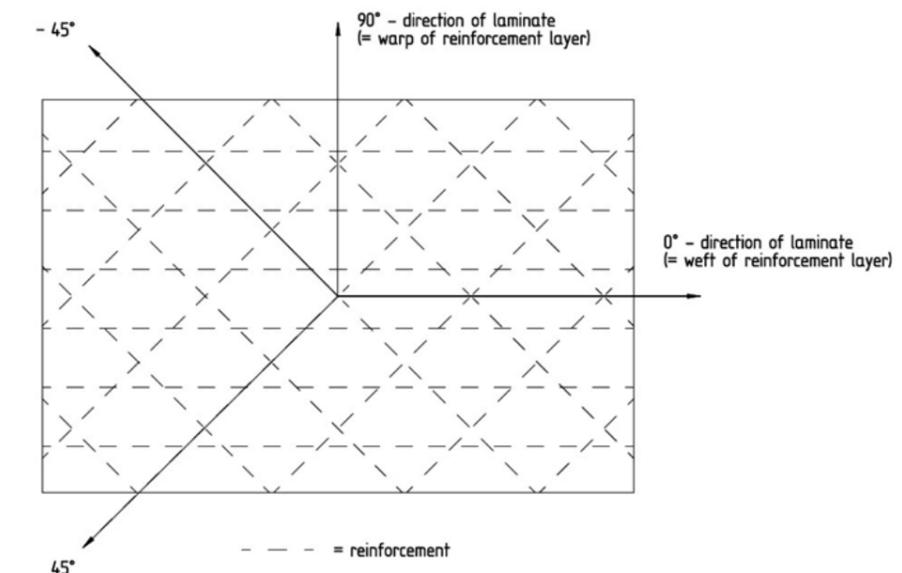
For the determination of the mechanical performance of A1 composite laminate panels have been made by hand lay-up of glass fibre reinforcement with A1 mixture:

Glass fibre reinforcement: Triaxial Fibre 300, 160 g/m²
 A1 mixture: A1 Liquid and A1 Powder (1 : 2 by weight)

The laminate panels have been made without a gelcoat-layer (non-reinforced resin layer) and without any other additives. Laminate panels were built up on a flat, smooth panel as a mould. All reinforcement layers have been stacked with the same orientation:

Test (AM)	Property and unit	0° direction m_x / V_x (%)	90° direction m_x / V_x (%)
In-plane tension (n=8)	E-modulus (MPa)	2312 / 5.3	550 (*) / 8.2
	Tensile strength (MPa)	57 / 6.4	18 / 6.0
Bending (n = 16)	E-modulus (MPa)	3726 / 21.3	2984 / 35.5
	Flexural strength (MPa)	43 / 17.6	32 / 22.7
ILSS (n = 16)	Shear strength (MPa)	4.5 / 8.2	
Transverse tension (n = 20)	Tensile strength (MPa)	0.8 / 7.4	

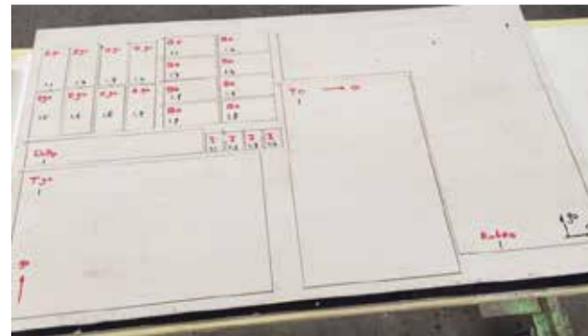
Design values	Property and unit	0° direction	90° direction
In-plane tension	E-modulus, stiffness (MPa)	1228	215 (*)
	E-modulus, glob. stab. (MPa)	812	142 (*)
	E-modulus, loc. stab. (MPa)	625	105 (*)
	Tensile strength (MPa)	29	7
Bending	E-modulus, stiffness (MPa)	1363	477
	E-modulus, glob. stab. (MPa)	901	315
	E-modulus, loc. stab. (MPa)	693	233
	Flexural strength (MPa)	11	6
ILSS	Shear strength (MPa)	1.50	
Transverse strength	Tensile strength (MPa)	0.27	



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.



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).

Tensile tests

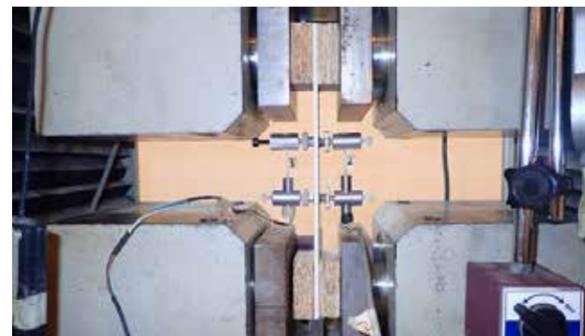
The tensile tests have been performed according to ISO 527-4 by testing strips of 50 x 250 mm. For clamping, tabs have been applied on the ends of the strips. Testing is performed with a speed of 1 mm/min until fracture. Sets of n = 8 specimens have been tested, both in 0° and 90° directions and conditioned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

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

*) For this 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.

Property in humid condition	Test	Loss compared to standard condition
Strength	0°	16 %
	90°	27 %
E-modulus	0°	8 %
	90°	14 %



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.

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

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.

Property in humid condition	Test	Loss compared to standard condition
Strength	0°	21 %
	90°	35 %
E-modulus	0°	27 %
	90°	43 %



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.

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 $\eta_{c,M}$ 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

$\eta_{c,M}$ 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.

(n = 16)	Strength (ILSS)	
	Mean value (MPa)	V.C. (%)
23 °C , 50% RH		
90° - direction	4.53	8.2



8. APPENDIX

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.

(n = 20)	Strength (interlaminar tension)	
	Mean value (MPa)	V.C. (%)
23 °C , 50% RH		
90° - direction	0.81	7.4



C. Literature

Eurocode – Basis of structural design
EN 1990: 2001/A1:2005

Eurocode – Actions on structures
EN 1991: 2002-2006

CUR 96 Recommendation 'Vezelversterkte kunststoffen in bouwkundige en civieltechnische toepassingen.
Second edition 2017, CROW, CRW AA96: 2017

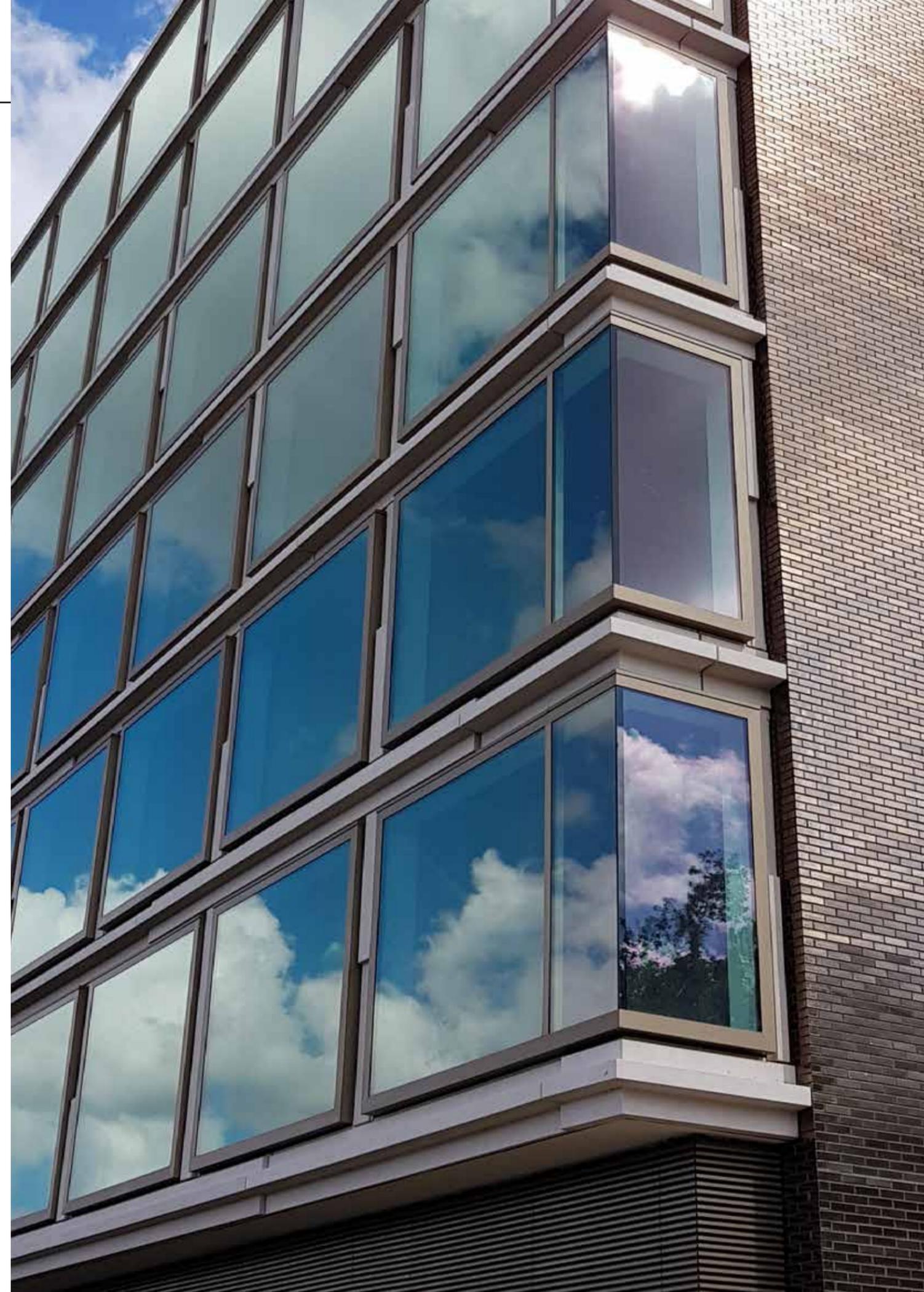
Outdoor Durability of Acrylic One
TNO-rapport MT-RAP-2008-02326-v2/rie (2008)

Classification to Reaction to Fire Performance in Accordance with EN 13501
Efectis-report: 2006-CVB-R0565 (2006)

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

Classification of Reaction to Fire Performance in Accordance with EN 13501-1: 2007+A1:2009
Efectis report: 2017-Efectis-R000322 (2017)

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.



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