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Durability of a newly developed carbon fibre epoxy glass façade

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ABSTRACT: Carbon fibre epoxy composite has been used in an experimental insulating glass façade. A test program was performed to investigate the durability of the structure beforehand. The moisture absorption tests showed 1% and 1,5% moisture absorption for the non-post-cured and the post-cured carbon fibre epoxy specimens respectively. However, no difference in moisture diffusion is found between conventional insulating glass panels with steel spacers and panels with carbon fibre epoxy spacers and tubes. The dynamic loading of the tensioned façade causes friction in the carbon fibre epoxy tube and the nylon connection interface. Frictional wear tests to simulate this effect did not show any significant damage. Long term investigation is carried out over the coming years by means of a built-in monitoring system.

1 INTRODUCTION

A composite façade concept has been developed and patented in a joint research program between knowledge institutes and industry lead by the INHolland Composites Lab, see Hagenbeek (2006). The vision was to develop an innovative and minimalistic façade with the structural use of composite materials (Hagenbeek et al (2007a), Peters (2007) ,Wapenaar et al (2007)). The developed concept is based on the working principle of a sail (Hagenbeek et al (2007b), Gerkan et al (2006), Jahn (1994)). Tensioned aramid cables carry the wind loading and allow for out-of-plane deflection of the façade. The insulating glass panels consist of carbon fibre epoxy spacers and tubes that carry the weight of the façade.

The idea to use composite material as a moisture barrier was motivated by diverse studies in literature, which showed the limited moisture uptake and strong thickness effect on the diffusivity (Kumosa et al (2004)), the observed Non-Fickian behaviour in some cases due to continuing chemical reactions or other causes (Marsh et al (1984), Lin et al (2005), the possible desorption (Lin et al (2005)), and the significantly decreased through-the-thickness diffusivity which can be found for pultruded composites (Karbhari et al (2008), Kondi et al (1982)).

In order to evaluate the developed concept a building block approach was used. Starting from coupon testing and verification, structural testing was performed and finally a full scale experimental façade has been build. The panels in this experimental façade are monitored in service on temperature and relative humidity. Due to the continuous vibration of the façade under wind loading frictional damage and wear on the mechanical connections between each set of panels was investigated. The effect of temperature and humidity was investigated by moisture uptake and moisture diffusion tests on the insulating glass panels with carbon fibre epoxy spacers and conventional steel spacers.

2 CONCEPT DEVELOPMENT

The working principle of the 13.2 meters high experimental façade is based on a sail. The double-glazed panels are stacked together and can mutually rotate. The panels are guided by aramid cables, which ensure the effective transfer of the wind load. The cables run through the composite tubes and have a high tensile strength and excellent fatigue resistance. In strong winds the façade can translate up to 330 mm with respect to the centre line. Carbon fibre epoxy tubes placed within the insulating glass panels carry the weight of about 2.5 tons and transfer the wind loading to the cables. The specially developed tubes deliver compression stiffness values of 370 GPa, which is more than 70% higher than steel. Moreover, the tube protects the cable and the panel against environmental effects and thus integrates many functions.

The spacers of the insulating glass panels are also made out of carbon fibre epoxy. In addition to stiffness the material provides good thermal insulating properties as tested in previous research for glass fibre epoxy (Hagenbeek (2004)) and an aesthetically attractive look. Through a combination of strong cables and rigid panels a super slim façade of only 45 mm width has been created. In Figure 1 the developed composite façade concept is shown and details of the indicated cross-section A-A' in Figure 2. The moisture diffusion barrier and frictional wear properties of the material, however, needed further investigation.

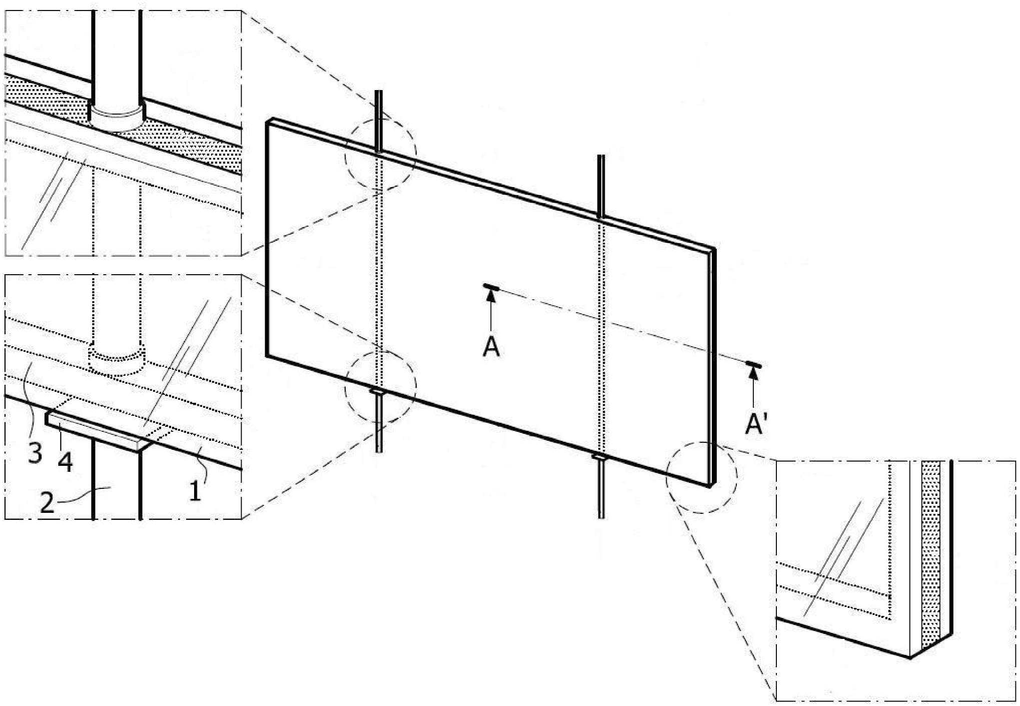

Figure 1. The developed and patented composite façade concept with (1) the glass plate, (2) the carbon fibre epoxy tube, (3) the carbon fibre epoxy spacer, and (4) the carbon fibre epoxy support. The cross-sectional view A-A' is shown in Figure 2.

3 TEST PROGRAM DEFINITION

In order to evaluate the developed concept a building block approach was used. Starting from coupon testing and verification, structure testing was performed and finally a full scale demonstrator has been build. The ultimate verification is obtained from an experimental composite façade, which was assembled in 2009. The panels in this experimental façade are monitored in service on temperature and relative humidity.

The total test program was aimed at the structural and durability properties of the façade. The durability testing is described in this paper and focuses on the mechanical connection between each two panels and the effect of temperature and humidity on the panels. Since wind loading results in continuous vibration of the façade the frictional damage and wear on the connections was investigated. The effect of temperature and humidity was investigated by moisture uptake and moisture diffusion tests on insulating glass panels.

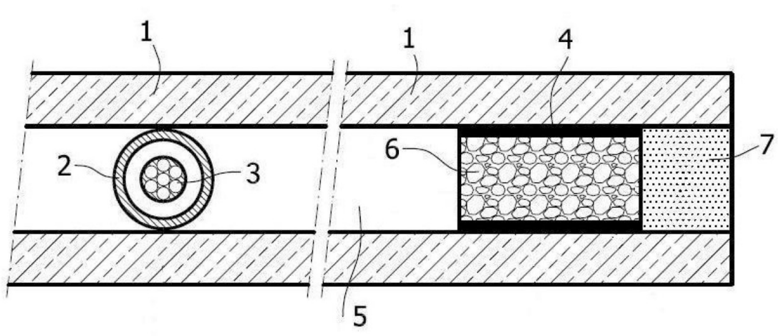

Figure 2. Cross-sectional view A-A' of the insulating glass panel, see Figure 1 for the total view, with (1) the glass plate, (2) the carbon tube, (3) the aramid cable, (4) the butyl sealant, (5) the argon filled double glass inner space, (6) the carbon spacer, and (7) the silicone structural adhesive.

4 FRICTIONAL DAMAGE

The spacer and tubes were designed out of composite in the developed concept. The tubes have three functions in this concept; a) carrying the total weight of the façade, b) allowing the aramid cable being transferred through the centre of the insulating glass panels, and c) preventing any moisture diffusion through the tubes to the inside of the panel. For aesthetic reasons the design objective was a maximal panel height and width and a minimal number of cables and thus tubes. The spacer height was not without bounds as heights beyond 30 mm were expected to give convection inside the panel thus reducing the thermal insulating capabilities (Manz (2004)). Moreover thermal cycling of the air inside the panel could cause a strong pumping effect with large forces on the cover glass at both sides of the panel (Wolf (1992)). These combined starting points led to the wish for a high stiffness tube with a minimal cross sectional dimension and a sufficient compression strength. Special pultruded tubes have been developed based on a 610 GPa pitch based carbon fibre. This resulted in a tube with 370 GPa stiffness in compression.

The panels are placed on top of each other allowing rotation of the total façade due to wind loading. Thus all wind loading is transferred to the aramid cables and large bending forces on the panel are avoided. The connection between the tubes of each two panels is made out of nylon. This connection or ‘cartilage’, must be able to sustain the compression loading due to the weight of all panels on top. The connection must, however, allow 2 degrees of rotation between each two panels.

Due to the variable wind loading the durability of this connection needed to be investigated as well. The damage occurrence, for example fibre-matrix debonding or fatigue, might be counteracted by the lubricating effect of carbon fibre composites (Gopal et al (1995)). The difficult replacement or repair of the connection and the brittle behaviour of the chosen pitch fibre increased the necessity for this investigation. A specific test set up was made to simulate the loading and to investigate the frictional wear of the pultruded carbon fibre epoxy tubes and the nylon connection.

The maximum deflection of the 13,2 meter façade is 330 mm to each side of the neutral axis and the calculated occurrence is once in the aimed design life of 50 years (Peters (2007)). The corresponding maximum rotation of 2 degrees at the connection was used in the constant amplitude cycling tests. The number of cycles was set to 1 million, which would mean 2,3 vibrations per hour over the whole life. To apply the load, a steel bolt was used over the length of two 15 cm short carbon tubes and the nylon connection. The load on the tube was measured by a strain gage and corresponds with the load of 6,54 kN found on the severest loaded connection. A total of three connections have been tested. The outside and inside diameter of the carbon fibre epoxy tubes are 25 mm and 20 mm respectively. During the tests the applied load, the cycling displacement and the temperature were monitored. To avoid undesirable damage effects and warming up of the tube a test frequency of 2 Hz was used.

5 MOISTURE ABSORPTION

The investigation of the moisture absorption was an important step in the concept development of the composite façade. In conventional insulating glass panels the moisture absorption is specified in the sealant and structural adhesive, the spacer itself is most commonly a metal. However, in case of the use of composite spacers, the moisture uptake and diffusion of the spacers must be evaluated as well.

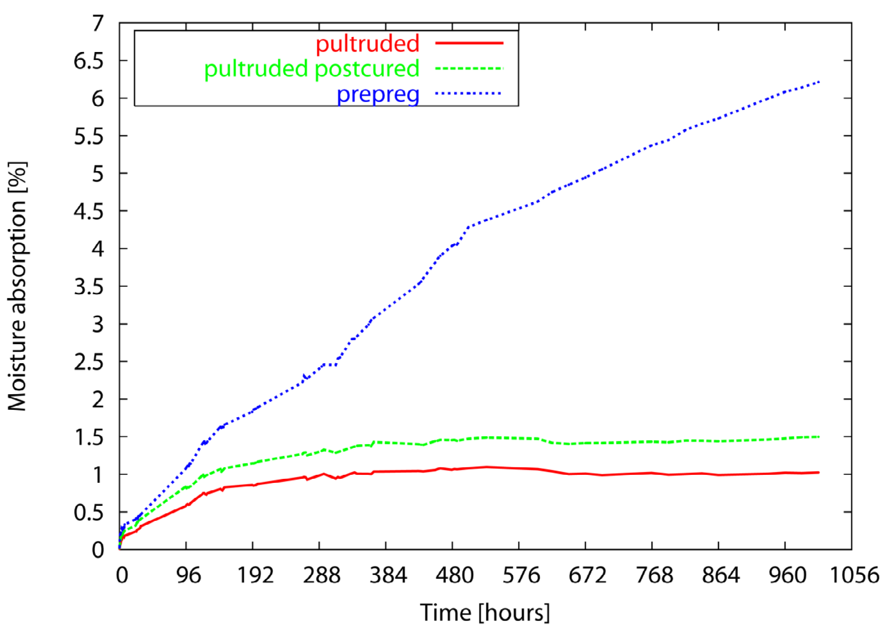

Figure 3. The results of moisture absorption tests on pultruded carbon fibre epoxy specimen (as received and with an additional post-cure) and autoclave cured carbon fibre epoxy prepreg.

The first step in this investigation were moisture absorption tests on autoclave cured 0/90º glass fibre epoxy prepreg (fibre volume fraction 60%, Hexcel 920) and pultruded unidirectional carbon fibre epoxy specimens (fibre volume fraction 70%, Hexion 4434). From the latter, a post-cured variant was also tested, which meant a two hour cure at 160ºC . Three test specimens were used for each of the three test variants. The specimen dimensions were sized 100 by 100 mm and had a nominal thickness of 2,2 mm for the pultruded specimen and 2,0 mm for the autoclave cured specimen.

The specimens were immersed in 70ºC water during 1008 hours (42 days). The results of the moisture absorption in time are shown in Figure3. An indicative test was also performed for 504 hours (21 days) on a 23,8 gram butyl mass, Tremco JS 680, for comparison with the composite specimens.

6 DIFFUSION RATE

For the determination of the moisture diffusion in insulating glass panels the characteristics of all used materials must be known. In traditional panels the materials used are steel or aluminium as spacer, butyl as a sealant, silicone structural adhesive and (hardened and coated) glass plates. The metal spacer and the glass plates can be assumed to have a zero diffusion coefficient. The silicone adhesive will only prevent direct water contact on the butyl, but does not function as a diffusion barrier. The diffusion of the traditional double glass panel is therefore solely dependent on the butyl characteristics and of course the environmental effects, such as temperature, relative humidity, et cetera.

Table 1. The results of the initial diffusion tests on insulating glass panels with spacers from either carbon fibre epoxy, glass fibre epoxy, or steel. A series of panels with carbon fibre epoxy spacers and two carbon fibre epoxy tubes was tested as well. The tests were performed up to 1488 hours of which the results up to 960 hours are shown, since after 456 hours 5 out of 8 panels already showed maximum relative humidity and internal condensation.

Material	**Relative humidity (%)**														
Carbon 1	35	25	35	40	75	75	80	80							
Carbon 2	35	25	25	40	40	55	55	75	70	55	55	55	55	70	70
Carbon 3	35	25	35	70	75	75	80	80	40	70	70	70	70	55	55
Mean	35	25	32	50	63	68	72	78	55	63	63	63	63	63	63
SDEV	0	0	6	17	20	12	14	3	21	11	11	11	11	11	11
Glass 1	35	20	20	25	50	55	55	55							
Glass 2	35	20	20	50	50	75	75	75							
Mean	35	20	20	38	50	65	65	65							
SDEV	0	0	0	18	0	14	14	14							
Steel 1	40	20	30	60	65	70	75	75							
Steel 2	35	10	10	10	70	75	80	80							
Steel 3	35	10	10	10	70	75	80	80	60	55	55	55	60	70	70
Mean	37	13	17	27	68	73	78	78							
SDEV	3	6	12	29	3	3	3	3							
Time (hr)	0	24	48	72	144	168	240	288	456	576	648	672	744	792	960

For the insulating glass panels with carbon fibre epoxy spacer and tubes the effect on the moisture diffusion have been examined.

Test standards to determine through-the-thickness diffusivity or water vapour transmission of materials are available in literature (ASTM (2005), ASTM (1998)). However, a priori assumptions in the calculation are required, such as single-phase Fickian material with constant moisture absorption properties through the thickness. Since relatively thick composite material and butyl is used in the insulating panel, the decision was made to perform comparative tests to standard insulating glass panels.

The spacers were either made of steel, glass fibre epoxy prepreg layup, or pultruded carbon fibre epoxy. Besides this also panels with carbon spacers and carbon tubes were examined according to the developed concept. The dimensions of the initially tested panels were 360x240x36mm and of the additionally tested panels were 240x180x36mm. The height and thickness of the glass fibre and carbon fibre spacer was 20x4mm and the used butyl was Tremco JS 680.

It is important to mention that no silica or other drying agent was used inside the panels. The advantage of leaving out the silica and using a moisture indicator instead, is that the diffusion is directly coupled to its measured density. The indicator strips were placed inside the panels, which give an indication of the relative humidity on a colour scale from 10 to 80%. The panels with steel spacers are used as reference.

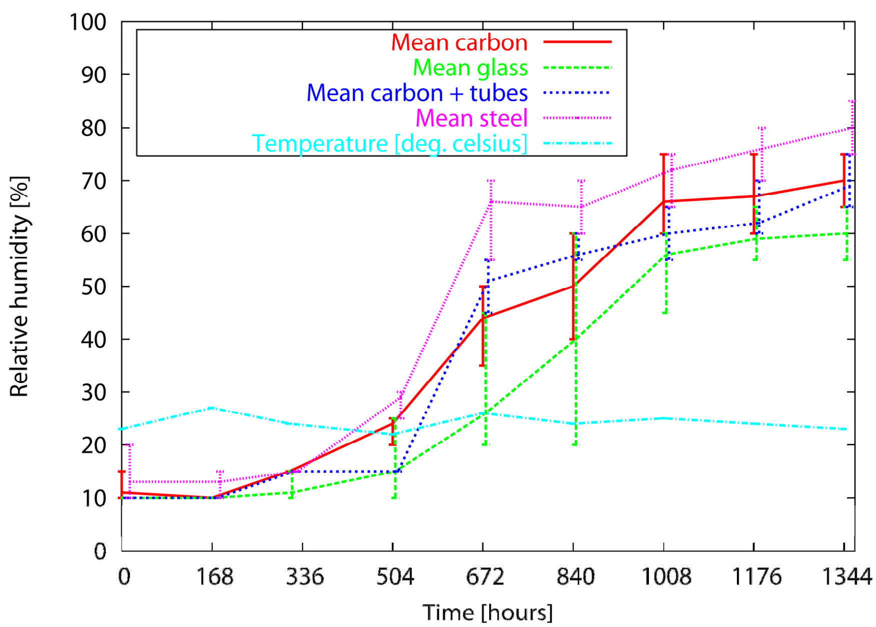

Figure 4. The results of additional moisture diffusion tests on insulating glass panels with spacers from carbon fibre epoxy (with and without tubes), glass fibre epoxy, and steel. The temperature at each determined relative humidity point is also shown. The first 4 weeks of thermal cycling between -18ºC to 53ºC was followed by a period of 7 weeks at a constant temperature of 58ºC .

Initial testing was performed by emerging 8 insulating glass panels in water of 57ºC (±5ºC): 3 panels with steel spacers, 2 panels with carbon fibre spacers, and 2 panels with glass fibre spacers. The results are shown in Table 1.

Additional tests were performed according to the standard glass panel test method NEN (2002). For each material a series of 5 panels were made and exposed in a weathering cabinet. 5 extra panels were made, each of which included 2 pultruded carbon tubes of 16 mm nominal diameter and 1,75 mm nominal thickness. During 4 weeks a continuous thermal cycle from -18ºC to 53ºC was performed, followed by a period of 7 weeks at a constant temperature of 58ºC . Again, moisture indicator strips were used and the panels were tested without drying agent for the previously mentioned reason. The results are shown in Figure 4.

7 RESULTS AND DISCUSSION

The frictional wear tests on the carbon fibre epoxy tube and nylon connection interface did not cause any significant damage. The tests only showed some minor quantity of carbon powder on the inside of the nylon connections.

The results of the moisture absorption tests are shown in Figure 3. After 504 hours (21 days) the pultruded unidirectional carbon fibre epoxy specimens stabilize at 1% and 1,5% moisture absorption for the non-post-cured and the post-cured variant respectively. The autoclave cured unidirectional glass fibre epoxy prepreg specimens reached over 6% moisture absorption and had not yet stabilized after 1008 hours (42 days). The butyl reached a 5,5% weight increase after 504 hours.

From the experimental results, a large difference between the pultruded and autoclave cured specimens was found of about 5%. It should of course be noted that besides the different manufacturing method, the material and fibre volume fraction is different as well. Post curing showed a clear effect on the moisture absorption as large as 50% higher absorption was found on average. This is confirmed with results found by Kootsookos (2004). From the indicative test on butyl it is clear that this material has an almost doubled moisture absorption as the glass fibre epoxy specimens and a more than five times higher absorption percentage than the non-post-cured carbon fibre epoxy specimens. To further investigate whether composite can be used as spacer material diffusion tests have been performed.

The results of the initial diffusion tests are shown in Table 1. The panels with glass fibre spacers were removed after complete (visual) condensation after 288 hours. The last panel with steel spacers was removed after 1488 hours of testing, when complete (visual) condensation had been reached. One panel with carbon fibre spacers reached 80% relative humidity at this point, though no visual condensation was found. The results for the additional diffusion tests are shown in Figure 4.

CONCLUSIONS AND OUTLOOK

The durability of pultruded carbon fibre epoxy spacers for façades was investigated by means of frictional wear, moisture absorption and moisture diffusion tests. Only limited frictional damage manifested as carbon powder was found in the conceptual connection between the carbon fibre epoxy tube and the nylon 'cartilage'. The carbon fibre epoxy specimens showed a maximum moisture uptake of 1.5% after a long term immersion in water of 53ºC. However, in the diffusion tests no difference was found between the panels with steel spacers and the ones with carbon fibre epoxy spacers. This is thought to be mainly explained by the characteristics of the butyl. For this reason, the panels of an experimental composite façade, which was realised after the research, were equipped with wireless weather station sensors to monitor relative humidity and temperature over the years. The weather station will furthermore monitor wind speed, outside temperature, and air pressure. The results for the panels will directly be compared to two larger façades build at the same time by conventional panels with steel spacers.

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