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Measuring the wind suction capacity of plastics-based cladding using foil bag tests: A comparative study

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ABSTRACT

Wood–plastic composites (WPC) represent a new generation of bio-based materials which have raised the interest of the building industry. Investigations of the performance of WPC cladding under wind suction demand an application-oriented approach. So far façade planners have not been able to obtain a satisfactory estimate of the structural resistance of WPC cladding. This study contains a comparison between two wood-fiber polypropylene-based WPC products (WPC-1; WPC-2) and two PVC-plastics cladding products not containing fibers (PVC-1; PVC-2). A non-standardized test was used to examine the wind resistance of cladding under varying fixation distances. Wind suction was simulated with reference to the EU guideline ETAG 034 and ASTM E 72 both recommending using inflated foil bags at the rear side of each test façade section. Panel deformations were measured at the test section's midspan. Local failure around a fixation device was investigated by microscopy analysis. It was found that WPC cladding failed due to edge cracking, whereas the PVC claddings failed due to pull-through of the fasteners. Product WPC-1 showed the lowest failure load at F_{max} =3.80 kN/m^2, whereas product WPC-2 reached failure loads exceeding 13.00 kN/m^2. The resistances of both PVC cladding products were close to that of product WPC-1. The results confirm that the resistance of plastics-based cladding is governed by its fixation mechanism rather than its bending strength. Moreover, bio-fiber reinforcement did not necessarily differentiate the WPC cladding from the plastics-based cladding without fiber reinforcement in terms of wind load capacity.

1. Introduction

Bio-based plastics consist of a polymer matrix which is strengthened by plant fibers such as wood or grass fibers. They represent a new generation of sustainable materials – biofiber-reinforced composites. They contain up to 70% fibers which significantly reduces the amount of crude oil used in their production and support the use of agricultural waste [1]. Wood–Plastic Composites (WPC) are among the most popular biofiber-reinforced composites. Their annual production worldwide was approximately 2.43 million tons in 2012, and future increases of more than 50% have been forecasted. Core markets are North America, followed by China and Europe. Russia and India are expected to emerge as future markets [2]. Europe accounted for 260`000 t in 2012 with a potential to reach 450`000 t in 2020. Most applications are in decking, automotive and cladding panels. The latter, however, so far only accounts for 6% of WPC sales in Europe [3]. Therefore, it currently plays a subordinate role in the building industry. Despite its ecological potential given its high proportion of biological components, architects and engineers hardly select this composite to increase the sustainability of buildings. One of the main reasons for this is its plastics-like appearance. Claddings made from thermoset plastics are often perceived as low-price products. They consist mainly of recycled bulk plastics which makes them less prestigious [4]. Furthermore, in terms of UV-resistance, plastics tend to fade and the encapsulated wood fibers slightly get grey throughout the years [5,6].

Another reason is the lack of product attributes in the field of façade design. According to the European Building Products Regulation (EU) No 305/2011 [7], a façade construction must satisfy seven basic requirements which are: (1) Mechanical resistance and stability; (2) Safety in case of fire; (3) Hygiene, health and the environment; (4) Safety in use; (5) Protection against noise; (6) Energy economy and heat retention and (7) Sustainable use of natural resources. Previous research by the author has shown that particularly architects and engineers select a cladding product according to 21 product attributes which are derived from these basic requirements. Within a cladding product selection process, stability-related criteria are seen as most decisive followed by fire resistance and durability. Thermal and noise protection were comparatively less interesting [8]. It was also found,

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that it is currently not possible for engineers to undertake a strength calculation for a projected WPC façade as demanded by national building laws. Such a proof is obligatory for all kinds of buildings and building parts in order to ensure the public's livelihood throughout the building's life-time. Strength calculations mostly consist of a comparison between the expected wind load on a building's façade and its structural resistance against wind impacts [9]. As far as fire protection is concerned, façades additionally must comply with local building specifications. Taking the example of Germany, such requirements depend on the building height. High-rise buildings are more than 22 m and their façades must then consist of fire-resistant materials. Irrespective of the building dimension, such strict fire-related requirements are also demanded for commercial buildings, schools, hospitals and other special constructions [10]. WPC mostly has a normal combustibility and is therefore classified class D and E according to EN 13501-1 [11]. However, by the addition of flame-retardants WPC could become upgraded by one class. It thus seems plausible that particularly WPC cladding is currently rather appropriate to residential buildings.

WPC cladding panels could not yet conquer the professional market segment and even not for residential houses. The reason is that most of the manufacturers have a plastics industry background and are not very familiar with building peculiarities. In general, reliable planning attributes, as proposed by the European Building Products Directive, are elaborated by normative test methods. Besides this, some EU member states demand an approval document for cladding kits because they are not entirely covered by standards, unlike concrete or timber elements for façades. For the mostly small and medium-sized manufacturers (SME), this is a lengthy and costly approach. As far as the availability of planning parameters, such as the design bending strength of the cladding or the design tensile strength of the fixings, is concerned, WPCs still lag behind similar plastics-based products such as high-pressure laminates (HPL) or glass fiber-reinforced plastics (GFR) cladding [12]. Although this new material has been used in façades in Central Europe for several years, its structural performance has not yet been proven sufficiently by laboratory experiments. Presumably, due to the unlimited number of different formulations for WPCs, separate investigations must be executed for each particular composite. After all, the performance of WPC cladding in a façade application under various loads is highly dependent on the nature and proportion of fiber used, the type of plastics of the matrix and the additives [13]. Further, the production process also influences the material characteristics, for example the extrusion temperature and feed rate [1]. Therefore, it is rarely feasible to provide standardized material characteristics for WPC cladding kits. However, the material standard EN 15534-1 [14] specifies methods according to which WPC manufacturers can determine selected attributes for their compound which is meant for injection molding and extrusion. These characteristics are rather useful for quality comparisons among different formulations if not for the evaluation of the performance of a final product, and they give at least an idea on how well a product made from this formulation is expected to behave in a façade application. For instance, a bending strength value determined according to EN 310 [15] is available for most WPC claddings. This value describes the performance of a point-loaded panel section. However, it is doubtable, if this value is appropriate to calculate the load capacity of a complete façade section which consists of several profiles connected to each other via groove-and-tongue. Theoretically, the load capacity of one m^2 WPC façade can be computed using the bending strength of the compound which is the modulus or rupture (MOR). From this value, the load capacity of a hollow WPC profile can be derived by the use of its section modulus W_y and this result can be referred to one m^2. By experience, capacity values gained by large-scale tests which expand on a complete façade section are mostly higher than the capacity received from calculations using test results from small specimens. Even though a planner could design a WPC façade using bending strength values of the compound, this would not be in accordance with general engineering practice, where design values are used. According to EN 1990 [9] such a design value for bending strength is far less than the strength of a virgin WPC compound because in practice the material becomes degraded by natural weathering throughout the cladding's life-time. Further, it has not been confirmed that bending failure is the expected failure mode of a WPC cladding under excessive wind suction. Based on the literature reviewed, WPC material research solely focusses on bending strength values as main predictor. It is commonly assumed that they give orientation in the expected performance of future products made from such compounds. Published values range from 13 MPa to 60 MPa depending on the compound formulation [16–19]. However, no research so far examined whether the fixation resistance of a WPC façade correlates with its bending strength. In fact, a connector's wind resistance not solely depends on the compound properties but also on the connector's shape and the way how it is embedded in the product. This demands a case-wise approach when investigating such aspects.

The way to describe the performance of a WPC product in a future façade application is independent of the material itself. Therefore, established testing methods for other cladding materials such as timber, metal, ceramics or plastics could be applied to WPCs also. Such methods are described well by the European Technical Approval Guideline (ETAG) 034:2012 [20], which is mostly applied for approval processes for cladding kits. The ETAG demands the proof of the wind suction resistance of cladding which can be determined by testing a reference façade section in a wind-suction and pressure chamber. Such wind tunnels are widely used for wind up lift tests particularly for lightweight bitumen or plastics waterproofing membranes for roofs [21,22]. However, the guideline alternatively allows the use of foil bags which is particularly helpful for resource-poor SMEs. Unfortunately, the ETAG does not provide any further information about the foil bag test apparatus. A similar case presents itself in the German standard DIN 18516 [23] which also proposes foil bags to be positioned at the rear side of the cladding and inflated until panel failure occurs. Again, no detailed approach is given. More precise information is provided by ASTM E 72 [24] which is widely used for racking tests on sheathing boards mounted on steel studs or on complete masonry walls [25,26]. Such tests are mostly applied to verify finite-element models (FEM) against experimental results. Papers also report on how this norm is employed to such large-scale specimens loaded by transverse forces where bending failure of the complete masonry or failure of fixations due to pulling through the boards is investigated [27,28]. In such cases an air pressure bag is placed between a reaction-platform and the tested construction. E 72 clearly states that this method is appropriate to investigate the deformation behavior of a structural element for a particular building purpose. Test sections are spanned over one filed under serviceability loading. Although it is feasible running the test until failure, this approach is recommended when comparing different constructions or the failure potential of fasteners under repeated loads. However, for the study on hand the rupture behavior of façade sections under static loading is from paramount interest. In this regard, the wind-suction test using a foil bag seems feasible for investigations on failure loads of special façade coverings. However, none of the referenced standards could satisfyingly determine the testing process for panel-like specimens which are spanned over more than one field and which are incrementally loaded until failure. Even more, all identified papers which reported about transversely loaded rainscreen façades solely focused on large-scale sheathing boards and not on panel-like claddings. Therefore, the following test method is a non-standardized approach which uses applicable contents from the referenced norms and adopts them to the research purpose.

In this study, foil bags were used to simulate wind suction for a comparative analysis of two cladding product categories of plastics-based panels. The research targets were to (1) find out which mode governs the failure of these materials under wind suction, (2) position

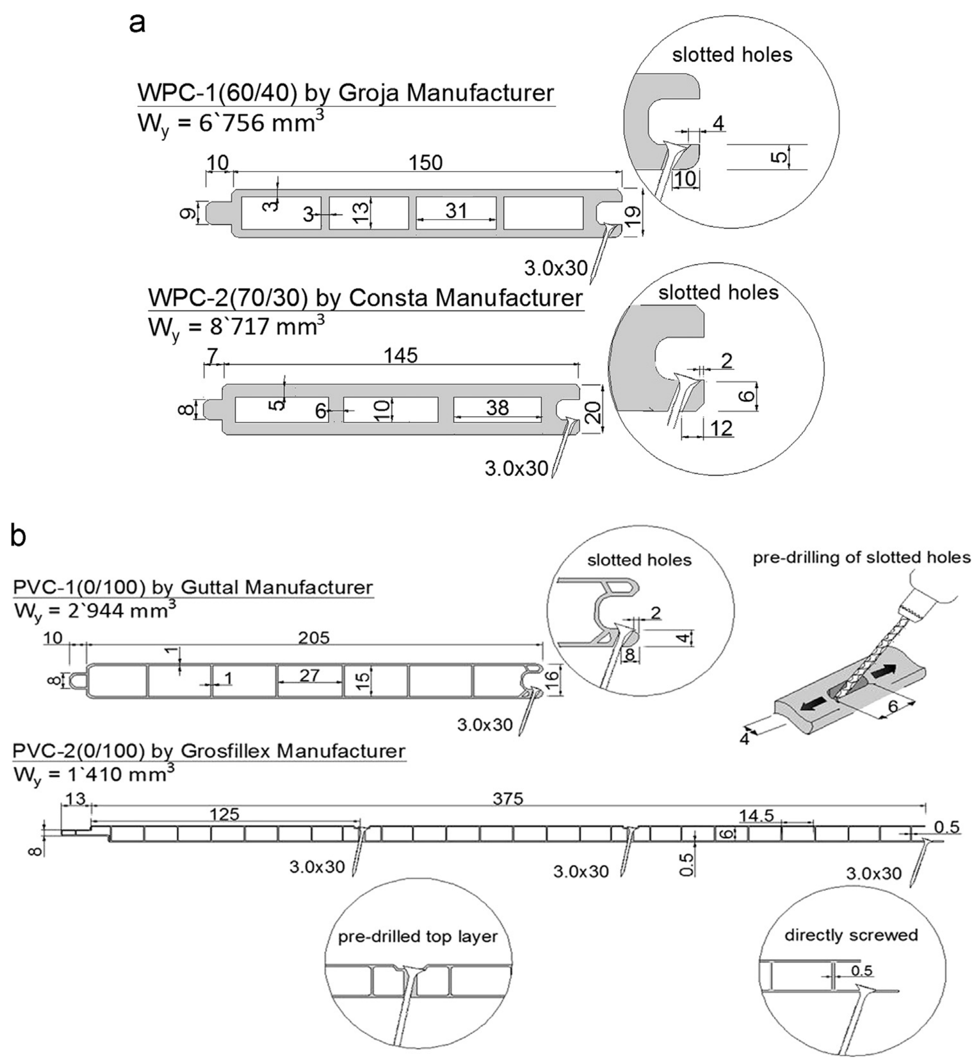

Fig. 1. Cross-sections of tested WPC-profiles (1a) and PVC-profiles (1b) and pre-drilling of slotted holes (dimensions in mm).

WPC cladding relative to PVC as a competing material in terms of load capacity and to evaluate the value-adding of fiber-reinforcement and (3) test the use of foil bags as an alternative to wind chambers particularly for SMEs in the WPC industry. For lack of a normative guideline, an appropriate test apparatus had to be implemented first and calibrated prior to testing. The apparatus needed to be able to provide a realistic simulation of wind suction so as to allow the adequate determination of the resistance of the cladding products. At the same time it needed to strike a balance between practicality of use for SMEs and reliability of the test results.

2. Materials and methods

2.1. Tested materials

The specimens used in this study are cladding panels with a large proportion of plastics. All products were available for sale in the building market and meant for outdoor use in Europe as can be concluded from the product's trade mark (Figs. 1a, b). The profiles had a hollow core and their cross-sections varied in width, thickness and dimensions of the webs and flanges. They were attached to each other by groove-and-tongue connections and installed in horizontal position. The panels were designed to be fixed with stainless-steel 3.0×30 mm countersunk head screws with 6 mm head diameter. The testing surface was defined by the number of panels installed parallel to each other in one direction and twice the fixation distance s in the other direction. The fixation distance was either 500 mm or 600 mm, which are values commonly used in practice. The façade sections were between 1`000 mm and 1`200 mm long and between 725 mm and 820 mm wide.

As far as the material composition is concerned, the proportion of bio-based constituents ranged from 0–70%. WPCs were represented by two products, both of which, according to the information provided by the manufacturer, contained polypropylene (PP) reinforced with wood-fiber contents of 60% (WPC-1(60/40)) and 70% of bamboo-fibers (WPC-2(70/30)). The standard panel length of WPC-1 was 1.80 m and of WPC-2 3.0 m. The comparison group consisted of polyvinylchloride (PVC) hollow-profile panels: products PVC-1(0/100) with a standard length of 2.0 m and PVC-2(0/100) which was 2.60 m in length. All panel types are extruded and the WPC specimens contain fiber species, such as bamboo and wood, which are determined by EN 15534-1 [14]. Therefore, the WPC specimens are both covered by this material base norm as introduced in Section 1. Although the pure plastics-based panels are manufactured by the same technology, they do not comply with this norm because they have no biofibers inside.

Bending resistance and panel fixation to the sub-construction are seen as most crucial when measuring the failure load of a façade section. However, bending strongly depends on the plastics matrix and the fibers which act as a reinforcing element. This product feature is entirely predetermined by the compound and the production process as explained by Section 1 of this paper. As far as the fixation resistance is concerned, this property is also influenced by the type of fixation mechanism and a proper installation. In general, plastics-based claddings can be installed either by metal clips, which are put to the panel edge and nailed to the sub-rail, or by direct mounting using screws. For the latter, however, the panels should contain long holes in order to allow thermal expansion of the panels. In such a case the panel ends can move horizontally. To ensure that both panel ends move to the same extent, it is essential that the hole for the fixation at the middle of the panel should not be slotted or the screw should be much more tightened than the others. It is important to note that particularly WPC panels, which are designed as open profiles, contain long holes each 50 mm along the panel edge and which are pre-manufactured right after extrusion by CNC-controlled milling. Other panels, which have a hollow-core structure, as used in this study, don`t provide such installation aid and pre-drilling is done on site not each 50 mm but above a support rail. As far as this study is concerned, suppliers did not recommend long hole pre-drilling prior to fixation most probably because their panels were maximum 3 m in length. However, when sales are directed to the professional segment, longer panels are demanded and this issue must be clarified prior to commercialization. To the author's experience from the WPC industry, panels deform significantly if entirely fixed directly. This visible effect is caused by thermal expansion which makes approximately 2 mm per m panel length and which deflect the panel between the support rails to the outside. Although WPC is an elastic material, deformations not always completely disappear when the panels contract because not all screws are equally tightened. As a consequence, some single panels in the façade completely move to the left or to the right and expansion joints between the panel ends become closed or double as wide. So far, no research has assessed the pros and cons of mounting by round or long holes in terms of wind resistance of the complete façade and in terms of durability of the fixation mechanism particularly if the material around the hole permanently becomes restrained throughout the life-time. Presumably, pre-drilling on site of hollow profiles seems to be the most crucial case because the quality of the drilled holes most probably is less constant. It is yet unsure if manual pre-drilling is at all recommendable because this method could significantly reduce the façades wind suction resistance compared to direct mounting. However, thermal expansion lead to excessive stresses around the screws if directly mounted and this could lead to material fatigue. If pull-through resistance of fasteners indeed matters under wind suction, this negative effect could decrease a durable wind resistance of the panels. Furthermore, depending on the kind of driller and the revolution speed, the hole surface becomes rough or smooth which additionally affects the stress distribution in the material. And finally, it is also unsure how creeping of the panels due to the self-weight, which is a permanent load, might negatively affect the resistance of fixation points. Given a panel self-weight of 2.0 kg/m, as exposed by Table 1 for the PVC-specimens, and a fixation distance of 0.5 m, each screw is then expected to become permanently loaded by 1.0 kg vertical load. As can be seen from Fig. 1, the panels are installed with the groove being at the bottom in order to prevent rain water from getting into the groove of the previous panel underneath. Creeping will most probably deform the surface of the long hole above the screw. However, if the panel is mounted with the groove at the bottom (Fig. 2a), there is enough material above the screw to cover the local stresses from creeping which keep deformations rather small. Creeping might be a crucial factor for open profiles where the long holes are usually positioned at the top of the panels. If pre-drilled holes have an edge distance of 4–5 mm, creeping will most likely bulge the material above the screws which particularly hampers the panel movement due to thermal expansion. However, the self-weight of open profiles is only half compared to hollow ones which might overcome this negative effect.

After all, this study investigated the wind suction resistance of pre-drilled WPC cladding panels in order to clarify if manufacturers should limit the panel length to a level which allows direct mounting without negative consequences or alternatively go for pre-drilled long holes which are better for unhindered thermal expansion. The latter would allow sales in the professional segment where long panels are preferred. If, however, the wind resistance might not sufficiently meet normative requirements it becomes doubtable that manual pre-drilling, without an appropriate quality control either by visual inspection or the use of a drill template, represents an appropriate alternative. Insights thus give orientation in future product developments.

Because of their thin walls, the specimens PVC-2(0/100) were fixed onto the sub-rails by screws, without pre-drilling through the PVC material at the panel's tongue. All other specimens were pre-drilled by a 4 mm drill to make slotted holes and fixed by screws (Figs. 1a,b). During assembly, the screws were placed at the center of each long hole and tightened by hand. To enable a comparison of the different façade sections, the measured loads were referred to the number of screws per unit surface area and presented for a fixation distance of s =500 mm and 600 mm; see Table 1.

2.2. Test assembly

The first basic question was to whether a vertical building element, such as a façade, could be tested in a horizontal position which simplifies the test execution. Given the self-load of 12,91 kg/m^2 for specimen WPC-2 as per Table 1, the area load which additionally becomes measured in the foil bag test due to the façade's self weight is some 0.13 kN/m^2 which compared to usual wind loads of 3.0 kN/m^2 indeed becomes negligible. This speaks for a horizontally positioned test stand. The second question to consider was if temperature should play a dominating role during the test execution. It is commonly assumed that the elastic modulus (MOE) of thermoplastics decreases by increasing temperatures which thus matters in a façade application. If bending resistance of the panels will limit the wind suction capacity of the complete façade, high temperatures most probably lead to lower results. As far as the fixation points are concerned, although they are covered in the panel's groove, their resistance also might become affected by high temperatures. However, in practice the façade's temperature at failure is much less because if a storm approaches, intensive sunshine becomes interrupted by heavy clouds and winds

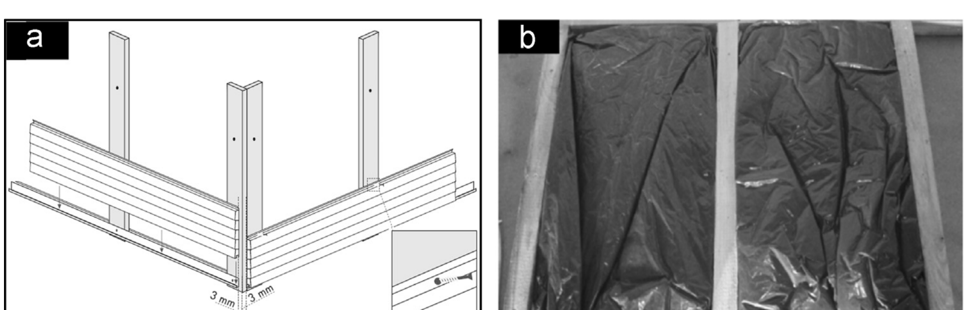

Fig. 2. a: Sub-framing in practice - Timber rails build a ventilation gap [29]. b: Sub-framing in the test assembly - Foil bags installed between the timber rails.

Table 1
Characteristics of tested façade sections.

Specimen	Wall thickness t [mm]	s=500 mm		s=600 mm		Self-weight [kg/m^2]
		Surface area [m^2]	No. of fixings/m^2	Surface area [m^2]	No. of fixings/m^2	
WPC–1(60/40)	3	0.75	24.0	0.90	20	10.75
WPC–2(70/30)	5	0.725	24.8	0.87	20.7	12.91
PVC–1(0/100)	1	0.82	18.3	0.98	15.3	2.27
PVC–2(0/100)	0.5	0.75	28.0	0.90	23.3	1.64

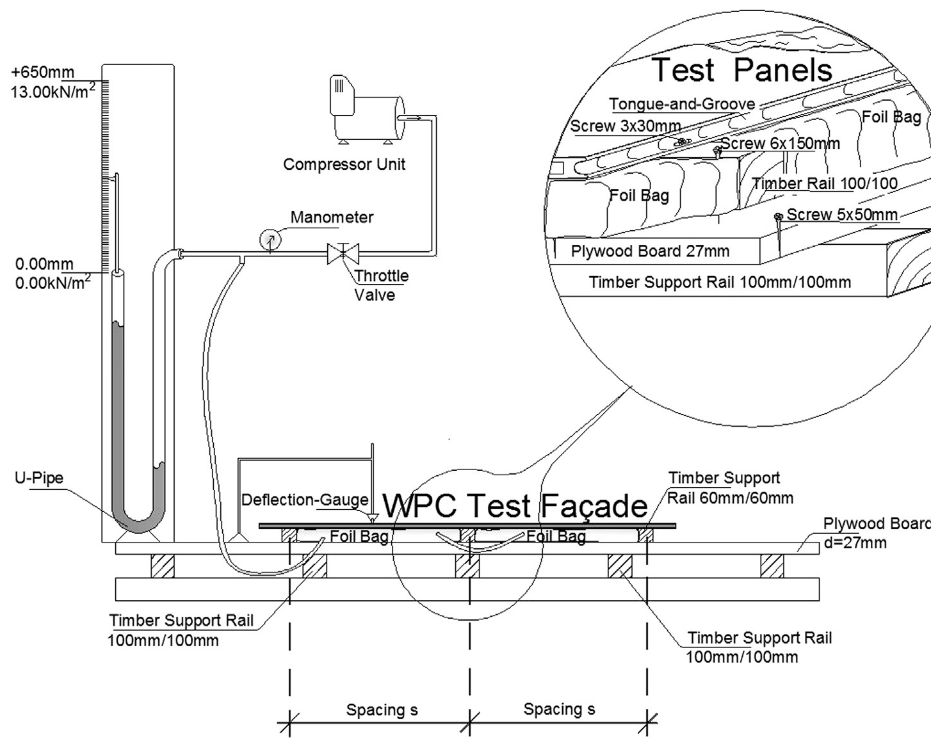

Fig. 3. Test assembly showing the U-shaped water pipe as measuring device Elevation view: Test specimens over the middle support.

cool down the surface temperature. It is therefore doubtable that intensive wind suction and sunshine occur at once which speaks for a test being executed at laboratory room temperature. As illustrated by Fig. 3, the test stand consisted of a stiff 27 mm plywood board to simulate the base of a façade (the building surface). The sub-construction was made of 60 mm wide and 60 mm high spruce rails which were fixed onto the base by countersunk head screws 6.0 mm x 150 mm each 250 mm along the rails. The plastic foil was made from polypropylene and installed in the 60 mm thick space between the sub-rails which in practice build a ventilation gap of the reinscreen façade (Fig. 2a). The front ends of the ventilation space were closed by further timber rails in order to prevent the foil bag to bulge or burst. The tested specimens were façade sections containing 2 spans supported by 3 sub-rails, which required the use of two foil bags (Fig. 2b). The test specimens were stored in the laboratory for more than 24 h in order to ensure acclimatization.

Both bags were connected to each other by a pipe so that they could be inflated simultaneously. The bags were filled by an 8-bar compressor. The air supply was regulated by a throttle valve which was placed in front of the foil bags. This enabled a manually time-controlled inflow of the air and the keeping of a particular pressure over a set period of time. The air pressure was measured via a water column. For that purpose, a U-shaped cylindrical pipe system was installed vertically next to the test stand (Fig. 3). One end of the U-pipe was connected to the air-feeding pipe leading to the foil bags and the opposite end was kept open. With increasing air pressure the water level could rise by at most h =0.65 m. This height h was measured with a scale on the vertical flange of the U-pipe. Wind suction F [kN/m^2] was calculated from h [m] using the following equation:

$$F = N/A\ [kN/m^2] \tag{1.0}$$

$$N = 2^*h^*r^{2*}\pi^*\rho\,[kN] \tag{1.1}$$

$$A = r^{2*}\pi\,[m^2], \tag{1.2}$$

where r is the radius of the U-pipe, N is the weight force of water (density =1`000 kg/m^3) and h is the rise of the water level. Inserting Eqs. (1.1) and (1.2) into Eq. (1.0) leads to the following result:

$$F\,[kN/m^2] = 20kN/m^{3*}h. \tag{2.0}$$

It is important to note that even though the water level increases by h, the water column is twice as high, which is due to the U shape of the pipe system. This fact is taken into account in Eq. (2.0).

The test stand was calibrated prior to the investigations using a digital manometer (pressure gauge HMG1, K8947) with a maximum capacity of 1`500 mbar. The stresses measured from the pipe system and those from the pressure cell differed by less than 5%. This was due to the fact that the data from the pipe scale and from the pressure gauge were not read exactly at the same time because the measurements were carried out manually.

2.3. Testing procedure

The test procedure consisted of the application of air pressure to the rear side of the cladding via both foil bags and by then increasing it step by step. Starting at 0.4 kN/m^2, the pressure was raised by 0.2 kN/m^2 at each step, which equals a 10 mm rise of the water level. The rate of applied pressure was approximately 1.0 mm/second for the water column or 0.02 kN/second for the load. After each increase in 10 mm column high, the pressure was kept constant for 30 s. During this time the panel deflection e [mm], at the center of a span where the highest deflection took place, was measured by the deflection-gauge. For each product type and spacing s two tests were carried out and their mean value was exposed as F_{max} [kN/m^2] which subsequently was referred to the number of fixations given as F^*_{max}.

3. Results

3.1. Mode of failure under wind suction

Sixteen tests in total were run using the foil bag method. WPC-1(60/40) panels exhibited edge cracking around a screw head as their basic failure mode (Fig. 4a), whereas the PVC-based cladding sections failed due to pull-out of the screws through the panel flange or web (Fig. 5a). No panel failed in bending although right after fixation failure there was an abrupt increase in defection (Fig. 5b). Figs. 6a to d show the results from the microscopy analysis which reveals that WPCs exhibit brittle failure by nature (Fig. 6a). Specimen WPC-2(70/30) did not fail at all during the test, which is why the undamaged specimen is shown in Fig. 6b. As can be seen, the hole surface of WPC-2 is much rougher compared to WPC-1 which might come from different drilling quality. Obviously this did not act to the detriment of WPC-2 which showed much higher loads. Both PVC specimens exhibited ductile material failure. In specimen PVC-1(0/100) the hole edge bulged (Fig. 6c) and in PVC-2(0/100) the comparatively thin profile wall ruptured (Fig. 6d).

3.2. Measured wind suction capacities

Figs. 7a and b show the mean deflections e [mm] with respect to the measured air pressure F [kN/m^2] (calculated with Eq. (2.0)) for each product group. The load curves represent the mean values from both tests per product and spacing. The graph shows a monotonous increase of the deflection per unit of load. The ultimate deflections for spacing s=500 mm (Fig. 7a) are lower than for spacing s=600 mm (Fig. 7b), except in the case of specimen PVC-1(0/100).

It was found that, at least for the two applied spans s, the capacity of these plastics-based façades can be predicted using the resistance of their fixation mechanism. To asses the dependence between wall thickness and edge cracking, the mean ultimate area load F_{max} was expressed with respect to the number of fixings per m^2 which lead to F^*_{max}. Finally, this value was condensed to $\overline{F}_{max}$ over both distances s, see Table 2.

As can be seen from the figures in Table 2, $\overline{F}_{max}$ of the fiber-reinforced WPC-1, which has three times thicker walls, is inferior to $\overline{F}_{max}$ of PVC-1. In other words, a plastics-based cladding without fiber reinforcement exceeded the load capacity of a fiber-reinforced WPC cladding because its fixation mechanism showed higher resistance. Obviously, the fiber reinforcement was not necessarily a prerequisite to distinguish this WPC from a pure plastics cladding in terms of load capacity. However, things look different when the consideration is group-wise. Then, the correlation between wall thickness and fixation strength for both WPCs and PVC-based products is 100%. In this case WPCs with thicker walls around the fixation points are most likely to resist higher wind suction loads than with thinner walls.

3.3. Practicability of the foil bag test method

Fig. 2b shows the foil bag at the end of a test right after failure of a test façade. It was found that by increasing the stiffness of the foil, the bags tend to buckle at the rear side of the cladding. It was therefore theorized that the load transfer between foil bag and cladding might be disturbed if the bag is too small or does not fill out the ventilation gap of the façade section in a uniform manner, which could negatively influence the test results. Obviously, this effect would have occurred mainly at the borders of the ventilation area. It is suspected that the effective area for load transfer is smaller than the actual area of the rear side of the cladding.

Furthermore, during each test the compressor refilled its air tank several times. When this occurred, the pressure in the pipes increased, which required a prompt intervention by hand to slow down the air inlet in the throttle valve. Failure to do so would have resulted in the panels becoming overloaded which can lead to early failures. Therefore, a permanent fine-tuning via the valve was essential for a smooth load application to the test area.

4. Discussion and conclusions

4.1. Optimization of test method

In this study a testing method was applied which is not sufficiently standardized. During its execution it was found that the foil bag could not fill the entire ventilation cavity and that the foil formed creases at the cladding rear side (Fig. 2b). This disadvantage can be avoided by using thinner foil. Thinner foil, however, is more likely to burst under high pressure, particularly inside the hollow spaces. Therefore, as a basic rule, the stiffer and more highly loaded a cladding is, the thicker the foil should be. Distortion effects caused by improper expansion of the bag become negligible with increasing pressure because the amount of empty space will decrease. Hence, the loads measured at low deformations show larger errors than those measured at high deformations. The discrepancies become progressively smaller and will be minimal close to the failure of the specimen. As this testing method is

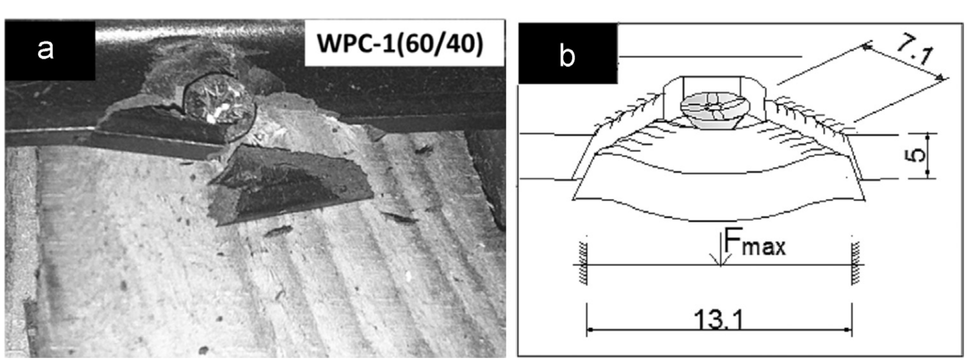

Fig. 4. Brittle WPC fracture (4a) and design model for calculations (4b).

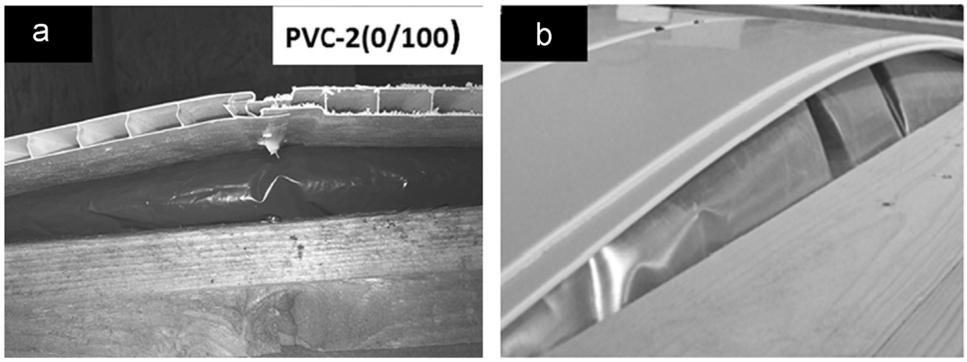

Fig. 5. Ductile PVC fracture (5a) and deflected PVC-2 specimen (5b).

designed to yield failure loads it is sufficient to adapt the foil thickness to the panel stiffness in order to achieve the highest possible reliability of the data.

4.2. Influence of fiber-reinforcement

As far as the influence of the wall thickness on the failure is concerned, it could not be demonstrated by correlation analysis that the failure loads from all considered products correlate with their wall thicknesses. This is because obviously WPC-1 failed at minor loads compared to PVC-1 which even had three times thinner walls around the screw and which were not fibered at all. With regard to the Young's Modulus (MOE), both specimens are comparable because adding wood fibers to pure PP increases MOE from approximately 1`500 MPa by 200% to nearly 3`000 MPa [19] which thus makes PP-based WPC comparable to pure PVC's MOE of 2`800 MPa. Apart from MOE, the bending behavior also strongly depends on the profile geometry described by its section modulus W_y. High cross-sections and thick walls increase W_y which is why specimen WPC-2 showed minor deflections compared to PVC-2. It can therefore be theorized that fiber addition positively affects the test results because they increase MOE and W_y by thicker walls. However, WPC with higher wall thickness due to fiber contributions does not per se show superior fixation strength compared to pure PVC claddings. The elevation view of specimen PVC-1 (Fig. 1b) shows that the profile's groove was additionally strengthened by an inclined wall which acts like a compression strut. This additionally stiffens the cantilever arm in which the screw is placed. As can be seen from Fig. 6c, the screw head was completely pulled through the PVC material which is in addition to Fig. 6a where the WPC-based cantilever arm broke. It can thus be concluded that in terms of cladding applications, the addition of wood fibers to the plastics matrix is not necessarily value adding to its wind suction resistance if fixation failure matters. Further, fixation resistance is not predominately up to a high MOE- and W_y-value but rather to an optimized fixation mechanism. Presumably, particularly thinner profiles with high fixation resistances are more likely to fail by bending rupture. In such a context fiber-reinforcement indeed supports the capacity of the overall façade. If the comparison is drawn between the WPC-specimens, thicker walls and even higher fiber-content speaks for higher wind load resistance of the cladding. As can be seen from the elevation views of Fig. 1a, the wall thickness of WPC-1, which fails before WPC-2, is 17% less. Thus, among WPCs the wall thickness indeed matters.

4.3. Use of test results in practice

The tests revealed that under high wind suction the tested plastics-

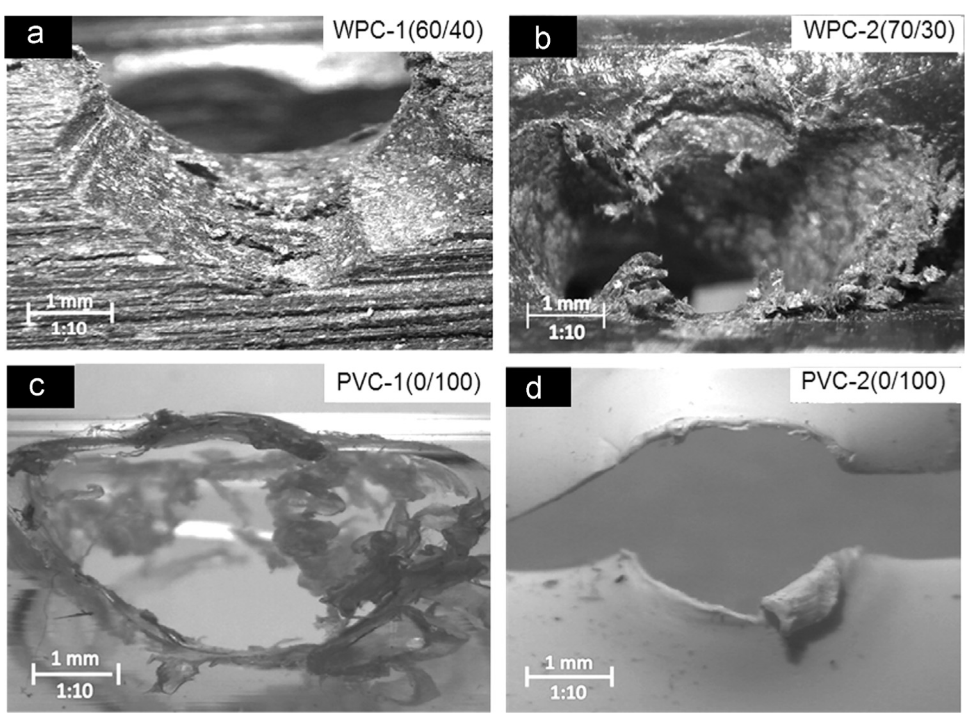

Fig. 6. Microscopy analysis of the fixation holes after failure.

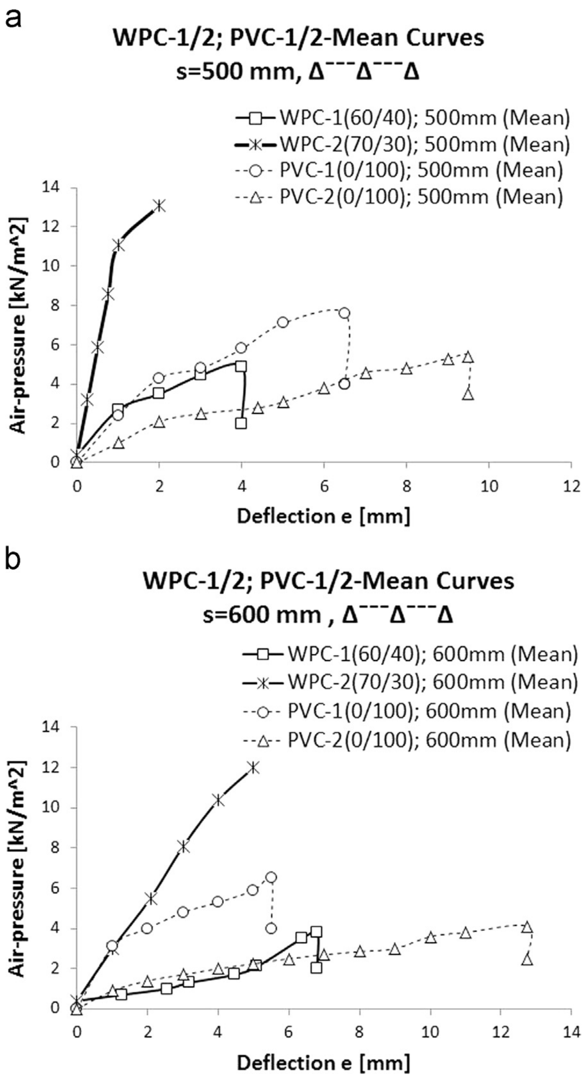

Fig. 7. Measured air pressure vs mid-panel deflection for s=500 mm (7a) and s=600 mm (7b).

based cladding products are most likely to fail by break-out of their fixings rather than by bending failure of the panel itself. However, this does not mean that wind pressure loads can be neglected in strength considerations of WPC cladding. Depending on the building geometry, pressure loads also occur and might even be higher. Failure of fixations was observed for the two spans of 500 mm and 600 mm. If WPC cladding products are expected to be applied in the professional segment, such distances most likely become relevant. If furthermore the failed specimens are used in applications where even higher wind resistances are demanded, it is then recommended reducing the spacing down to 400 mm or even 300 mm particularly at building parts where wind loads reach a peak value, which is mostly the case for building edges. In return, the exercised distances could theoretically and practically become enlarged when minor resistances are demanded. Only in this case bending rupture might dominate the test results. However, the study could not prove if bending indeed matters within a range of distances which are still applicable in façades. From the author's experience in the building industry, spans exceeding 750 mm are no more recommendable for such plastics-based panels, particularly taking into account that the more is the span the more possible are irreversible distortion effects due to thermal expansion and water immersion.

In order to much better estimate the relevance of rupture failure in applications, additional calculations were carried out on the bending stresses in the panels at the measured failure loads, which in the study were restricted by the fixations. At first, the MOR-value of WPC-2 was found to be 23.9 MPa (s=1.2 MPa) which was determined by Zwick Z010 bending tester on material specimens cut from WPC-2. Presumably, MOR for WPC-1 is a bit below this value because it contains 10% less fibers. The calculation of the stresses was using the inner moment W_y (Figs. 1a,b) multiplied by the number of panels within the testes façade section and it was using the calculated bending moment. Bending stresses above the middle-support were found to be only 3.80 MPa for WPC-1 and 9.65 MPa for WPC-2. In addition, PVC specimens showed values which were 16.0 MPa for PVC-1 and even 49.0 MPa for PVC-2. From a broader view it seems plausible that, particularly for the WPC specimens, also higher spans up to 750 mm most probably provoke a failure of the fixations rather than a bending rupture because the measured bending stresses are still far from the WPC rupture stress (MOR) of 23.9 MPa. As can be seen from Fig. 7, deflections of all specimens ranged from 2.5 to 12.5 mm which under serviceability aspects vary between L/250 and L/50. Depending on the occurring wind load, the deflections thus might not always meet serviceability criteria.

As can be seen from Table 2, the failure loads F_{max} significantly decrease with increasing fixation distance s. This makes sense because if the screw withdrawal is a constant value and the loaded area per screw is increased due to a larger spacing s, the applicable wind load must decrease. For the correct design of claddings it is therefore essential to prove if the expected wind loads can be covered by the fixings with the given distances of the sub-rails. The distances must generally be reduced for higher wind loads. From a broader perspective, both WPC and PVC claddings showed wind load resistances which might sustain the standard loads generally assumed for Central Europe, which usually range between 0.60 kN/m^2 and 3.50 kN/m^2. The measured breaking loads vary between 3.80 kN/m^2 and 13.00 kN/m^2, the latter value refers to specimen WPC-2(70/30) which did not fail.

Nonetheless, for a façade design the characteristic loads, either received by tests or computed, must be reduced by a conversion and safety factor which takes into account the strength degradation of the material over its life-time and which ensures an appropriate safety level for the application [30]. Hence, some design values derived from the tested products will not be high enough to meet current wind loads occurring all over Central Europe.

Table 2
Mean failure loads $\overline{F}_{max}$ per fixation device.

Specimen	Wall thickness t [mm]	s=500 mm		s=600 mm		Mean failure load $\overline{F}_{max}$ per fixing [kN]
		Failure load F_{max} [kN/m^2]	Failure load F^*_{max} per fixing [kN]	Failure load F_{max} [kN/m^2]	Failure load F^*_{max} per fixing [kN]	
WPC−1(60/40)	3	4.9	**0.20**	3.8	**0.19**	**0.195**
WPC−2(70/30)	5	13.0	**0.53**	12.9	**0.62**	**0.575**
PVC−1(0/100)	1	7.6	**0.42**	6.4	**0.42**	**0.420**
PVC−2(0/100)	0.5	5.4	**0.19**	4.1	**0.18**	**0.185**

4.4. Verification against computed results

As already mentioned, ASTM E 72 recommends using the foil bag test for serviceability considerations rather than for a strength design of a façade. However, computed results give insights about the scale effect because findings from large-scale tests appear to be better. If and how additional small-scale tests should be considered in façade strength calculations is a basic question for a façade engineer. Besides the rupture load received from the foil bag test, it is common practice to compute the applicable load by the use of the modulus of rupture (MOR) gained from three-point bending tests on small specimens. Therefore, a comparative stress calculation was executed for the test façade WPC-2 for its bending and fixation capacity. The calculated deflection of all 5 panels under the measured 12.9 kN/m^2 is (12.9 kN/m^2 *(5*145 mm) *(600 mm)^4) /(192*3`000 N/mm$^2$ *87`166 mm^4 *5) =4.8 mm, where 192 is a factor considering the 2-span orientation, 3`000 N/mm$^2$ is the MOE-value of this kind of WPC and 87`166 mm^4 is the moment of interia I_y. The calculated deflection for WPC-1 under 3.80 kN/m^2 was found to be 5.5 mm. Compared to the deflections shown by Fig. 7b, the calculated values are off by only 5%. Both methods coincide in terms of serviceability aspects.

The calculation of the maximal applicable load under bending should as well consider the two-span geometry, the span length of 600 mm and the 5 panels which were connected to each other via groove-and-tongue. The rupture load is ((8`717 mm$^3$ *5) *23.9 N/mm$^2$) /(0.125*(600 mm)$^2$ *(5*145 mm)) =31.93 kN/m$^2$ where 8`717 mm^3 is the inner moment W_y of the hollow profile as per Fig. 1, 0.125 a factor considering the bending under 2-span geometry, 600 mm is the span length, 145 mm is the panel breadth, 5 is the number of panels which together built the test façade. In addition, the calculated rupture load due to bending for WPC-1 is some 20 kN/m^2. Both results are far above the applied load at fixation failure which confirms that the foil bag test indeed provided significant results for wind suction proofs. Besides, the wall thickness of WPC-1 was 1.0 mm less compared to WPC-2. It can therefore be concluded that WPC-2 was close to failure of fixation. Overall, the computed results thus plausibly confirm that fixation resistance indeed mattered.

The foil bag test found out that within usual distances of the support rails, the strength of the fixation tools are a better predictor for the façade's load capacity than the bending strength. It is so far not proven if fixation resistances comply with computed results. Therefore, a calculation on the material stresses at the long hole's surface was executed. As can be seen from Fig. 4a, the mode of failure for the WPC claddings was an edge cracking where WPC material next to the long hole is pulled down by the screw head. This panel edge complies with a beam which is restrained on both ends (Fig. 4b). If this beam becomes excessively loaded by the screw head, its ends most probably fail by bending rupture. Given a MOR of 23.9 MPa for WPC-2, the calculated load on the screw which lead to failure is (8*23.9 N/mm^2 *42.6 mm^3) /13.1 mm=622 N where 8 is a factor considering the bending behavior of a beam restrained at both ends and 42.4 mm^3 is W_y of the rupture surface (wall thickness=6 mm). As can be seen from Table 2, the measured load $\overline{F}_{max}$ per fixing is 575 N which makes an error of 8%. However, the same calculation applied to WPC-1 revealed a fixation failure at 361 N. Compared to $\overline{F}_{max}$ =195 N (Table 2), the error now makes 45%. To much better estimate the error for WPC-2, the pull-through resistance of a screw, measured by a Zwick Z010 static testing machine, was found to be only 292 N (5%-percentile value). This was derived from a series of 10 plates with 5 mm thickness made from specimen WPC-2 where the edge distance of the long hole was 5 mm. 292 N is about half of the result from the foil bag test which increases the error to 50%. Overall, the foil bag test did not in both cases show better results. It can therefore be concluded that calculated values or results from small-scale tests are essential to verify large-scale test results if considered for use in a façade design.

4.5. Conclusions for product developments

Nevertheless, after all these calculations there is reason to believe that the strength value for the fixations correlate somehow with the bending strength but also with the wall thickness. Fiber content of WPC-1 was less compared to WPC-2 which affects bending and most probably shear strength as well. Further, the wall thickness of WPC-1 at the long hole was also less. Hence, this specimen failed at loads which are about one third compared to WPC-2. It can therefore be concluded that WPC claddings with higher fiber content and thicker walls enhance the overalls façade's wind suction resistance.

The previous section revealed that deflections received from calculations comply with results from the foil bag test. This gives credit to the statement given in ASTM E 72, Appendix X1 “Technical Interpretation”, which recommends using this test for serviceability proofs or comparative analysis between several façade constructions. This is also in accordance to the main purpose of this study which is to compare WPC cladding with competing products for deriving insights for strategic product development. However, results received from the foil bag test additionally provide valuable input for the determination of deformation factors which describe the bending behavior of the façade section spanned over several fields. These factors were so far assumed to be 0.125 for the bending moments over the mid-support and 192 for the calculation of deflections. However, they might vary in practice. The exact factor can be derived from the test results and used in FEM analysis which could then replace costly large-scale tests.

It may happen that the foil bag test reveals much higher fixation resistances and presumably also for bending. This was explained by the scale effect. Moreover, plastics-based claddings which are connected to each other via tongue-and-groove build a membrane in which the bi-axial load transfer dominates the deformations and point loads at the fixations. If considering a WPC cladding panel as a uniaxial beam, the computed results obviously differ from reality but tend to be on the safe side. Further research herein is necessary to much better understand how bi-axially loaded large-scale WPC boards behalf in this regard.

This study also has some limitations. The quality of the data obtained from this test method is influenced by distortion effects from the installation process, particularly from pre-drilling by hand, a limited potential for automatization and the low number of tests. The stepwise increase of air pressure and keeping it constant for half a minute at a time makes this a lengthy test method. The installation and dismantling of the sections add further time to the test.

5. Summary and recommendations

This study examined the loading capacity of plastics-based cladding panels under simulated wind suction. For this purpose two-span façade sections were built. Two foil bags on the cladding rear side were inflated by compressed air until failure of the test section.

It was found that all the tested WPC claddings failed by edge cracking and PVC profiles collapsed by pull-through of the screw heads. Presumably, the verification of the fixation capacity is equally important for the design of claddings as the bending capacity. From a broader perspective, WPC façades which are new to the market should generally perform satisfactorily under normative wind load assumptions for Central Europe. Their fixation distance, however, must be adjusted to the expected wind loads given by the relevant standards and must be decreased with increasing loads. As a rule, the thicker the profile walls around the fasteners, the higher the wind load capacity of the cladding.

Wind suction can be simulated by laboratory tests. An appropriate method consists of foil bags which are inflated by compressed air at the cladding rear side. The amount of wind suction at panel failure can be measured with a water column. This method is recommended for comparative studies of several cladding products with varying fixation distances and different fixation devices and profile geometries. However, for strength poofs of projected WPC façades, the use of computed results is recommended because they plausibly verify test results.

Failure of the fixation mechanism was the basic observed mode of failure of the test façades. Product improvements should also focus on the fixation mechanism. Reducing the thickness of the webs so as to increase the flange thickness around the screws and therefore improve the pull-through resistance is the most promising way for optimizing the wind suction capacity of current WPC cladding. However, cladding manufacturers also offer special clips made from steel or injection molded from WPC. Such connectors most probably enhance the façade's wind suction capacity if the fixation distance is the same. As can be seen from Fig. 4b, the load transfer from the WPC panel edge to the connector is at the screw head's rears side which in addition to clips is a small contact area where local stresses occur. The same stresses are expected around the clips only if loads are higher which means that the overall façade's capacity is increased. Another advantage is that milling of long holes is avoidable. On the other hand, clips must be purchased from other manufacturers and they produce storage costs. Screws are available everywhere and therefore seems to be the best alternative to maximize a manufacturer's profit.

Further studies are planned which quantify the difference between clips and screw fixation in terms of load capacity and which investigate optimal edge distances and wall thicknesses of slotted holes versus round holes.

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