Zurich, June 15-17 2016
Sustainable Built Environment (SBE) Regional Conference
Expanding Boundaries:
Systems Thinking for the Built Environment

BIO-BASED PLASTICS-COMPOSITES FOR SUSTAINABLE BUILDING SKINS: LIFE EXPECTANCY OF CLADDING DERIVED FROM WIND SUCTION TESTS

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Abstract
Wood-plastics composites (WPC) consist of wood fibres embedded in a matrix made from petrochemical or bio-based polymers. Cladding produced from such green plastics is considered to be more ecological than current PVC panels. Its sustainability as a building product can be assessed with life cycle assessments. Life cycle analysis, however, requires reliable data about the life expectancy of the WPC façade. It is commonly assumed that if the structural resistance of cladding is shown to resist the wind loads given in the standards, long-lasting performance is guaranteed. Currently, the suitability of using WPC cladding in façades is judged merely by the bending strength and modulus of elasticity of a single cladding panel. Whether these parameters can indeed be used to design the entire façade has never been examined. In this study, the structural capacity of WPC façade elements was investigated with wind suction tests. It was found that WPC façade elements possess a structural resistance that is adequate for wind loads for Central Europe given in the relevant standards, which is an indication of their durability. The basic failure mode observed in the tests was not bending failure of the cladding panel, as expected, but pull-out failure of the fasteners or edge failure. The life expectancy of a WPC cladding panel is therefore governed by the mechanical strength of its connections. Hence, it is recommended that façade planners select WPC products based on the design strength of the fixation mechanism rather than on bending resistance of the cladding panels.

Keywords:
Bio-based plastics; cladding; wind resistance; simulated wind suction; basic failure mode

1 INTRODUCTION

Wood-plastic composites (WPCs) represent a new generation of bio-based materials. They consist of a plastics matrix incorporating bio fibres, such as wood or grass. The European market for WPC used in constructions is expected to increase to 450,000 t in 2020. The highest growth rates are in the area of decking, which in 2012 made up 67% of the WPC products in Europe. WPC cladding only amounted to 6.1% of the total in 2012 [1,2].

Polypropylene (PP), polyethylene (PE) or polyvinylchloride (PVC) is used for the matrix of WPCs, partly as recycling granulate [3]. These bulk plastics, however, are produced from scarce fossil resources. Recent developments include attempts to produce matrices from polymerized corn starch, such as polylactides (PLA). Products made from PLA could theoretically be biodegradable and used for composting [4,5].

As far as the material is concerned, green-composite façades (GCFs) certainly show great promise for use in future buildings. The global warming potential of PLA, for example, is 30 times less than that of bulk plastics [6,7]. A life cycle assessment (LCA) could easily show that a GCF product is the best alternative to competing conventional materials. However, considerations should include the complete product life cycle, as a short life expectancy distorts the results of life cycle assessments [8,9]. Also, PLA is far more costly than traditional products, resulting in an expensive investment for house owners. However, the ecological product attributes can, to a certain extent, compensate for the higher prices and lower durability [10].

The development of bio-based plastics cladding requires investigations of the technical, ecological, economic and social product attributes. Life cycle sustainability assessments are an accepted way of quantifying such attributes for a given life expectancy. It does appear that the durability of a product plays a key role, but it is difficult to estimate its life span prior to development. Regarding standards and codes, Regulation (EU) No. 305/2011 [11] stipulates that products must meet the requirements for mechanical resistance and stability, as well as safety. These requirements are formulated as verifications of limit states according to EN 1990 (EUROCODE 1) [12]. When developing WPC cladding, it is therefore essential to make sure that the structural resistance matches the design loads stipulated in the relevant standards, thus ensuring that the product will perform adequately under wind loads. It is also important to note that the wind loads given in EUROCODE 1 are 50-year wind loads representing an extreme event that will statistically occur once every 50 years [13]. The underlying philosophy is that compliance with this standard ensures structural health for at least this time span, leading to more reliable life cycle analyses over the entire design life.

New WPC cladding products with bio-polymer matrices should be consistent with conventional WPC regarding technical performance [14]. By doing so, green-composite cladding would add value at least with respect to environmental friendliness. In past research it was observed that very few tests of WPC cladding have been carried out so far [15]. This study is the first to assess the life expectancy of WPC cladding based on its structural capacity under realistic conditions. In particular, the wind suction resistance of a façade section is investigated. From the results it is concluded whether existing WPCs can resist the design loads stipulated in the relevant standards and hence represent the state of the art. Findings will serve as the basis for the development of future green-composite façades by acting as a reference in comparative studies. Finally, results from this study will provide penetrating insights into realistic façade design with current WPC cladding.

2 MATERIALS AND METHOD

2.1 Characterization of the materials

In this study, only commercially available and randomly selected products were used. Specimens were made from two types of WPC containing bamboo wood flour (WF) embedded in a thermoplastics matrix. The product-related data were collected from manufacturers' specifications. Product 1 was a polymer composite containing recycled high-density polyethylene (HDPE). The ratio of WF to PE was 60:30, and about 10% of additives (pigments and compatibilizer) were added. The moment of inertia (I_y) was 63,606.5 mm^4.

Product 2 was a WPC made from high-density polypropylene. The fibre ratio of WF to PP was 70:30. The thermoplastics matrix also contained additives. The moment of inertia I_y was calculated to be 87,516.5 mm^4.

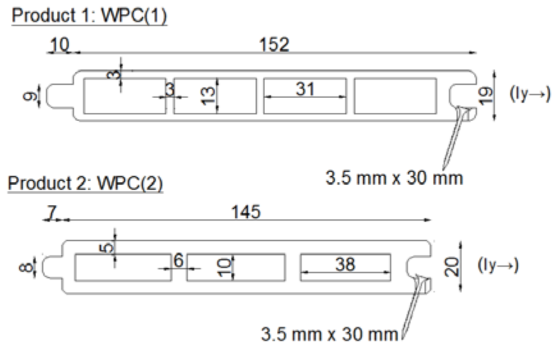

Fig. 1: Dimensions of tested cladding profiles.

Both types of WPC showed similarities with respect to dimensions (Figure 1), type of plastics and fibre components. Product 2 mainly differed in the proportion of fibres and wall thickness of the hollow profile. Modulus of elasticity (MOE) for both products was determined with the same apparatus described in Section 2.2. Force q [N/mm^2] was applied to a single span (e = 1100 mm) consisting of two panels with a tongue-and-groove connection. The non-standardized MOE was calculated as follows:

$$MOE\ [N/mm^2] = (5 * Q * e^4)/(384 * I_y * f), \quad (1)$$

where f is the deflection of the specimen [mm], I_y is the moment of inertia of the panel [mm^4] and Q [N/mm] is the applied wind load calculated with the following formula:

$$Q\ [N/mm] = q * b, \quad (2)$$

where b [mm] is two times the width of the panel.

This testing procedure captured more realistically the behaviour of a complete façade than that of a single panel as is the case with the usual three-point bending tests. Overall, the MOE of both products were higher than those reported in literature, which might be due to the tongue-and-groove coupling effect. Product 2 was 60% stiffer than product 1 (Figure 2).

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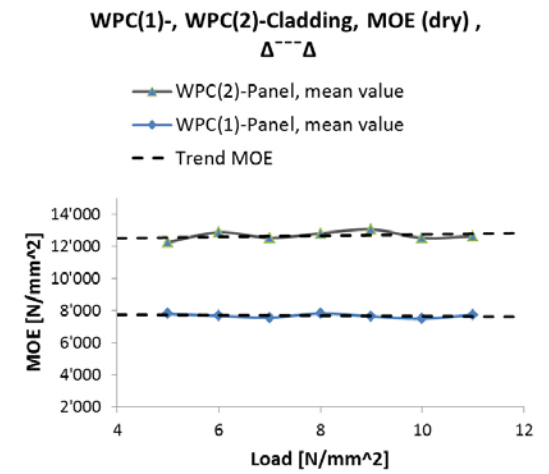

Fig. 2: MOE of tested WPC cladding.

2.2 Methodology

One of the primary goals of this study was to investigate the basic failure mode and wind suction resistance of two selected WPC profiles under service conditions as specified by their manufacturers. To obtain the most application-oriented results possible, large-scale façade sections were tested, which were built according to the respective manufacturer`s installation manual. Each section had two spans and contained four individual panels which were interlocked by groove and tongue. At the points of attachment, 4 mm holes were drilled through the flanges of the panels to accommodate the dilatation of the matrix under a realistic temperature increase. The profiles were fixed to the timber sub-rails using 3.5 mm x 30 mm fillister head screws, which were placed at the centre of each long hole and tightened by hand. As both products had similar widths, the number of fixing points per m^2 was the same for both.

As the panels were provided with groove and tongue, the building skin was considered to be almost wind tight and the tests were carried out according to the European Technical Approval Guideline (ETAG) 034:2012 [16]. The test layout further followed the specifications of DIN 18516-1:2010 [17]. Both standards propose placing plastic foil bags at the rear of the cladding and inflating them with air until the panel fails. For the study at hand, two bags were installed in the 60 mm ventilation gap behind the panels (Figure 3). Deformation along the inflated bags was measured using mechanical sensors placed at the front of the panel at mid-span. The air pressure was produced by an 8-bar compressor. The air inflow to the bags was manually controlled by a throttle valve. The pressure was applied in steps of 0.2 kN/m^2 and interrupted only for 30 seconds to record the deformation. Wind suction between 0.4 kN/m^2 and 12 kN/m^2 was thus simulated as stipulated by EUROCODE 1 [12] for Central European wind loads. A test ended when a panel failed or the upper load limit was reached. Tests were executed for spans given by the manufacturer`s specifications which varied from 400 mm to 700 mm for Product 1, and 500 mm to 600 mm for Product 2 (Figure 4). Two tests were carried out for each span length.

Fig. 3: Plastic foil bags at the rear of the cladding.

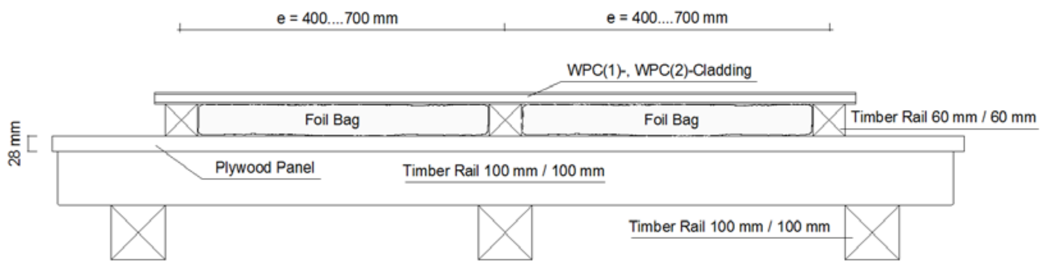

Fig. 4: Experiment setup showing the WPC specimen spanned over two fields.

3 RESULTS AND DISCUSSIONS

3.1 Basic failure mode

Twelve tests were run in total. Two thirds of the tests ended with failure of the façade section. The remaining tests were terminated when the upper load limit of 12 kN/m^2 was reached. Surprisingly, the only observed failure modes were pull-out failure of the screw at the panel flange and edge failure next to a screw. The connection of the panel therefore governed the basic failure mode of the tested specimens (Figure 5).

DOI 10.3218/3774-6_101, ISBN 978-3-7281-3774-6, http://vdf.ch/expanding-boundaries.html

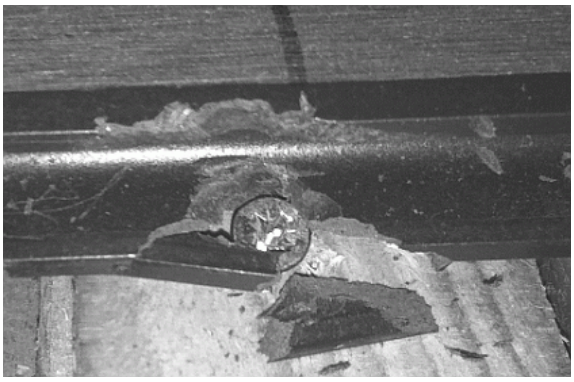

Fig. 5: Edge failure under wind suction.

3.2 Resistance to wind suction

Figure 6 lists the mean deflections of the panels with span *e* along the path of the applied wind load. Product 1 failed by connection failure, irrespective of span length and magnitude of wind load. The load curves are continuous and show an increase in deformation with increasing air pressure. The trend line illustrates the interdependence of span *e* and failure load $F_{mean,k}$. As expected, $F_{mean,k}$ is inversely related to the span length. However, the curve does not decrease monotonically, because the results for both the 600 mm and 700 mm spans were the same. From Figure 6 it can be seen that Product 1 cannot withstand the wind loads stipulated in the standards. However, by reducing the distance between the sub-rails, the resistance of the façade can be increased. The specimens of Product 2 did not fail in any tests – they withstood all wind loads (Figure 7). As the tests stopped at the upper load limit, no trend line for failure of the façade segment could be drawn. However, as far as the objective of this study is concerned, these tests showed that even for Product 2 bending failure is not the basic failure mode under the wind loads stipulated by the relevant standards.

In Section 2.1 each tested product was characterized according to its MOE. It is commonly assumed that a higher modulus of elasticity means smaller deflection of the panel under wind suction. Product 2, which is 60% stiffer than Product 1, therefore deflected 4 to 5 times less than Product 1. Due to the small number of specimens, however, it could not be proven that the resistance of the fixing points increases with panel stiffness. To the authors' knowledge, WPC cladding manufacturers provide no test data of the screwed connections. Thus, not enough application-oriented design values for WPC façades are available, which could be used by façade planners to carry out the design checks for building projects. This might explain the lack of success of WPC cladding as opposed to WPC decking, which is subjected to point loads only, and bending failure hence governs. Providing design values for WPC cladding could go a long way toward making this product more interesting to designers and builders.

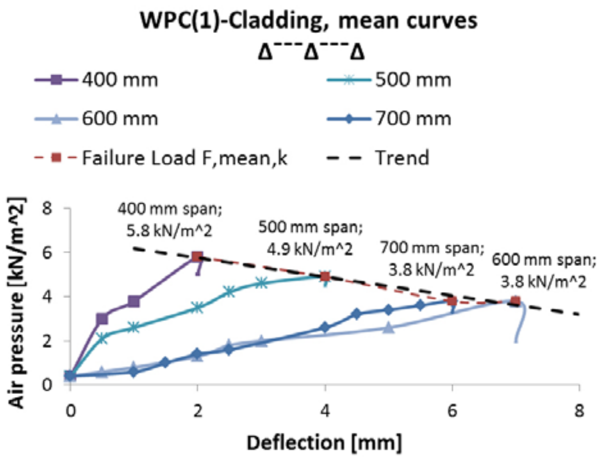

Fig. 6: Load curves of Product 1.

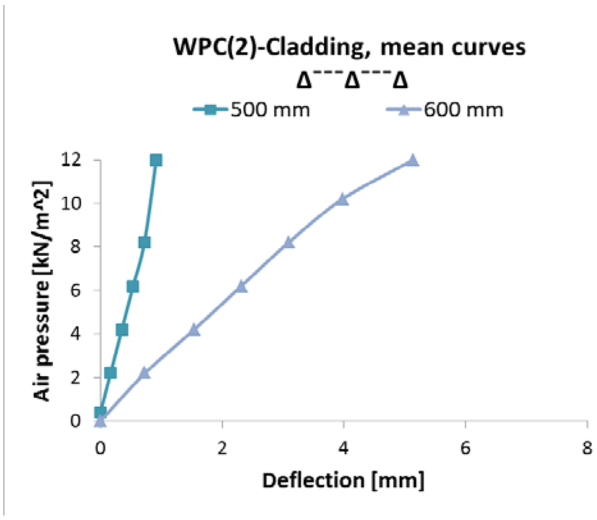

Fig. 7: Load curves of Product 2.

3.3 Life expectancy

It has been demonstrated that both tested products can resist particular design wind loads given in the standards. Hence, it can be concluded that they will perform their function in the long term, which includes resisting peak wind loads statistically occurring every 50 years. The results of a life cycle analysis could show that WPC cladding could indeed compete with current façade materials in terms of durability. However, in this study only specimens in their virgin state were tested. The strength of the material will probably deteriorate due to material degradation over the decades. As pull-out of the screw heads is the basic failure mode, it can be assumed that material degradation in the area of the fixings is much less pronounced than in the outer layer of the cladding, which is exposed to hazardous UV-radiation and humidity.

Such aging effects are usually covered by a conversion factor η, which translates characteristic

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DOI 10.3218/3774-6_101, ISBN 978-3-7281-3774-6, http://vdf.ch/expanding-boundaries.html

properties into design properties and reduces the design strength of the cladding or a single screw accordingly [12]. In preparation of this study, investigations showed that the aging coefficient for today's WPCs is about 2.0 [14]. If a safety factor γ of 2.0 is applied also, the design value for wind resistance of a WPC would be approximately 3–4 kN/m^2, which is an acceptable value for most building projects.

3.4 Development constraints for future green-composite façades

The results from this study have managerial implications. With respect to the development of future green-composite façades, it is important to focus on the fastenings rather than on optimizing bending strength, which is usually the emphasis of basic WPC material research. It is therefore recommended to use cladding profiles with a bending resistance only slightly higher than the pull-out strength of the fasteners. By adding more material to the flange where the fasteners are located (Figure 1), and less to the profile walls, bending resistance is reduced, while the strength of the connection is increased. In this regard, the ETAG 034, chapter 5.4.2.4.1, suggests using small-scale cladding samples applied to a 50 mm ring where a screw head is either pushed or pulled through and the breaking loads are measured. These tests should be conducted prior to the large-scale foil bag test which then should verify whether the optimized profile geometry indeed provokes higher wind load resistance in practice. Such an approach renders the cladding product more sustainable and economical in terms of resource use and production costs.

4 SUMMARY

This paper deals with the compliance of current WPC cladding with design wind loads. Test results confirm that the investigated panels have sufficient structural capacity to resist the wind loads. As a consequence, the life expectancy for life cycle analyses can be derived from the statistical occurrence of the peak wind loads given in the relevant standards. However, whether the 50-year wind applies to WPC cladding strongly depends on additional aging effects during its lifetime. It can be argued that material degradation in the vicinity of the hidden fasteners of WPC cladding is much less pronounced than at the outer profile layer. Because of this fact and the results of this study, currently available WPC cladding can be assumed to have a long life span. However, further comparative studies should be carried out to confirm this assumption.

Finally, pull-out failure of the fasteners and edge failure at the connections have been shown to be the basic failure modes. This raises the question if today`s WPC cladding products can be designed correctly by façade planners, as product specifications solely focus on the modulus of elasticity and the bending strength. The presented findings support the recommendation that in the development of WPC cladding with either petrochemical or bio-based matrices the strength of the connection should be considered as the better predictor for structural capacity.

This study also has some limitations. The tested products represent a rather small number of WPCs, and the fact that only two tests were carried out for each product and span length weakens the statistical significance of the results. However, the large-scale foil bag test is arguably the most application-oriented test possible, which is why only so few tests were run in this study.

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