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Standard-compliant development of a design value for wood–plastic composite cladding: An application-oriented perspective

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ABSTRACT

Bio-based materials, such as wood–plastic composites (WPC), have gained the interest of the resource-intensive building industry. Presently, this novel composite is being used in decking and cladding. The structural design of façades made from WPC compounds, however, has been difficult in the past due to a lack of design principles and experience.

In this case study a design concept is developed, which combines material attributes describing the strength loss of the material due to different weathering processes on façades. Although this approach is widely used for approvals of cladding kits in Central Europe, it has not yet been used for WPCs. This paper is unique because for the first time research findings taken from a literature review on WPC attributes are used to obtain a realistic WPC design value for engineered façades. Simulations of WPC aging in three main categories predicted a strength loss of approximately 50% compared to the virgin material. Nevertheless, a WPC material design value which includes the effects of material aging is still useful for a façade planner's practical work in view of the mandatory codes and standards in this field.

1. Introduction

Wood–plastic composites (WPC) are an example of a novel highly sustainable building material. They consist of wood fibers embedded in a petrochemical plastics matrix. Main applications are decking and cladding. There is an emerging body of literature concerning the use of bio-fiber reinforced plastics instead of pure petrochemical polymers, which relieves the pressure on scarce resources such as fossil fuels. However, their use in "green" façades is still in its infancy because their development constitutes a challenge, particularly for the medium-sized industry. The global WPC production has experienced an overwhelming boost in the past years. In 2012, 1.5 million tons of WPC were produced worldwide, and this was mainly driven by decking and the North-American market. The production volume of WPC decking in Europe was 174,000 tons in 2012, whereas only 16,000 tons of WPC cladding were produced [1]. According to literature reviews on WPC technology, recent research mostly focuses on single aspects of compound properties rather than on multiple attributes

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and the extent of their mutual interaction. Despite a growing market, WPC investigations are generally not very application oriented.

The literature review revealed that WPC producers publish very little information about technical properties, certificates and approval documents. It appears that current WPC cladding products in particular are marketed at private house owners rather than architects and engineers who are in charge of material selection within a building project and assess products under technical aspects. It can be theorized that by not disclosing specific product details, the WPC industry is overlooking a potential market segment which is continuously increasing.

In view of the current research deficiencies, this paper aims to develop and apply a method for deriving a WPC-cladding material design value. The following approach agrees well with engineering methods because it is mainly based on material and building design codes. This could motivate façade planners to not only choose WPC cladding because of its sustainability but also because available performance data supports their design process.

2. Concept for deriving a design value from test results: EN 1990

"Eurocode EN 1990: Basis of structural design" [2] is a standard that regulates how calculations for engineering structures should be carried out. Whenever design checks for a building element or a material are carried out, this standard specifies how to deal with material-related properties derived from performance tests. This is necessary because such tests only reflect the properties of a particular series of test samples and could hardly serve as a reference for all imaginable cases where the material is used in practice. A 30-year-old WPC product in a façade, for example, exhibits significantly different properties than the originally tested specimens in the laboratory. Therefore, results from the tests must be translated from the characteristic values representing the virgin material state into the design values for the design codes. Obviously, the design value of the material resistance is smaller than the characteristic value, as it takes into account any distortion effects within the test procedure and, in particular, the material degradation due to aging within the relevant time frame. In EN 1990 [2], these material-related aspects are taken into account with the following factor:

$$\text{Conversion factor}: \eta \leq 1.0 \tag{1}$$

Besides the influence of testing conditions and aging, further corrections are necessary to account for uncertainties within the cladding product system, such as size effects resulting from small test samples, and future large-scale applications. Therefore, a partial safety factor is defined as follows:

$$\text{Safety factor}: \gamma_M = \{\gamma_m \times \gamma_{Rd}\} \geq 1.0, \tag{2}$$

where γ_M can be subdivided into two partial factors:

$$\text{Material safety factor}: \gamma_m \geq 1.0 \tag{2.1}$$

$$\text{Construction safety factor}: \gamma_{Rd} \geq 1.0 \tag{2.2}$$

The resulting design material property is:

$$\text{Material design strength}: R_d = \eta \times \left(\frac{X_k}{\gamma_M}\right) \tag{3}$$

where X_k is the material property according to EN 1990 [2], expressed as 5th-percentile. This value was calculated from the arithmetic mean of a test series. Based on normal distribution and unexpected variation, the mean value is additionally reduced by the k_n-fold variation coefficient. If, as usually recommended in approval documents for cladding, ten individual tests on virgin specimens were run within a series, the k_n-factor is 1.92. With a higher number of tests k_n decreases and X_k becomes more precise.

Whenever a structural engineer wants to perform a design check for WPC cladding under a particular load, the material design value R_d must be superior to the wind load E_d:

$$\text{Design requirement for WPC wall cladding}: E_d \leq R_d \tag{4}$$

The capacity of cladding under a given load is thus assessed for the ultimate limited state, which is marked by the subscript "d". The wind loads are taken from national standards and the material design value is given either by the relevant material-related standards or the approval documents. The latter should further provide information about the bending strength of the WPC panel and the pull-out resistance of the fasteners used for attaching it. If the strength values have the subscript "d", a façade planner can be sure that any uncertainties regarding the material or its application are already taken into account.

However, there are still no approvals for WPC wall cladding, which is why a strategy for the standard-compliant design of such cladding is presented in this paper. It is essential to focus on the previously introduced coefficients, which requires a deeper knowledge of testing statistics and engineering design. Further information on this topic is given in EN 1990 [2]. The parameter X_k can be determined from tables given in Appendix D, which can be used to calculate the 5th-percentile value for a given test series. The parameter γ_M takes into account material and particularly construction-related deviations from the results of laboratory tests. Their assessment demands a high level of experience with similar, well-established materials. From a review of product approval documents of various façade products it was found that the value of γ_M generally ranges from 1.5 to 2.5. Conservatively, the upper limit, 2.5, could be chosen, which is applied in approvals for cementitious cladding. It is assumed that the construction safety factor $\gamma_{Rd,WPC}$ for WPC cladding does not differ much from that of other cladding products, as this parameter takes into account construction-related factors that are similar for all cladding products. The case is much more complex, however, when dealing with the conversion factor η. For this parameter, which takes into account the difference between a test sample and the same material applied in a structure, it is necessary to first determine the main reasons for these discrepancies. Particularly external effects that cause material degradation should be taken into account by this factor. This degradation of a composite‘s material properties is usually described in the relevant material standard, such as EN 15534-1 [3] for WPCs. The specified durability tests cover the following: (1) fungal decay, (2) exposure to natural weathering and (3) freeze–thaw cycling. These tests measure the weakening of the material due to pretreatments, which emulate most realistically the environmental conditions experienced by a WPC cladding façade.

Summarizing, EN 1990 [2] provides information about how WPC material properties determined from tests can be translated into applicable performance values. This process takes into account three different coefficients, which consider discrepancies regarding specimen characteristics, product composition and structural configuration of the façade.

However, in the literature no information could be found on how to determine the conversion factor for WPC cladding, which underscores the importance of the application-oriented investigations presented in this contribution. In the following chapter a concept will be introduced, which WPC manufacturers or research institutes can use to derive a WPC design value from the results of accelerated and natural aging tests of WPCs.

3. Methodology

Several WPC cladding coefficients have been identified in this paper so far. These coefficients should be investigated in a product development process aimed to obtain a product kit approval according to ETAG 034 [4] and to provide a design value for façade planners. The investigated standards focus on design checks under specimen pretreatment by natural and artificial weathering. It should be noted that the natural weathering test takes at least one full year. This test is supposed to emulate the climatic conditions in Southern France and therefore has long cycles of hot and dry conditions combined with UV-intensive sunlight. It is particularly demanded that within this year the UV-irradiation should not be less than 6.6 GJ/m^2 and the average temperature should be more than 15.5 °C. This test, as well as the freeze–thaw cycling and fungal decay tests, is described in EN 15534-1 [3]. The material degradation is mainly affected by temperature, humidity, radiation and biological factors, which emphasizes the vulnerability of the two main WPC components, plastics and plant fibers. WPC test samples are thus pretreated in varied climatic conditions, each representing different locations in the EU. For the Northern regions a freeze–thaw test is carried out, and for the southern parts of Europe field tests are done in the Mediterranean area. This underlines the basic principle that a European Technical Approval should be valid for all of the European Union. It can be assumed that the climatic conditions in a Mediterranean region are harsher than the actual conditions in many other European locations where WPC cladding might finally be installed. As a consequence, the conversion factor determined for WPCs is probably lower than it needs to be, which causes the design values to be lower as well, see Eq. (3). However, this is a disadvantage manufacturers must accept for being allowed to sell their products in all EU member countries. A national approval, on the other hand, should be able to give more precise design values.

In this study it is suggested to superimpose the results of three basic durability tests to obtain a conversion factor for WPC that takes into account the material degradation due to weathering. A material-related conversion factor η_{WPC}, depending on η_{fungi} from the fungal decay test, $\eta_{weather}$ resulting from the natural weathering test and $\eta_{therm\text{-}hygr.}$ from the freeze–thaw-cycle test, can be written as:

$$\text{WPC aging coefficient}: \eta_{WPC} = \eta_{fungi} \times \eta_{weather} \times \eta_{therm\text{-}hygr.} \{\eta_{fungi}; \eta_{weather}; \eta_{therm\text{-}hygr.}\} \leq 1.0, \tag{5}$$

where η describes the change in failure load of a test specimen before and after pretreatment within the mentioned categories. This concept hence takes into account basic standard tests for weathering of a material and combines their results. Of course this approach is not the same thing as obtaining data from a real-life application, but it has the following advantages: (1) It is based on normative tests which a WPC manufacturer must always carry out when producing a WPC cladding material according to EN 15534 [3]; (2) it reflects local climatic conditions for any EU member country and (3) it is similar to the procedure used for other façade-covering materials but based on different tests that appropriately reflect most of the properties of WPCs. As many material properties deteriorate due to weathering over the life span of a product, this effect could be considered material aging. It is important to note that Eq. (5) is not present in any of the relevant standards and codes and its application is usually at the discretion of manufacturers or authorities whenever a product approval is processed.

Cladding failure is caused either by bending failure of a single façade panel due to wind or by pull-out failure of the fasteners. In both cases the failure load is inversely related to the material age. Assuming that bending failure is the more relevant failure mode due to the exposure of the bent layer to the weather, the coefficient η could theoretically be used for the design checks of the fasteners as well. This should lead to conservative results as hidden fasteners in particular are not susceptible to UV-degradation and therefore $\eta_{weather}$ is probably closer to 1.0.

The following basic equation applies to any WPC cladding design value:

$$\text{WPC design value} : R_{\mathrm{d,WPC}} = \eta_{\mathrm{WPC}} \times \left(\frac{X_{\mathrm{k}}}{\gamma_{\mathrm{M}}}\right) \left\{1.5 \leq \gamma_{\mathrm{M}} \leq 2.5\right\} \quad (6)$$

4. Case study results and discussion

It was not possible to find a comprehensive WPC aging coefficient even from an intensive literature review. In all reviewed publications dealing with the material technology of WPCs only single aspects of material aging are investigated. Therefore, it was impossible to accurately determine η_{WPC} for a representative number of compounds. At first glance, the derivation of an aging coefficient is a time-consuming and costly undertaking for a WPC cladding manufacturer due to the one-year field test. However, because of the cascading principle which nowadays is common practice for value-added processes, a manufacturer can obtain at least two of the three partial aging coefficients from his WPC compound supplier, as EN 15534-1 [3] applies to the compound only. Cascading allows downstream manufacturers to rely on the declaration of their suppliers, who, according to Part 5 of EN 15534 [3], must release their results from fungal and freeze–thaw tests. Several of the reviewed papers from literature, for example Wang et al. [5] mention that the sample size strongly influences the test results, particularly in freeze–thaw tests. It is therefore essential to thoroughly investigate such size effects and to make sure that they are taken into account with a suitable safety coefficient γ_{m} as shown in Eq. (2.1).

Unfortunately, data on all three influences is rarely available for a given compound. Nevertheless, the following insights provide at least an idea of the extent of such degradation effects. The presented values originate from a literature review, and they were used with Eq. (5) to estimate a semi-realistic WPC cladding design value. Although it is difficult to find results for WPC compounds, the following papers from literature give at least some answers.

Material degradation was investigated by Schirp [6] using conventional pinewood, which he compared with robinia and thermo-pretreated pine fibers encapsulated in polypropylene (PP), with 3% of maleic anhydride grafted polypropylene (MAPP) as a coupling agent. The objective of his research was to investigate the effect of both hardwood and thermowood in WPCs, both of which generally hamper water absorption in the material. The fiber content was either 50% or 70%. Fungal resistance was tested according to EN 15534-1 [3]. It was found that the reduction in bending strength was related to the loss of mass due to the deterioration of wood fibers by fungi. To illustrate the impact of the fungi, the results for wet samples with and without fungal decay were compared. The maximum measured decrease in bending strength was approximately 14% ($\eta_{\mathrm{fungi}} = 0.86$).

A one-year outdoor weathering test was performed by Butylina et al. [7]. Besides adhering to the requirements given in EN 15534-1 [3] the test was carried out in Lappeenranta, Finland, using 70–75% softwood fibers embedded in a matrix made of recycled PP and 3% MAPP. The purpose of this test was to investigate the effect of different color additives on the durability of the selected WPC. The results indicated that the bending strength was reduced significantly by natural weathering and that the strength decreased with lower fiber content. The moisture content of the material increased threefold within one year, which caused a strength loss of between 26% and 40% depending on the compound.

For the present case study an assumed degradation of 33% was used as an average value ($\eta_{\mathrm{weather}} = 0.67$). Unfortunately no paper reported natural weathering tests performed in Southern France as required by EN 15534-1 [3], which would probably account more adequately for UV radiation.

Freeze–thaw-related WPC degradation was the topic of several reviewed papers. The wood-fiber source played a major role within another test series undertaken by Butylina et al. [8]. They found that a material with 75% thermally treated wood fibers in 22% PP and with 3% bonding agents exhibited a strength loss of up to 16%. The type of plastics was the focus of tests executed by Adhikary et al. [9]. Their results showed that a PP-based matrix generally performed worse than a polyethylene-based matrix. Their test specimens had a fiber content of 45% and 50% with up to 5% bonding agents. Besides PP and polyethylene (PE), a polyvinyl-chloride-based matrix strengthened with pine fibers was the subject of investigations conducted by Matuana and Pilarski [10]. After five freeze–thaw cycles they observed a significant decrease in bending strength: up to 12% for fiber contents of 50% and 75%. A similar result was obtained by McDonald et al. [11]. who carried out a literature review on durability aspects of current WPCs. Their paper reports a decrease in bending strength of between 5% and 12% due to freeze–thaw cycling. Lastly, rice-hull-reinforced PE composites were investigated by Wang et al [5]. A significant strength decrease was measured after the first freeze–thaw cycle, and with each of the following five cycles the strength decreased further. The final strength loss was 39%.

A wide range of freeze–thaw material degradation effects have been reported. These different effects can depend on the type of plastics, fiber source, type and proportion of additives, material density, production process or sample size. Based on the results by Adhikary et al. [9]. A coefficient $\eta_{\mathrm{therm\text{-}hygr}} = 0.85$ was used in this case study, which takes into account twelve freeze–thaw cycles for a WPC compound containing 45% PP, 55% wood fibers. This assumption appears plausible, but more pronounced degradation could also occur depending on the compound. It is also important to mention that in all the cited papers the samples of the freeze–thaw tests were frozen at −25 °C and defrosted at +25 °C, which best represents the conditions in Northern regions.

Finally, the cited findings from literature served as input data for calculating an example WPC conversion factor. Eq. (5) is used to determine a design value from a characteristic value obtained from test results. The garnered design value can theoretically be used to calculate a WPC design value for façade applications by applying the material safety factor in Eq. (6).

According to basic research results of current WPCs the characteristic bending strength of the material is $X_k = 30\,\text{MPa}$ gives as 5th-percentile. Assuming $\eta_{\text{fungi}} = 0.86$, $\eta_{\text{weather}} = 0.67$, $\eta_{\text{therm-hygr.}} = 0.85$ and a proposed $\gamma_M = 2.0$, the suggested approach yields the following cladding design value:

$$\text{WPC cladding design value}: R_{\text{d,WPC}} = [0.86 \times 0.67 \times 0.85] \times 30\,\text{MPa}/2.0 = 7.35\,\text{MPa}.$$

Summarizing, the chosen methodology can be used to translate a virgin material attribute into an attribute for the aged material under assumed loads and influences naturally occurring in façades. However, this result might incorrectly suggest that no further research on durability aspects is required, because the superposition of single degradation factors follows common practice, which is easy to apply but not scientifically founded. As the additional safety factors take into account potential inconsistencies, it can be argued that this concept sufficiently covers uncertainties and deviations occurring during the life span of WPC cladding. Although this case study uses a method developed from different research findings, a realistic WPC material design value for façade applications is obtained by reducing the virgin modulus of rupture MOR value by up to 75% based on a safety-level of 2.0. In comparison, the design strength for water susceptible fiber-cement panels listed in product approvals is currently approximately 5.50 MPa using a similar safety factor. Parameter X_k for such panels is 30 MPa, the same as for WPC cladding. This result is hence consistent with current WPC cladding, which suffers the same strength degradation under similar conditions.

5. Conclusions

Relevant codes and standards were reviewed in this paper in order to develop a WPC cladding design value for target application conditions. To assess the suitability of wall cladding products, façade planners are obliged to perform strength calculations, which take into account the loads and environmental impacts on buildings. Such calculations are based on material design values that are usually obtained from product approvals. It is demonstrated that in the absence of design values, a WPC cladding manufacturer can use available results obtained from the compound supplier or from initial tests which are required to be carried out prior to commercialization. This allows even small and medium-sized manufacturers to render their product attractive for the professional segment where engineers and contractors dominate product selection. It should be noted that the results of this case study are not free of uncertainties because they are based on findings from different WPC compounds. Research publications mainly deal with single aspects of WPC testing, and with investigations that focus on specific WPCs. Despite this limitation, a concept is derived in this publication that can be used by the WPC industry for the benefit of façade planners. From the current practitioner's point of view the derived WPC design value is sufficiently reliable for use in façade strength calculations, because it is mainly based on codes and standards. This paper therefore fills a gap that exists in current WPC façade design and will help move current WPC cladding products into the professional segment of façade products.

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