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Determination of Resistance to Freezing of Bonded Façade Joint

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***Abstract*—**Verification of vented wooden façade system with bonded joints is presented in this paper. The potential of bonded joints is studied and described in more detail. The paper presents the results of an experimental and theoretical research about the effects of freeze cycling on the bonded joint. For the purpose of tests spruce timber profiles were chosen for the load bearing substructure. Planks from wooden plastic composite and Siberian larch are representing facade cladding. Two types of industrial polyurethane adhesives intended for structural bonding were selected. The article is focused on the preparation as well as on the subsequent curing and conditioning of test samples. All test samples were subjected to 15 cycles that represents sudden temperature changes, i.e. immersion in a water bath at (293.15 ± 3) K for 6 hours and subsequent freezing to (253.15 ± 2) K for 18 hours. Furthermore, the retention of bond strength between substructure and cladding was tested and strength in shear was determined under tensile stress. Research data indicate that little, if any, damage to the bond results from freezing cycles. Additionally, the suitability of selected group of adhesives in combination with timber substructure was confirmed.

***Keywords*—**Adhesive system, bonded joints, wooden lightweight façade, timber substructure.

I. INTRODUCTION

WOOD is a traditional building material used in the construction industry since time immemorial. In the 20th century, the limitations of this renewable material became obvious, and in many applications its use gave way to that of ceramic or concrete masonry elements, leaving wood to be employed mainly in the areas of roof structures or interior cladding. Over the last approximately 15 years, a significant increase in the popularity of wood with designers as well as builders has become apparent in Central Europe, and this is clearly visible in the rapid increase in the amount of wooden buildings constructed. Wood is once again perceived as a suitable alternative for the load-bearing structures of buildings, and in well-designed structures it allows designers to comply with all statutory technical requirements for building structures [1].

Some types of wood are sufficiently resistant to climatic influences to be utilized in the external cladding of buildings, i.e. the wood is directly exposed to the external environment. Wooden structures and wood elements used in exterior can experience a series of chemical and physical changes that spoil its aesthetic appeal, durability and service life. Thus, civil engineers all over the world are currently very often meeting with obstacles as revitalization or redemption of wooden facades. The most popular design of nowadays wooden facades is usually with vented layer where all elements are connected by mechanical joints. However, the durability of these joints is limited. Moreover mechanical joints can cause premature degradation of façade cladding. Hence, the potential of bonded joints should be studied in more detail. Bonded joints are slowly becoming a viable and structurally simple alternative whose properties approximate those of mechanical joints. Bonded facade systems involve replacing the mechanical attachment of cladding materials by attachment via bonding, see Fig. 1. The installation technique is very demanding, requiring disciplined adherence to the exact procedure.

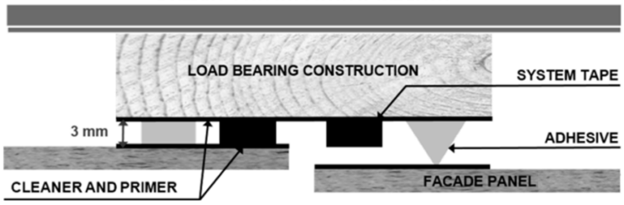

Fig. 1 Vented façade system with bonded joints

As mentioned in [2] adhesion is a phenomenon whose importance in numerous processes is significant. Special importance characterizes such adhesive bonds in which adhesion plays a dominant role in the constitution of their properties. This concerns especially such technologies as structural bonding, sealing, and cementing. Such bonds are used more and more frequently as substitute for welding, spot welding, soldering, or forced-in joints. The idea of mechanical adhesion is presented schematically in Fig. 2.

The term 'adhesive' is a very extensive and therefore a great number of standards which discuss adhesives in general already exist. However, they mainly deal with the classification of adhesives as such. The purpose of the research described here was not to create a new adhesive but rather to investigate existing, industrially-manufactured adhesive products available on the market which are potentially suitable for a given application, and to test their properties in conjunction with the intended specific application experimentally. For this purpose, testing procedures which are easy to carry out, versatile, provide the needed information and are related to the final finish of facades were selected.

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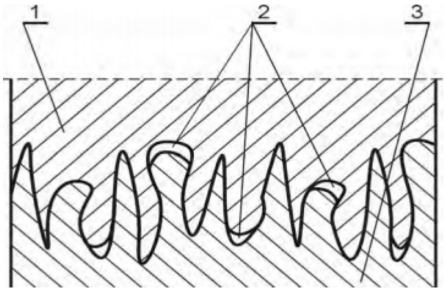

Fig. 2 Mechanical adhesion: 1 – adhesive, 2 – entrapped air, 3 – bonded material [2]

Besides these facts also the trend of sustainability is at present more intense and the importance of usage of renewable sources is starting to be obligatory. Currently, wooden buildings occupy quite a prominent place on the building market, replacing load-bearing structural elements made from fired clay or concrete. Taking into consideration these details authors of this research case decided to design a possible solution of vented façade supposed mainly for timber and wooden houses which are considered as environmental friendly.

For the purposes of this research it was decided that the weakest point of the whole system would be tested, i.e. the bonded joint. The following text describes the production of test samples themselves, as well as two mandatory tests procedure. Moreover, the main aim of this research case is to determine the resistance of the bonded joint to freezing.

II. State of the Art

Design of vented façades with wooden cladding is not a new technology as well as combination of wood elements and bonded joints. Nevertheless, there are quite a few examples where the entire façade system was designed from bonded wooden elements. In 1998, Straalen [3] introduced methods to draw up design rules to calculate the resistance of adhesive bonded joints for structural applications. The results obtained from series of tests revealed that in case of adhesive bonded joints also the durability effects have to be considered and because the experience in 1998 with design rules for structural adhesive bonded joints was limited, the use of probabilistic techniques occurred to be a promising opportunity. However, till now, the adhesive bonding technology has not been able to properly establish in construction and design rules anchored in Eurocode standards were not developed yet [4].

According to [5], adhesive bonding is a very demanding technique which requires procedures to be followed precisely and accurately, considering that even a small failure to comply with these requirements might result in the error of an entire system. Preliminary to the introduction of a complete bonded facade system to the market, the new design of such a structure has to endure series of load tests.

III. Materials

The selection of appropriate facade cladding components is a significant phase in the design of ventilated facade. Wrong combination of selected materials can cause a substantial reduction in durability of the entire façade system and in particular can lead to a remarkable increase of requirements concerning the maintenance. Therefore, it is important to pay close attention to the selection of the materials [6].

A. Selection of Cladding Material

The selection of the cladding material is usually given by the contractor, developer etc. and it should be the first step when considering bonded façade systems. Furthermore the material properties as are mechanical, physical or chemical performance have to be known even before the selection of adhesives.

When selecting the cladding material for the preparation of test samples, the emphasis was mainly on the possibility of usage of the material in an outdoor environment. In this research case it was also important to test only wooden or wood-based materials. On the basis of these criteria the wooden plastic composite and Siberian larch façade cladding was selected. Benefits of Siberian larch façade cladding are its dimensional stability, low maintenance and natural resistance to decay. Also, this material is suitable for vented facades without any other surface finish.

The wooden plastic composite (hereinafter WPC) is unique timber alternative which combines the traditional appearance of timber with the durability and resilience of an engineered composite that is capable to withstand the harsh weather changes. The principal ingredients are specially selected clean plastic polymers, thermoplastic resin (40%), and wood based fibres (50%) with additives (10%), as are pigments, lubricants, UV inhibitors or coupling agents. The material is lignin free and contains no harmful chemicals. Moreover, this material is suitable for vented facades without any other surface finish, material properties are listed in Table I.

B. Selection of Material for Load Bearing Substructure

Load – bearing substructure have to be above all homogeneous, coherent, firm and straight (both locally and overall). Standard spruce joists were selected as a material for substructure, since it is the most used material for timber façade substructures. The only demand on this material is the minimum strength class C22 and all used profiles have to be dressed (on the bonded side) and dried to a max. 15% humidity.

TABLE I
Material Properties

Species	Density [$kg{\cdot}m^{-3}$]	Shear strength [MPa]	Tensile stress* [MPa]
Siberian Larch	660	10 - 12	1.5
Spruce C22	410	3.8	0.4
WPC	890	8.0	5.0

*Tensile stress perpendicular to grain.

C. Selection of Adhesives

Two polyurethane high-strength adhesives, see Table II, were selected for experimental testing. Both adhesives are designed specifically for bonded façade systems. The selection of adhesives was made on the basis of suitability for use, i.e. the recommendation of the manufacturer, technical parameters and the total price of the entire bonding system. Furthermore, all manufacturers indicate that their material can be used in combination with timber substructure as well as with steel or aluminum structure.

TABLE II
ADHESIVES SELECTED FOR TESTS

Manufacturer	Sika CZ, s.r.o.	Dinol GmbH
Adhesive system	SikaTack – Panel*	Dinitrol F500 LP*
Ultimate tensile strength	4.0 N·mm-^{2}	9.0 N·mm-^{2}
Ultimate shear strength	2.5 N·mm-^{2}	5.5 N·mm-^{2}
Service temperature	233.15 to 363.15 K	233.15 to 373.15 K

*Adhesive system intended for bonded façades.

IV. METHODS

The presented series of tests are following requirements given by Czech standards [7]-[9].

A. Test of the Adhesion of the Surface Finish to the Substructure

The series of tests were designed according to the requirements of [7]. The aim is to observe and record the maximal force that would be able to tear off a given surface finish area from the substrate while applying the perpendicular tension.

1) Production of Test Samples

The components which represents the cladding material, WPC, are square in shape, with 100 mm long sides and a thickness of 9 mm. Likewise the components which represents Siberian larch cladding material are square in shape, with 100 mm long sides and a thickness of 19 mm. The total are of such sample is 10 000 mm^2.

All components which represents load bearing substructure, spruce joists, are also square in shape, however with 50 mm long sides. The thickness of the all samples is 19 mm and total area of 2 500 mm^2. The area of 2 500 mm^2 is stated by relevant standard [6].

The Czech standard [7] requires circular profiles of the substructure component in cross section; however, it would be very problematical to produce such a profile from timber as well as the fact that the square shape represents the real situation more suitably.

The production itself involved several steps. Each adhesive needs a different modification to be made to the bonded surfaces depending on the requirements of individual manufacturer. However, it is mandatory in all cases to mechanically remove the dust and other dirt. Also, the surfaces have to be roughened. The spot of the adhesive bonding of the cladding material was raised by sandpaper P80 or P100, as well as the substructure material. The situation in presented research case was simpler since all used materials are wooden or wooden composites.

Subsequently, when using Dinitrol adhesive system, the surfaces of all components were chemically treated by cleaning liquid, Dinitrol 520 Kleenact (FP), with the aim to achieve the maximal adhesion. That means that grease - free surfaces are created. The manufacturer Sika CZ, s.r.o. does not recommend to use chemical cleaner on wooden substrates due to their extreme liquid absorptivity.

After approximately 10 minutes the surfaces were treated one thin coat of liquid primer over the whole surface with an application brush. The treatment is specified in detail and serves for a good adhesion of the adhesive to the support frame and the back - side of the facade plate, see Fig. 3. The prepared samples were left to dry for a period of 0.5 to 1 hour, depending on the bonding system. After the application of the primer, surfaces were again protected against dirt, dust, grease etc.

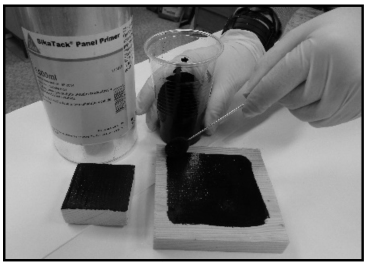

Fig. 3 Production of test sample – here with SikaTack – Panel and Siberian larch

Afterwards a sufficient quantity of adhesive was applied, to form a conical shape in the centre of the cladding element. This allowed the distribution of the adhesive all over the surface under the square shaped substructure element. After pushing the smaller element (substructure) onto the adhesive, four spacer elements ("beads") with a diameter of 3 mm were inserted into the adhesive. Distance of exactly 3 mm is demanded by the standard [6]. During application, the air temperature must not fall below 278.15 K or exceed 308.15 K. The relative air humidity must not be more than 75% [10], [11].

Subsequently, the square shaped element (substructure) was pushed down to the correct distance. The excessive adhesive was removed. A minimum of 6 samples had to be created for each adhesive system, as stipulated in the relevant standard [7]-[9].

2) Curing of Test Samples

The test samples were left to cure in a dry and clean environment as requires the relevant standard [7]. All test samples were stored in a room with an average air temperature of 294.15 K and a relative humidity of 52%. The samples have to be cured at least for one week as to obtain a sufficient desiccation of the bonded joint. As stated in [10] the samples have to be protected from weather and dust. For 5 hours after production, the temperature should not fall below the minimum temperature. The temperature of the part to be bonded (façade panels, subconstruction) have to be at least 3 K higher than the dew point temperature of the air in order to avoided the formation of condensation on the surface. Since the production as well as curing of the test samples took place

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in laboratory all listed restrictions were observed.

3) Conditioning

Conditioning essentially involves the alternating freezing and immersion into water bath of test samples in 15 cycles, and the subsequent testing of the adhesion of the surface finish to the substrate [9].

The test samples were immersed in a water bath with a temperature of (293.15 ± 3) K for 6 hours. After that time, they were taken out and placed in a refrigeratory chamber with a constant temperature of (253.15 ± 2) K for 18 hours. The period of placement in the water and in the refrigeratory chamber, i.e. 24 hours, formed 1 freezing cycle.

After the required 15 cycles had been completed, the samples were left to dry standing upright for a period of at least 14 days at an air temperature of (293.15 ± 3) K and with a relative humidity of (55 ± 10) %. Afterwards, tests described below were carried out.

4) General Steps of the Test Method

Test samples were placed in a special mould which allows attachment to a tearing device, as can be seen in Fig. 4. The process of tests was monitored and recorded. All test samples were strained until they reached the limit state.

Testing was carried out in an FP 10/1 tearing device with a maximum strength of 10 kN which enabled the monitoring and recording of the course of deformation with dependence on load. The speed of loading was 8.00 mm·min^{-1}.

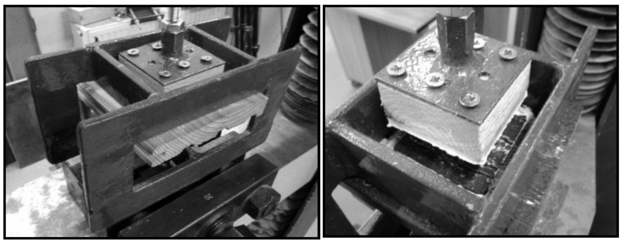

Fig. 4 Test of adhesion of the surface the substructure – here with SikaTack – Panel

B. Determination of the Tensile Lap-Shear of Bonded Assemblies

The series of tests were designed according to the requirements of [8]. The aim is to determine the strength during the exertion of shear stress on a single - lap joint under tensile loading.

1) Production of Test Samples

The test samples were composed of two identical plates, the area of such a plate is 25 by 100 mm, which is 2 500 mm^2. One of the plates represented the substructure, while the second plate represented façade cladding. Initially the distance of lapping, 12.5 mm (± 0.25 mm), was marked on one of the plates. Afterwards, the ends of the plates where both surfaces should lapped, were treated, as it is mentioned in the previous test, see Fig. 5.

An accurate amount of adhesive was applied to the one plate. The second plate was placed and pressed until the required thickness of approximately 3 mm was obtained. The thickness of the glue was ensured with the aid of "skewers", used as spacers. A minimum of 5 samples had to be made for each glue, as demanded by the relevant standard [8].

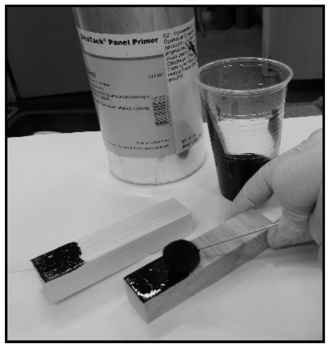

Fig. 5 Production of test sample – here with SikaTack – Panel and Siberian larch

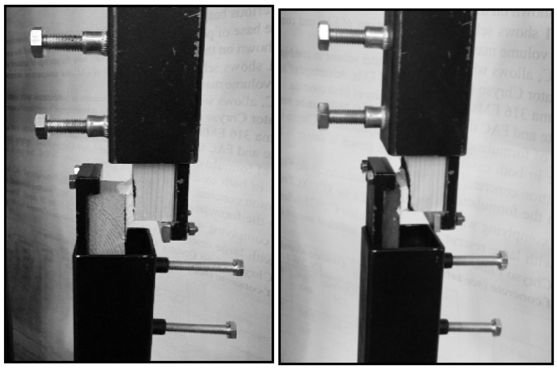

Fig. 6 Determination of the tensile lap – shear of bonded assemblies – here with SikaTack – Panel

2) Curing of Test Samples

The test samples were cured under the same conditions as in the previous test. All test samples were stored in a room with an average air temperature of 294.15 K and a relative humidity of 52 %. The samples have to be cured at least for one week as to obtain a sufficient desiccation of the bonded joint.

3) Conditioning

Again, the conditioning of test samples was under the same conditions as in the previous test. Conditioning involved the alternating freezing and immersion in a water bath of test samples in 15 cycles [9].

The test samples were immersed in a water bath with a temperature of (293.15 ± 3) K for 6 hours. After that time, they were taken out and placed in a refrigeratory chamber with a constant temperature of (253.15 ± 2) K for 18 hours. The period of placement in the water and in the refrigeratory chamber, i.e. 24 hours, formed 1 freezing cycle.

After the required 15 cycles had been completed, the samples were left to dry for a period of at least 14 days at an air temperature of (293.15 ± 3) K and with a relative humidity of (55 ± 10)%.

4) General Steps of the Test Method

Test samples were placed in sheaths which prevented the damage of the ends of the plates in the clamping pincers of the tearing device, as can be seen in Fig. 6.

Testing was carried out in an FP 10/1 tearing device with a maximum strength of 10 kN which enabled the monitoring and recording of the course of deformation with dependence on load. The speed of loading was 8.00 mm·min^{-1}.

V. Results

The bonding of the surface finish to the substrate and the determination of shear strength during stress was calculated according to the equation given by relevant standard [7], [8]. The values, which are presented in Tables III-VI, were calculated from the limit force required for debonding of the test sample in N. Also, the bonded area has to be taken into account.

The calculated values are presented as an arithmetic average of all test samples and the results are compared with results obtained from series of tests where test samples were tested immediately after curing, i.e. the test samples have not been exposed to the effect of freezing.

A. Test of the Adhesion of the Surface Finish to the Substructure

The bonding of the surface finish to the substrate is calculated according to (1):

$$\sigma_{adh} = \frac{F}{A}, \tag{1}$$

where F is the force required for debonding in N; A is the area of bonding in mm^2.

In Tables III and IV the calculated values are presented as an arithmetic average of six test samples, including a variation coefficient. The variation coefficient should not be higher than 30% according to relevant standard [7].

TABLE III
TEST RESULTS OF BONDING – SIBERIAN LARCH

Adhesive system	Bonding σ_{adh} [MPa]	Variation coefficient [%]	Bonding σ_{adh} [MPa]	Variation coefficient [%]
	Without Freezing		*With Freezing*	
SikaTack – Panel	1.33	18.86	1.64	17.29
Dinitrol F500 LP	1.51	22.89	1.45	12.73

TABLE IV
TEST RESULTS OF BONDING - WPC

Adhesive system	Bonding σ_{adh} [MPa]	Variation coefficient [%]	Bonding σ_{adh} [MPa]	Variation coefficient [%]
	Without Freezing		*With Freezing*	
SikaTack – Panel	1.07	11.73	1.18	9.48
Dinitrol F500 LP	0.82	15.77	0.81	3.45

B. Determination of the Tensile Lap-Shear of Bonded Assemblies

The determination of the tensile lap-shear of bonded assemblies is calculated according to (2):

$$\tau = \frac{F}{A} = \frac{F}{l * b}, \tag{2}$$

where F is the force required for debonding in N; A is the area of over lapping in mm^2; l is the length of bonded joint in mm; b is the breadth of bonded joint in mm.

In Tables V and VI the calculated values are presented as an arithmetic average of five test samples, including a variation coefficient. The variation coefficient should not be higher than 20% according to relevant standard [8].

TABLE V
TEST RESULTS OF LAP-SHEAR STRENGTH – SIBERIAN LARCH

Adhesive system	Shear strength τ [MPa]	Variation coefficient [%]	Shear strength τ [MPa]	Variation coefficient [%]
	Without Freezing		*With Freezing*	
SikaTack – Panel	1.17	18.65	1.85	9.83
Dinitrol F500 LP	0.92	14.82	2.27	30.59

TABLE VI
TEST RESULTS OF LAP-SHEAR STRENGTH – WPC

Adhesive system	Shear strength τ [MPa]	Variation coefficient [%]	Shear strength τ [MPa]	Variation coefficient [%]
	Without Freezing		*With Freezing*	
SikaTack – Panel	1.66	18.04	1.63	10.98
Dinitrol F500 LP	2.33	21.79	3.48	11.63

VI. Analysis

The results of the executed experiments are very varied and should be subjected to thorough analysis. The common feature of the resulting damage done to all test samples was the failure of the adhesive bond between the adhesive and the facade cladding. Even though the facade element detached from the substructure in the case of almost all the samples, the resulting strength measured is more than sufficient. Furthermore, the measured values for the SikaTack and Dinitrol systems fulfil the strength limit requirements set by the related legislation.

It can be seen from the results listed in Tables III and IV that the highest strength determined on the basis of the adhesion test was achieved in the case of the SikaTack – Panel adhesive system, where the average adhesion, even after exposure to freezing, measured is 1.64 N·mm^{-2} in a case of Siberian larch cladding. The achieved results are about 18.9% better than in the research case without exposure to freezing effect.

As it is apparent from Fig. 7 the failure of the bonded system was caused by the damage of the substructure, see the test sample on the right side. In the set of tests with SikaTack – Panel system combination of adhesive and cohesive failure have appeared, see the test sample on the right side in Fig. 7.

In Fig. 8 can be seen a very common type of failure. In both cases was used penetrative coating, this proved to be a very important element of the whole adhesive system in the series of tests. Despite this, the surfaces detached right where the adhesive and the penetrative layer connected in the case of both Sika and Dinitrol. Moreover, as can be seen in Fig. 8, samples with SikaTack bonding system showed also a failure of cohesion.

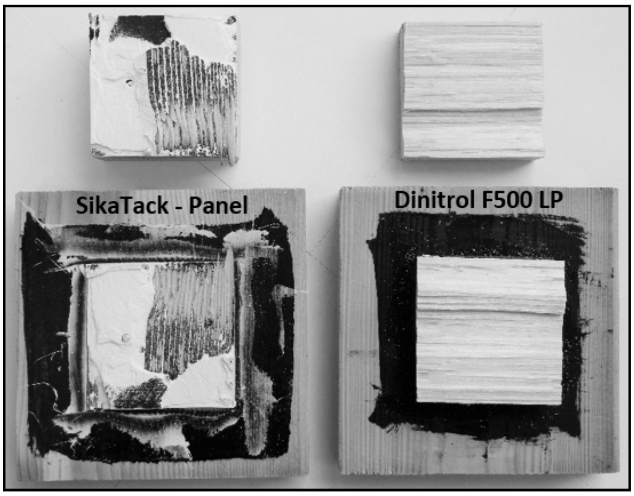

Fig. 7 Test of adhesion of the surface the substructure – Specimen failure during testing

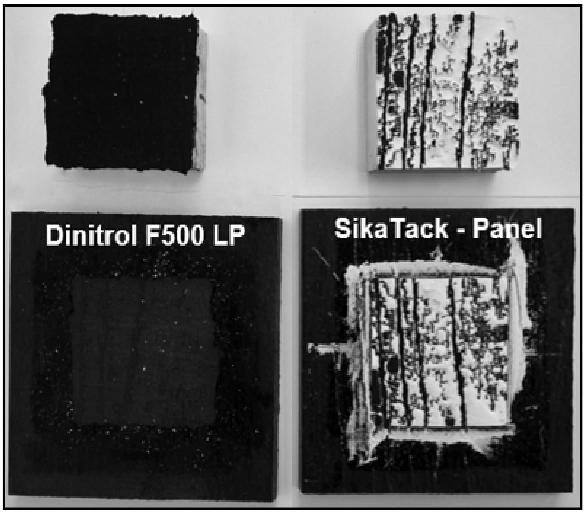

Fig. 8 Test of adhesion of the surface the substructure – Specimen failure during testing

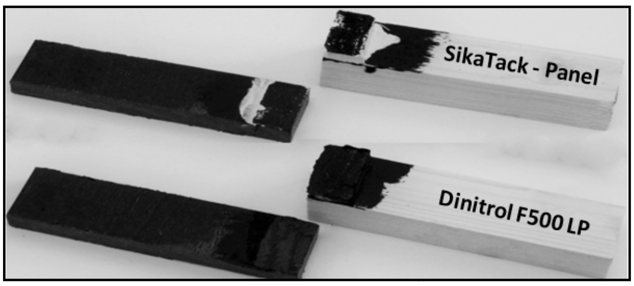

Fig. 9 Determination of the tensile lap – shear of bonded assemblies – Specimen failure during testing

In contrast, in the case of the tests for the determination of shear strength, test samples with combination of the Dinitrol system and WPC cladding showed the highest strength. The average shear strength of test samples without exposure to freezing is 2.17 $N \cdot mm^{-2}$, and after freezing cycles the recorded strength is 3.48 $N \cdot mm^{-2}$, that is improvement of the strength about 37.6%, see Table VI.

In the case of shear strength tests in combination with Siberian larch cladding within all test samples appeared the same failure, when the limit strength of the cladding material was achieved, see Fig. 10.

Fig. 10 Determination of the tensile lap – shear of bonded assemblies – Specimen failure during testing

VII. Discussion

Based on the measurements carried out and described above it was discovered that a wooden substructure is a suitable alternative in the construction of ventilated facades. Moreover, an immense advantage of wood is its sustainability and environmentally-friendly properties. A series of tests showed that in some cases the adhesion of the selected cladding material, i.e. exactly what was tested here, will be one area of weakness for bonded joints.

It was also demonstrated that the tested cladding materials are suitable for use in combination with bonded joints but that certain technical principles must be adhered to. It is mainly necessary to obtain information from the manufacturer of the given bonding system as to whether the system is suitable for use in combination with wood plastic composite, since the tests with this type of façade sheeting showed more cases where unstable behaviour of the adhesion have appeared, see Fig. 8.

In the tests with Siberian larch façade cladding and with SikaTack – Panel bonded system usually adhesive failure has appeared. However, in combination with Dinitrol system in almost all cases the failure of the substructure have appeared which shows that in this combination, the timber is the weakest point of the system.

Based on the presented test results, it can be assumed that the SikaTack - Panel and Dinitrol adhesive systems are both suitable bonding systems. In overall, bond strength was reached only in combination of SikaTack – Panel adhesive and Siberian larch cladding. This demonstrates the high quality of the selected adhesives and the low resistance of the cladding material.

However, testing also needs to be conducted in an environment which is not completely ideal. This would involve a series of tests which simulate the real outdoor environment, or the climate: the values subsequently determined would be a more authoritative indicator of the suitability of a selected combination of cladding and wooden substructure.

VIII. Conclusion

The performed tests showed the equivalence of the bonded joint system for ventilated facades in comparison with mechanical joints. Moreover, for certain types of cladding materials, joint bonding may appear to be a more suitable attachment method as it does not disrupt the structure of the cladding, thus preventing the degradation of the material e.g. via penetration of moisture into the cladding. However, the presented results also confirmed that the strength of the cladding material or load-bearing substructure is a decisive factor for bonded joints. The testing of specimens took place after their conditioning, when they were immersed into a water bath with a temperature of (293.15 ± 3) K for 6 hours and subsequently placed into a freezer with a temperature of (253.15 ± 2) K for 18 hours. These tests confirmed the measurements from previous testing without prior conditioning and did not feature greater differences between the selected adhesives.

Furthermore, the series of tests proved the fact that the installation procedure needs to be followed very strictly as the above-mentioned series of tests showed that the adhesion of wood plastic composite sheeting is unstable.

Another conclusion arising from the series of tests is the fact that the use of a wooden substructure for ventilated facades is not a limiting element for the whole system and is a more financially viable option in comparison with an aluminum or steel substructure.

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